Pollutant Thresholds for the Development of Management Guidelines for Corals: A Systematic Review and Meta-analysis

Prepared for
NOAA Fisheries Pacific Islands,
Pacific Islands Regional Office,
Habitat Conservation Division

Prepared by

Eileen M. Nalley, PhD[1]
Lillian J. Tuttle, PhD[1,2]
Alexandria L. Barkman[3]
Emily E. Conklin[1]
Devynn M. Wulstein[1]
Megan J. Donahue, PhD[1]

[1] Hawaiʻi Institute of Marine Biology, University of Hawaiʻi at Mānoa, 46-007 Lilipuna Road, Kāneʻohe, HI 96744 USA
[2] NOAA Fisheries Pacific Islands, Pacific Islands Regional Office, Habitat Conservation Division, 1845 Wasp Boulevard, Building 176, Honolulu, HI 96818 USA
[3] Kewalo Marine Laboratory, Pacific Biosciences Research Center, University of Hawaiʻi at Mānoa, 41 Ahui Street, Honolulu, HI 96813 USA

September 2021

ACKNOWLEDGEMENTS

This work was funded by the US National Oceanic and Atmospheric Administration (NOAA) [grant number NA19NMF4540068] "Developing stressor thresholds for reef-building coral species in the Pacific Islands Region" to PI Megan J. Donahue. Malia Chow, Anne Chung, Gerry Davis, and Stu Goldberg, all of the NOAA Pacific Islands Regional Office (PIRO) Habitat Conservation Division, gave feedback and organization support throughout the project.

ASSOCIATED PUBLICATIONS

Nalley, E.M.[1], Tuttle, L.J.[1,2], Barkman, A.L.[3], Conklin, E.E.[1], Wulstein, D.M.[1], Richmond, R.H.[3], Donahue, M.J.[1]. (2021). Water quality thresholds for coastal contaminant impacts on corals: A systematic review and meta-analysis. *Science of the Total Environment*, 794, 148632. https://doi.org/10.1016/j.scitotenv.2021.148632

[1] Hawaiʻi Institute of Marine Biology, Kāneʻohe, HI 96744 USA
[2] NOAA Fisheries Pacific Islands, Honolulu, HI 96818 USA
[3] Kewalo Marine Laboratory, Honolulu, HI 96813 USA

DATA STATEMENT

All data and code used in this study are available in the public repository: https://github.com/ljtuttle/coral_pollutant_thresholds

EXECUTIVE SUMMARY

BACKGROUND

Water quality is an important indicator of overall ecosystem health, and reefs with impaired water quality have a limited capacity to provide important ecosystem services. Establishing thresholds for coral responses to toxicant exposure can aid managers in the development of data-based water quality metrics, which is an especially urgent task in the face of climate change and other co-occurring stressors. To address this need, we conducted a systematic literature review and meta-analysis that assessed the impacts of chemical pollutants on scleractinian corals.

METHODS

To meet management needs, we conducted a systematic review of peer reviewed articles, academic theses and dissertations, and government reports to generate a comprehensive, global dataset. We focused on studies that quantified the impacts of a variety of pollutants on corals throughout their life cycle, with a specific interest on survival, reproduction, growth, behavior, and physiology. The search included pollutants of industrial, agricultural, and residential origin, and the results yielded studies that included tolerance thresholds for 13 metals, 18 pesticides, 5 polycyclic aromatic hydrocarbons (PAHs), a polychlorinated biphenyl (PCB), and an estrogenic pharmaceutical compound. The review identified 55 sources that met the predetermined criteria for inclusion, but some toxicants (i.e., copper and diuron) had far more robust experimental datasets than others. For these data-rich contaminants, we modified models developed for biopharmaceutical approaches to conduct Bayesian hierarchical meta-analyses. These models incorporate data from several sources to create dose-response (i.e., E_{max}) curves that characterize the relationship between applied pollutant concentrations and measured physiological responses in corals. These can be used to assess the estimated response and health of the coral at a range of pollutant concentrations. For toxicants that did not have sufficient comparable data, we conducted a quantitative review and provided reported threshold concentrations. These included the lowest observed adverse effect level (LOAEL), as well as the EC_{50}, or the concentration that results in an "effect" (e.g., mortality) in 50% of the individuals examined.

RESULTS

The only pollutants with sufficient data to conduct a meta-analysis were copper, diuron, and nickel. Copper had the most data available, and we were able to develop dose-response curves for the impacts of copper on fertilization success (EC_5 = 22.6 μg L^{-1}, EC_{50} = 48.6 μg L^{-1}), larval settlement (EC_5 = 27.7 μg L^{-1}, EC_{50} = 44.8 μg L^{-1}), larval survival (EC_5 = 44.7 μg L^{-1}, EC_{50} = 101.0 μg L^{-1}), and photosynthetic efficiency (EC_5 = 285.5 μg L^{-1}, EC_{50} = 365.3 μg L^{-1}). Diuron similarly had sufficient information for the development of a dose-response curve for photosynthetic efficiency (EC_5 = 2.5 μg L^{-1}, EC_{50} = 43.7 μg L^{-1}). Nickel had sufficient information for a meta-analysis on fertilization and chlorophyll concentration, but these responses did not exhibit a dose-response relationship. The inhibitory log-logistic (E_{max}) model used for copper and diuron was not appropriate in this case. The impacts of all metals examined on fertilization were also compared using molar concentration for standardization, and copper inhibited fertilization at the lowest concentration, followed by tin, zinc, and lead. Our systematic review highlighted additional threshold concentrations for these pollutants as available, and the gap analysis indicated that certain pollutants are extremely well studied, while others have little to no data available to support management efforts. Finally, we calculated the cumulative impacts of copper, a well-studied pollutant, over the life cycle of a coral, demonstrating that pollutant exposure can have cascading effects throughout the lifetime of a coral.

CONCLUSIONS & RECOMMENDATIONS

Copper, which has been used in antifouling paints, has been examined in numerous studies, and the impacts have been quantified on several different coral responses. Having sufficient data allows for more sophisticated dose-response analyses, as well as life cycle assessments. Our capacity to generate these estimates for pollutants with less data is more limited. Because it is well known that pollutants typically are found in the environment as a mix of several different toxicants, often alongside other environmental stressors such as ultraviolet radiation, high temperatures, or high sedimentation, we recommend using the precautionary approach in these data limited situations. In addition, many studies quantify lethal stress responses, but there is evidence that many sublethal responses occur as well, and in most cases likely go undetected prior to tissue loss, bleaching, or mortality. Establishing conservative water quality thresholds that account for the myriad of unknown and sublethal co-occurring and potentially synergistic stressors will provide a necessary buffer for coral health. As reefs continue to face the global stressor of climate change, it is also important that aggressive action be taken to mitigate local stressors that can increase the resilience and recovery capacity of coral reef ecosystems.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

POLLUTANT IMPACTS ON CORALS

A thorough review of measured pollutant thresholds is provided in the Supplemental Materials, which was completed as part of this project. A Bayesian hierarchical dose-response meta-analysis was used to determine thresholds for copper and diuron. Reported thresholds are provided for other pollutants based on a quantitative review, and a gap analysis is provided to summarize missing information. Oil and dispersants were not included in this analysis, so an independent review of these stressors is included below.

OIL AND DISPERSANTS

Oil and dispersants were not included in the primary meta-analysis and quantitative review because a thorough review has already been conducted by Turner and Renegar (2017). Variability in the types of oil and dispersants examined, as well as differences in experimental methodology and measurement techniques, result in data gaps that preclude a meta-analysis at this time (Nordborg et al., 2018). Though natural seeps constitute the greatest input of crude oil into marine ecosystems, accidental releases of hydrocarbons as a result of anthropogenic activities pose a grave threat to coral reefs and other coastal ecosystems when they occur (Downs et al., 2006; Frometa et al., 2017; Guzman et al., 2020). The sudden input of large volumes of oil can be especially detrimental to otherwise pristine areas that have not adapted to continuous or periodic hydrocarbon exposure (Turner and Renegar, 2017).

Corals may be exposed to oil acutely during a spill event from extraction or transportation activities, or oil may be introduced chronically through land-based runoff, recreational vessels, and natural seeps. Oil is actually a complex mixture of thousands of compounds that include hydrocarbons, olefins, and aromatics (Turner and Renegar, 2017). Polycyclic aromatic hydrocarbons (PAHs) are often the component of greatest concern for accumulation in organisms because of their lipophilic nature, meaning they are easily absorbed into the tissues of marine organisms. PAHs can also become orders of magnitude more toxic in the presence of ultraviolet radiation, which is significant on shallow reefs (Nordborg et al., 2018; Pelletier et al., 1997; Roberts et al., 2017). In addition to the components of oil itself, the waste products of offshore oil operations, such as produced formation water, can also be toxic to corals, with exposure to these waste products leading to reduced photosynthetic efficiency and bleaching (Jones and Heyward, 2003).

In the case of spills and acute exposures, oil is intentionally broken down with the addition of chemical dispersants containing surfactants and solvents, which facilitates degradation in the water column (Epstein et al., 2000). This intentional breakdown process has implications for the distribution of oil and dispersants and their eventual uptake by marine organisms (Turner and Renegar, 2017). As oil is broken down and made more miscible with seawater, the concentrations of oil in the water accommodated fraction (WAF) increase as compared to the amount remaining on the surface. As benthic, sessile organisms with larvae that can spend months in the water column, corals have a greater likelihood of being exposed to this dispersed oil than they are to surface slicks. Problematically, experimental studies indicate that the chemical dispersants used tend to increase the toxicity of the oil to corals (e.g., Shafir et al., 2007).

Laboratory studies that examine the effects of oil and chemical dispersants on corals use a variety of oil types (e.g., Arabian crude oil, Iranian crude oil, Louisiana sweet crude, motor oil), dispersant types (e.g., Corexit, Ardrox, Slickgone), oil components (e.g., total hydrocarbons, benzene, PAHs), and exposure types (e.g., flow through, static, direct pressure) (Turner and Renegar, 2017). In some cases the concentrations of toxicant are measured in the experiment *in situ*, but in other cases the concentrations are measured prior to the removal of the WAF without accounting for the percentage remaining on the surface, which results in overestimated concentrations (Loya and Rinkevich, 1979). Rather than reporting the measured concentrations, some studies also report the percent dilution of the WAF, which results in an estimated concentration rather than a measured value. For the purpose of comparison in this report, all toxicant concentrations have been converted to a comparable concentration reported in ppm (Tables 1-3), and it has been noted when the WAF was used in place of measured concentrations.

The species of coral examined, source of the oil used in experiments, and type of dispersant can all impact the magnitude of the responses recorded (Negri et al., 2018; Reimer, 1975; Shafir et al., 2007; Villanueva et al., 2008). Oil and dispersant concentrations can vary with location and depth as well. For example, hydrocarbon concentrations of up to 50 ppm have been found in droplets of chemical dispersed oil, and these can persist down to more than 9 meters (McAuliffe et al., 1980). Co-occurring environmental conditions such as flow rate, ultraviolet radiation, and water temperature can also influence the magnitude of impact (Nordborg et al., 2018). These differences, combined with variability in life history stage, species, location, and response type, make it difficult to compare between experimental studies in a way that allows for the development of consistent stressor threshold.

The tolerance of corals to exposure to oil and dispersants may vary by species, morphology, location, or other factors. For example, corals that are found in or near harbors may be exposed to oil on a more regular basis than corals found further away from human activities. Mortality was also higher in static experiments than in those using flow through systems or aeration (Turner and Renegar, 2017), suggesting that reefs in areas with low flow or high residence times may be more susceptible to oil exposure, possibly due to decreased oxygen availability. Reefs that have been impacted by oil spills have demonstrated a decline in coral cover, especially in branching taxa such as *Acropora, Seriatopora,* and *Stylophora* (Bak, 1987; Fishelson, 1973; Guzman et al., 1991). However, in experimental studies, *Pocillopora* spp. appear less vulnerable to oil exposure than *Seriatopora* spp., indicating differences even within branching taxa, and variability in responses have also been reported among congeneric species (Te 1991; Villanueva et al., 2008).

The likelihood and degree of exposure also varies within the life cycle of corals. Adult corals are benthic and may only come into direct contact with an oil slick during extreme low tides (Villanueva et al., 2008). Coral gametes and larvae, however, are more likely to come into direct contact with a surface slick of oil if a spill or leak occurs during a broadcast spawning or planulation event. The soluble portion of oil, or the WAF, is more likely to threaten adult corals, and the use of chemical dispersants to break down oil can increase the amount of WAF that adult corals encounter. In many cases, the combination of oil and dispersants is also more toxic to corals (Table 1) than either oil (Table 2) or dispersant (Table 3) on their own (Elgershuizen and De Kruijf, 1976; Lewis, 1971; Shafir et al., 2007). Some studies have even recorded additive impacts of oil and dispersants (Negri and Heyward, 2000). However, exposure to oil on its own may still induce bleaching, tissue loss, and reduced growth (Reimer et al., 1975; Shafir et al., 2007).

Reefs near sites with known oil pollution had fewer juvenile corals and decreased rugosity, indicating that the effects of oil pollution may also manifest over time and impact future generations in ways that are not immediately apparent (Bak, 1987; Fishelson, 1973). Reports of fewer juvenile corals following exposure to oil is supported by evidence that oil pollution decreases fecundity in adult corals by reducing the number of gonads per polyp and inducing premature ejection of coral larvae (Loya and Rinkevich, 1979; Rinkevich and Loya, 1979; Villanueva et al., 2011). Even months after a spill, upregulation of xenobiotic metabolizing enzymes used for detoxification has been seen in *Porites lobata* and *Pocillopora damicornis* (Downs et al. 2006; Downs et al., 2012). Commonly used dispersants (e.g., Corexit 9527) can also independently trigger a cellular stress response (Venn et al., 2009).

The early life stages of corals are typically more sensitive to toxicants than adult stages (Byrne, 2012), and settlement appears to be a period that is particularly vulnerable to hydrocarbon exposure (Negri et al., 2016; Nordborg et al., 2018). It is thought that the WAF of oil may disrupt chemical cues from crustose coralline algae that corals rely on to trigger metamorphosis (Negri et al., 2016). The presence of oil and dispersant in the water column reduces the likelihood of larval settlement, and increased mortality in coral larvae was seen as a result of longer durations of exposure to oil, dispersant, and dispersed oil (Epstein et al. 2000; Goodbody-Gringley et al. 2013; Lane and Harrison, 2000; Negri and Heyward 2000). Species with larvae that undergo spontaneous metamorphosis quickly may be more vulnerable to oil exposure as well because they are forced to settle in suboptimal conditions (Villanueva et al., 2008). Inhibited metamorphosis and sublethal responses, including impacts on development and morphology, have all been observed in larvae exposed to environmentally relevant concentrations of hydrocarbons (Hartmann, 2015; Lewis, 1971; Negri et al., 2016; Nordborg et al., 2018).

In addition to the increased likelihood of being exposed to dispersed oil as compared to a surface slick or even the WAF of oil alone, the combination of oil and chemical dispersant has a greater negative impact on fertilization than either oil or dispersant independently (Negri and Heyward, 2000). Similarly, coral larvae are also more sensitive to chemically dispersed oil than oil or dispersant alone (Epstein et al., 2000; Goodbody-Gringley et al. 2013; Lane and Harrison, 2000; Negri and Heyward, 2000). Ultraviolet radiation also increases the magnitude of the impact of oil on early life stages of corals and other marine invertebrates, nearly doubling the sensitivity of coral larvae to hydrocarbons in some cases (Negri et al., 2016; Nordborg et al., 2018). High temperatures can similarly increase the toxicity of fuel in the marine environment, with this interaction affecting photosynthesis in corals that did not respond to exposure to fuel alone (Kegler et al., 2015). Chemically dispersed oil is also more toxic to adult corals, with the two combined inhibiting photosynthesis in corals that did not respond to either oil or dispersant alone (Knap, 1987).

Combinations of oil and dispersant had greater impacts on the health of corals at all life stages than oil did independently, so it is recommended that caution be used when adding dispersant to spilled oil near coral reefs. Some dispersants are more toxic to corals than others, so when dispersants are used, it is important to choose the least toxic options (Negri et al., 2018). Early life stages appear to be especially impacted by hydrocarbons and dispersants (Epstein et al., 2000), so it is critical that additional caution be taken during and after spawning events. Because coral larvae can be in the water column for months, they are particularly vulnerable to spills and dispersant applications (Nordborg et al., 2018). Additional standardized experimental research is needed to better identify the threshold concentrations of oil, dispersants, and the combination of the two that present physiological thresholds for corals exhibiting a stress response. Many shallow reefs also experience intense sunlight, high temperatures, and limited water movement, which are conditions that are known to exacerbate oil and dispersant toxicity and therefore must be incorporated into experimental designs. There is, however, conclusive evidence at this time that exposure to oil and dispersed oil can negatively affect critical processes in corals, such as settlement, and at some concentrations exposure to oil and dispersant can cause mortality.

Table 1. Reported effects of dispersant and oil on corals from experimental studies. If a range of values was provided, the minimum (i.e., most biologically conservative) value is reported below. When noted, concentrations are based on stock solutions prepared prior to the removal of the water accommodated fraction (WAF), meaning reported concentrations are much higher than the actual concentrations used in the experiment (Loya and Rinkevich, 1979). The LC_{50} values refer to the toxicant concentration that is lethal to 50% of the individuals.

Oil and Dispersant Concentrations	Reported Effect	Species	Source
0.03 ppm total hydrocarbons from heavy crude oil from Wandoo platform in Western Australia and 0.003 ppm Corexit 952 (10:1 oil to dispersant)	Reduced fertilization and larval metamorphosis	*Acropora millepora*	Negri and Heyward, 2000
0.12 ppm BP Horizon crude oil with Corexit 9500 (oil to dispersant ratio not given)	96-hour LC_{50}	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
0.23 ppm total hydrocarbons from heavy crude oil from Wandoo platform in Western Australia and 0.002 ppm Corexit 952 (100:1 oil to dispersant)	Reduced fertilization and larval metamorphosis	*Acropora millepora*	Negri and Heyward, 2000
0.6 ppm Bunker Fuel Oil 467 and 8.3 ppm Ardrox 6120 (LC_{50} measured separately for hydrocarbons and dispersant in dispersed oil)	LC_{50} of larvae after 96 hours of exposure	*Acropora tenuis*	Lane and Harrison, 2000
0.8 ppm Bunker Fuel Oil 467 and 12.5 ppm Ardrox 6120 (LC_{50} measured separately for hydrocarbons and dispersant in dispersed oil)	LC_{50} of larvae after 96 hours of exposure	*Goniastrea aspera*	Lane and Harrison, 2000
1.5 ppm Bunker Fuel Oil 467 and 23.7 ppm Ardrox 6120 (LC_{50} measured separately for hydrocarbons and dispersant in dispersed oil)	LC_{50} of larvae after 96 hours of exposure	*Platygyra sinensis*	Lane and Harrison, 2000
1.84 ppm BP Horizon crude oil with Corexit 9500 (oil to dispersant ratio not given)	LC_{50} of larvae	*Porites astreoides*	Goodbody-Gringley et al., 2013
4.28 ppm BP Horizon crude oil with Corexit 9500 (oil to dispersant ratio not given)	Reduced larval settlement and survival	*Porites astreoides*	Goodbody-Gringley et al., 2013
14.73 ppm BP Horizon crude oil with Corexit 9500 (oil to dispersant ratio not given)	Reduced larval settlement	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
19 ppm Arabian Light crude oil and 1 ppm Corexit 9527 (19:1 oil to dispersant)	85% reduction in photosynthetic efficiency	*Diploria strigosa*	Cook and Knap, 1983
20 ppm Arabian Light Crude oil and 1 ppm Corexit 9527 (20:1 oil to dispersant)	Mesenterial filament extrusion, extensive tissue rupture, depression of tentacle extension, and increased mortality	*Diploria strigosa*	Wyers et al., 1986

500 ppm WAF of Egyptian crude oil and 50 ppm Bioreico, Emulgal, Biosolve, Inipol, and Petrotech (10:1 oil to dispersant)	Reduced larval survival after 96 hours of exposure	*Stylophora pistillata*	Epstein et al., 2000
1824 ppm WAF Nigerian crude oil and 182.4 ppm Shell LTX dispersant (10:1 oil to dispersant)	LC_{50} of adult corals	*Madracis mirabilis*	Elgershuizen and De Kruijf, 1976
2025 ppm WAF Forcados crude oil and 202.5 ppm Shell LTX dispersant (10:1 oil to dispersant)	LC_{50} of adult corals	*Madracis mirabilis*	Elgershuizen and De Kruijf, 1976
5000 ppm WAF Egyptian crude oil and 250 ppm Slickgone (20:1 oil to dispersant)	Increased nubbin mortality	*Stylophora pistillata, Pocillopora damicornis*	Shafir et al., 2007
5000 ppm WAF Egyptian crude oil and 125 ppm Bioreico, Emulgal, Inipol, and Petrotech dispersants (40:1 oil to dispersant)	Increased nubbin mortality	*Stylophora pistillata, Pocillopora damicornis*	Shafir et al., 2007
5000 ppm WAF Egyptian crude oil and 50 ppm Dispolen (100:1 oil to dispersant)	Increased nubbin mortality	*Stylophora pistillata, Pocillopora damicornis*	Shafir et al., 2007
5000 ppm WAF Egyptian crude oil and 50 ppm Biorecio, Emulgal, Inipol (100:1 oil to dispersant)	Increased nubbin mortality	*Pocillopora damicornis*	Shafir et al., 2007
7264 ppm WAF Tia Juana Pesado crude oil and 762.4 ppm Shell LTX dispersant (10:1 oil to dispersant)	LC_{50} of adult corals	*Madracis mirabilis*	Elgershuizen and De Kruijf, 1976

Table 2. Reported impacts of oil on corals from experimental studies. If a range of values was provided, the minimum (i.e., most biologically conservative) value is reported below. When noted, concentrations are based on stock solutions prepared prior to the removal of the water accommodated fraction (WAF), meaning reported concentrations are much higher than the actual concentrations used in the experiment (Loya and Rinkevich, 1979). The LC_{50} values refer to the toxicant concentration that is lethal to 50% of the individuals. The EC_{10} values similarly refer to the toxicant concentration that elicits a negative response in 10% of the individuals examined.

Concentration	**Reported Effect**	**Species**	**Source**
0.02 ppm (without UVR) and 0.015 ppm (with UVR) of heavy fuel oil	Settlement EC_{10}	*Acropora tenuis*	Nordborg et al., 2018
0.08 ppm total hydrocarbons (crude oil from the Wandoo platform in Western Australia)	Reduced larval metamorphosis	*Acropora millepora*	Negri and Heyward, 2000
0.1 ppm (without UVR) and 0.064 ppm (with UVR) of water accommodated fraction of North West Shelf Condensate	Metamorphosis EC_{10}	*Acropora tenuis*	Negri et al., 2016
0.135 ppm crude oil hydrocarbons (from oil contaminated sea water)	Reduced larval survival and settlement	*Orbicella faveolata*	Hartmann et al., 2015
0.145 ppm crude oil hydrocarbons (from oil contaminated sea water)	Reduced larval settlement	*Agaricia humilis*	Hartmann et al., 2015
0.3 ppm (without UVR) and 0.12 ppm (with UVR) of diesel	Settlement EC_{10}	*Acropora tenuis*	Nordborg et al., 2018
0.35 ppm (without UVR) and 0.13 (with UVR) North West Shelf Condensate	Lowest significant observed adverse effect level (LOAEL) for metamorphosis	*Acropora tenuis*	Negri et al., 2016
0.45 ppm BP Horizon crude oil	96-hour LC_{50} of larvae	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
0.49 ppm BP Horizon crude oil	Reduced larval survival	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
0.51 ppm BP Horizon crude oil	LC_{50} of larvae	*Porites astreoides*	Goodbody-Gringley et al., 2013
0.62 ppm BP Horizon crude oil	Decreased larval settlement and survival	*Porites astreoides*	Goodbody-Gringley et al., 2013
0.65 ppm BP Horizon crude oil	Decreased larval settlement	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
1.29 ppm naphthalene (PAH)	Metamorphosis EC_{10}	*Acropora tenuis*	Negri et al., 2016
2.16 ppm xylene (PAH)	Metamorphosis EC_{10}	*Acropora tenuis*	Negri et al., 2016
3.8 ppm naphthalene (PAH)	LOAEL for metamorphosis	*Acropora tenuis*	Negri et al., 2016
3.8 ppm bunker Fuel Oil 467	LC_{50} of larvae	*Acropora tenuis*	Lane and Harrison, 2000
5.0 ppm WAF Egyptian crude oil	Reduced larval settlement	*Stylophora pistillata*	Epstein et al., 2000
6.8 ppm bunker Fuel Oil 467	Reduced larval survival after 96 hours of exposure	*Goniastrea aspera*	Lane and Harrison, 2000
8.28 ppm toluene (PAH)	Metamorphosis EC_{10}	*Acropora tenuis*	Negri et al., 2016
9.6 ppm xylene (PAH)	LOAEL for metamorphosis	*Acropora tenuis*	Negri et al., 2016

20 ppm Arabian Light Crude oil	Mesenterial filament extrusion, extreme tissue contraction, and localized pigment loss	*Diploria strigosa*	Wyers et al., 1986
30.0 ppm toluene (PAH)	LOAEL for metamorphosis	*Acropora tenuis*	Negri et al., 2016
31.1 ppm benzene (PAH)	Metamorphosis EC_{10}	*Acropora tenuis*	Negri et al., 2016
50 ppm WAF crude oil from Barbados General Crude Oil Co.	Reduced tentacle expansion and feeding behavior	*Porites porites, Madracis asperula, Favia fragum*	Lewis, 1971
69.0 ppm benzene (PAH)	LOAEL for metamorphosis	*Acropora tenuis*	Negri et al., 2016
100 ppm WAF Iranian crude oil	Premature abortion of planula larvae	*Stylophora pistillata*	Loya and Rinkevich, 1979
500 ppm WAF crude oil from Barbados General Crude Oil Co.	Reduced tentacle expansion	*Agaricia agaricites*	Lewis, 1971
1000 ppm WAF IFO 180 marine fuel oil	Increased expression of enzymes associated with detoxification and oxidative stress	*Pocillopora damicornis*	Rougée et al., 2006
3000 WAF ppm Iranian crude oil	Reduced number of gonads per polyp, and increased adult mortality in six-month experiment	*Stylophora pistillata*	Rinkevich and Loya, 1979
2500 ppm WAF Malampaya natural gas condensate (primary components are paraffins and aromatic hydrocarbons)	Premature abortion of larvae and increased fragment mortality index	*Pocillopora damicornis*	Villanueva et al., 2011
1000 ppm WAF Malampaya natural gas condensate	Reduced polyp count in juveniles	*Stylophora pistillata, Seriatopora guttatus*	Villanueva et al., 2008
5000 ppm WAF Malampaya natural gas condensate	Reduced larval metamorphosis after 96 hours of exposure	*Seriatopora hystrix, Seriatopora guttatus*	Villanueva et al., 2008
5000 ppm WAF Malampaya natural gas condensate	Reduced spat diameter	*Stylophora pistillata, Seriatopora hystrix, Seriatopora guttatus*	Villanueva et al., 2008
10,000 ppm WAF Malampaya natural gas condensate	Reduced larval metamorphosis after 96 hours of exposure	*Stylophora pistillata*	Villanueva et al., 2008
10,000 WAF ppm Malampaya natural gas condensate	Reduced polyp count in juveniles	*Seriatopora hystrix, Pocillopora verrucosa*	Villanueva et al., 2008
10,000 ppm WAF Malampaya natural gas condensate	Reduced larval survival in 96-hour experiment	*Seriatopora hystrix, Seriatopora guttatus*	Villanueva et al., 2008
100,000 ppm WAF Nigerian, Forcados, and Tia Juana Pesado crude oil	LC_{50} of adult corals after 24 hours of exposure	*Madracis mirabilis*	Elgershuizen and De Kruijf, 1976

Table 3. Reported effects of dispersant on corals from experimental studies. If a range of values was provided, the minimum (i.e., most biologically conservative) value is reported below. The LC_{50} values refer to the toxicant concentration that is lethal to 50% of the individuals. The EC_{10} values similarly refer to the toxicant concentration that elicits a negative response in 10% of the individuals examined.

Dispersant Concentration	**Reported Effect**	**Species**	**Source**
1.6 ppm Slickgone LTSW	Settlement EC_{10} after 24 hours of exposure	*Acropora millepora*	Negri et al., 2018
1.9 ppm Finasol OSR52 and Ardrox 6120	Settlement EC_{10} after 24 hours of exposure	*Acropora millepora*	Negri et al., 2018
2.5 ppm Corexit EC9500A	Settlement EC_{10} after 24 hours of exposure	*Acropora millepora*	Negri et al., 2018
5 ppm Bioreico, Emulgal, Biosolve Inipol, and Petrotech	Changes in morphology and behavior of larvae, as well as decreased settlement and survival	*Stylophora pistillata*	Epstein et al., 2000
5 ppm Corexit 9527	Reduced larval metamorphosis	*Acropora millepora*	Negri and Heyward, 2000
5.6 ppm Slickgone NS	Settlement EC_{10} after 24 hours of exposure	*Acropora millepora*	Negri et al., 2018
8.3 ppm Ardrox 6120	LC_{50} of larvae after 96 hours of exposure	*Acropora tenuis*	Lane and Harrison, 2000
10 ppm Corexit 9527	Reduced fertilization	*Acropora millepora*	Negri and Heyward, 2000
12.5 ppm Ardrox 6120	LC_{50} of larvae after 96 hours of exposure	*Goniastrea aspera*	Lane and Harrison, 2000
19.7 ppm Corexit 9500	LC_{50} of larvae	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
23.7 ppm Ardrox 6120	LC_{50} of larvae after 96 hours of exposure	*Platygyra sinensis*	Lane and Harrison, 2000
25 ppm Corexit 9500	Reduced larval settlement	*Porites astreoides*	Goodbody-Gringley et al., 2013
33.4 ppm Corexit 9500	LC_{50} of larvae	*Porites astreoides*	Goodbody-Gringley et al., 2013
50 ppm Corexit 9500	Reduced larval survival	*Porites astreoides*	Goodbody-Gringley et al., 2013
50 ppm Corexit 9500	Reduced larval settlement and survival	*Orbicella faveolata*	Goodbody-Gringley et al., 2013
50 ppm Corexit	Reduced tentacle activity and feeding	*Madracis asperula*	Lewis, 1971
100 ppm Corexit	Reduced tentacle activity	*Porites*	Lewis, 1971
100 ppm Corexit	Reduced feeding activity	*Favia fragum*	Lewis, 1971
500 ppm Corexit	Reduced tentacle activity	*Agaricia agaricites*	Lewis, 1971
500 ppm Corexit	Reduced tentacle activity	*Favia fragum*	Lewis, 1971
700 ppm Shell LTX	LC_{50} of adult corals	*Madracis mirabilis*	Elgershuizen and De Kruijf, 1976

REFERENCES

Bak, R. (1987). Effects of chronic oil pollution on a Caribbean coral reef. *Marine Pollution Bulletin*, 18(10), 534–539. https://doi.org/10.1016/0025-326X(87)90537-6

Byrne, M. (2012). Global change ecotoxicology: identification of early life history bottlenecks in marine invertebrates, variable species responses and variable experimental approaches. *Marine Environmental Research*, *76*, 3-15. https://doi.org/10.1016/j.marenvres.2011.10.004

Cook, C. & Knap, A. (1983). Effects of crude oil and chemical dispersant on photosynthesis in the brain coral *Diploria strigosa*. *Marine Biology*, 78(1), 21–27. https://doi.org/10.1007/BF00392967

Downs, C., Richmond, R., Mendiola, W., Rougée, L., & Ostrander, G. (2006). Cellular physiological effects of the MV Kyowa violet fuel-oil spill on the hard coral, *Porites lobata*. *Environmental Toxicology and Chemistry*, 25(12), 3171–3180. https://doi.org/10.1897/05-509R1.1

Downs, C., Ostrander, G., Rougée, L., Rongo, T., Knutson, S., Williams, D., Mendiola, W., Holbrook, J., & Richmond, R. (2012). The use of cellular diagnostics for identifying sub-lethal stress in reef corals. *Ecotoxicology*, 21(3), 768–782. https://doi.org/10.1007/s10646-011-0837-4

Elgershuizen, J. & De Kruijf, H. (1976). Toxicity of crude oils and a dispersant to the stony coral *Madracis mirabilis*. *Marine Pollution Bulletin*, 7(2), 22–25. https://doi.org/10.1016/0025-326X(76)90305-2

Epstein, N., Bak, R.P.M., & Rinkevich, B. (2000). Toxicity of third generation dispersants and dispersed Egyptian crude oil on Red Sea coral larvae. *Marine Pollution Bulletin* 40(6): 497-503.

Fishelson, L. (1973). Ecology of Coral reefs in the Gulf of Aqaba (Red Sea) influenced by pollution. *Oecologia*, 12(1), 55–67. https://doi.org/10.1007/BF00345470

Frometa, J., DeLorenzo, M.E., & Pisarski, E.C. (2017). Toxicity of oil and dispersant on the deep water gorgonian octocoral, *Swiftia exserta*, with implications for the effects of the Deepwater Horizon oil spill. *Marine Pollution Bulletin* 122: 91-99. http://dx.doi.org/10.1016/j.marpolbul.2017.06.009

Goodbody-Gringley, G., Wetzel, D.L., Gillon, D., Pulster, E., Millier, A., & Ritchie, K.B. (2013). Toxicity of Deepwater Horizon source oil and the chemical dispersant, Corexit 9500, to coral larvae. *PLoS ONE* 8(1): e45574. https://doi.org/10.1371/journal.pone.0045574

Guzman, H., Jackson, J., & Weil, E. (1991). Short-term ecological consequences of a major oil spill on Panamanian subtidal reef corals. *Coral Reefs*, *10*(1), 1–12. https://doi.org/10.1007/BF00301900

Guzman, H.M., Kaiser, S., & Weil, E. (2020). Assessing the long-term effects of a catastrophic oil spill on subtidal coral reef communities off the Caribbean coast of Panama (1985-2017). *Marine Biodiversity* 50:28. https://doi.org/10.1007/s12526-020-01057-9

Hartmann, A., Sandin, S., Chamberland, V., Marhaver, K., de Goeij, J., & Vermeij, M. (2015). Crude oil contamination interrupts settlement of coral larvae after direct exposure ends. *Marine Ecology Progress Series,* 536, 163–173. https://doi.org/10.3354/meps11437

Jones, R.J. & Heyward, A.J. (2003) The effects of Produced Formation Water (PFW) on coral and isolated symbiotic dinoflagellates of coral. *Marine and Freshwater Research*, 53, 153-162. https://doi.org/10.1071/MF02108

Kegler, P., Baum, G., Indriana, L.F., Wild, C., & Kunzmann, A. (2015) Physiological response of the hard coral *Pocillopora verrucosa* from Lombok, Indonesia, to two common pollutants in combination with high temperature. *PLoS ONE,* 10(11), e0142744. https://doi.org/10.1371/journal.pone.0142744

Knap, A.H. (1987). Effects of chemically dispersed oil on the brain coral, *Diploria strigosa*. *Marine Pollution Bulletin*, 18(3), 119-122. https://doi.org/10.1016/0025-326X(87)90131-7

Lane, A. & Harrison, P (2000). Effects of oil contaminants on survivorship of larvae of the scleractinian reef corals *Acropora tenuis, Goniastrea aspera and Platygyra sinensis* from the Great Barrier

Reef. In: Proceedings of the Ninth International Coral Reef Symposium, Bali, 23–27 October 2000, pp. 403–408.

Lewis, J. (1971). Effect of crude oil and an oil-spill dispersant on reef corals. *Marine Pollution Bulletin*, 2(4), 59–62. https://doi.org/10.1016/0025-326X(71)90211-6

Loya, Y., & Rinkevich, B. (1979). Abortion Effect in Corals Induced by Oil Pollution. *Marine Ecology Progress Series*, 1, 77–80. https://doi.org/10.3354/meps001077

McAuliffe, C.D., Johnson, J.C., Greene, S.H., Canevari, G.P., & Searl, T.D. (1980). Dispersion and weathering of chemically treated crude oils on the ocean. *Environmental Science and Technology*, 14(12), 1509-1518. https://doi.org/10.1021/es60172a012

National Research Council, 2003. Oil in the Sea III: Inputs, Fates, and Effects. *National Academy Press*, Washington, DC.

National Research Council. 2005. Oil spill dispersants: Efficacy and effects. *National Academy Press*, Washington, DC.

Negri, A.P. & Heyward, A.J. 2000. Inhibition of fertilization and larval metamorphosis of the coral *Acropora millepora* (Ehrenberg, 1834) by petroleum products. *Marine Pollution Bulletin* 41(7-12): 420-427.

Negri, A.P., Brinkman, D.L., Flores, F., Botte, E.S., Jones, R.J., & Webster, N.S. (2016). Acute ecotoxicology of natural oil and gas condensate to coral reef larvae. *Scientific Reports*, 6, 21153. https://doi.org/10.1038/srep21153

Negri, A.P., Luter, H.M., Fisher, R., Brinkman, D.L., & Irving, P. (2018). Comparative toxicity of five dispersants to coral larvae. *Scientific Reports,* 8, 3043. https://doi.org/10.1038/s41598-018-20709-2

Nordborg, F.M., Flores, F., Brinkman, D.L., Agusti, S., & Negri, A.P. (2018). Phototoxic effects of two common marine fuels on the settlement success of the coral *Acropora tenuis*. *Scientific Reports,* 8, 8635. https://doi.org/10.1038/s41598-018-26972-7

Pelletier, M.C., Burgess, R.M., Ho, K.T., Kuhn, A., McKinney, R.A., & Ryba, S.A. (1997). Phototoxicity of individual polycyclic aromatic hydrocarbons and petroleum to marine invertebrate larvae and juveniles. *Environmental Toxicology and Chemistry*, 16(10), 2190-2199. https://doi.org/10.1002/etc.5620161029

Reimer, A. (1975). Effects of crude oil on corals. *Marine Pollution Bulletin*, *6*(3), 39–43. https://doi.org/10.1016/0025-326X(75)90297-0

Rinkevich, B., & Loya, Y. (1979). Laboratory experiments on the effects of crude oil on the Red Sea coral *Stylophora pistillata*. Marine Pollution Bulletin, 10(11), 328–330. https://doi.org/10.1016/0025-326X(79)90402-8

Roberts, A.P., Alloy, M.M., & Oris, J.T. (2017). Review of the photo-induced toxicity of environmental contaminants. *Comparative Biochemistry and Physiology, Part C* 191, 160-167. http://dx.doi.org/10.1016/j.cbpc.2016.10.005

Rougée, L., Downs, C., Richmond, R., & Ostrander, G. (2006). Alteration of normal cellular profiles in the scleractinian coral (*Pocillopora damicornis*) following laboratory exposure to fuel oil. *Environmental Toxicology and Chemistry*, *25*(12), 3181–3187. https://doi.org/10.1897/05-510R2.1

Shafir, S., Van Rijn, J., & Rinkevich, B. (2007). Short and long term toxicity of crude oil and oil dispersants to two representative coral species. *Environmental Science & Technology*, 41(15), 5571–5574. https://doi.org/10.1021/es0704582

Te, F.T. (1991) Effects of two petroleum products on *Pocillopora damicornis* planulae. *Pacific Science* 45(3): 290-298.

Turner, N.R. & Renegar, D.A. (2017). Petroleum hydrocarbon toxicity to corals: A review. *Marine Pollution Bulletin,* 119, 1-16. https://doi.org/10.1016/j.marpolbul.2017.04.050

Venn, A.A., Quinn, J., Jones, R., & Bodnar, A. (2009). P-glycoprotein (multi-xenobiotic resistance) and heat shock protein gene expression in the reef coral *Montastrea franks* in response to environmental toxicants. *Aquatic Toxicology*, 93, 188-195. https://doi.org/10.1016/j.aquatox.2009.05.003

Villanueva, R., Montaño, M., & Yap, H. (2008). Effects of natural gas condensate – water accommodated fraction on coral larvae. *Marine Pollution Bulletin*, *56*(8), 1422–1428. https://doi.org/10.1016/j.marpolbul.2008.05.008

Villanueva, R., Yap, H., & Montaño, M. (2011). Reproductive effects of the water-accommodated fraction of a natural gas condensate in the Indo-Pacific reef-building coral *Pocillopora damicornis*. *Ecotoxicology and Environmental Safety*, 74(8), 2268–2274. https://doi.org/10.1016/j.ecoenv.2011.08.003

Wyers, S.C., Frith, H.R., Dodge, R.E., Smith, S.R., Knap, A.H., & Sleeter, T.D. (1986). Behavioural effects of chemically dispersed oil and subsequent recovery in *Diploria strigosa* (Dana). *Marine Ecology,* 7(1), 23-42. https://doi.org/10.1111/j.1439-0485.1986.tb00146.x

SUPPLEMENTAL MATERIALS

The peer-reviewed, published manuscript associated with this project comprises much of this report and is provided below.

Science of the Total Environment 794 (2021) 148632

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Water quality thresholds for coastal contaminant impacts on corals: A systematic review and meta-analysis

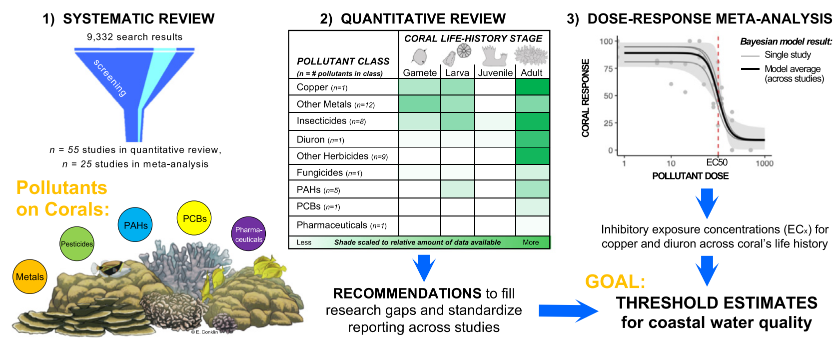
Eileen M. Nalley [a,*], Lillian J. Tuttle [a,b], Alexandria L. Barkman [c], Emily E. Conklin [a], Devynn M. Wulstein [a], Robert H. Richmond [c], Megan J. Donahue [a]

[a] Hawai'i Institute of Marine Biology, University of Hawai'i at Mānoa, 46-007 Lilipuna Road, Kāne'ohe, HI 96744, USA
[b] NOAA Pacific Islands Regional Office, Honolulu, HI 96860, USA
[c] Kewalo Marine Laboratory, Pacific Biosciences Research Center, University of Hawai'i at Mānoa, 41 Ahui Street, Honolulu, HI 96813, USA

HIGHLIGHTS

- Pollutants impair coral health in different ways and stages of the coral life cycle.
- Thresholds derived for coral toxicants from Bayesian dose-response meta-analysis.
- Exposure levels leading to declines in coral health were compiled for 39 toxicants.
- Efforts to quantify water quality targets need more standardized research practices.
- Systematic review provides crucial data and identifies gaps for resource managers.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 20 April 2021
Received in revised form 15 June 2021
Accepted 19 June 2021
Available online 23 June 2021

Editor: Jay Gan

Keywords:
Pollutant
Management
Coral reef
Scleractinia
Dose-response
Bayesian model
Data synthesis

ABSTRACT

Reduced water quality degrades coral reefs, resulting in compromised ecosystem function and services to coastal communities. Increasing management capacity on reefs requires prioritization of the development of data-based water-quality thresholds and tipping points. To meet this urgent need of marine resource managers, we conducted a systematic review and meta-analysis that quantified the effects on scleractinian corals of chemical pollutants from land-based and atmospheric sources. We compiled a global dataset addressing the effects of these pollutants on coral growth, mortality, reproduction, physiology, and behavior. The resulting quantitative review of 55 articles includes information about industrial sources, modes of action, experimentally tested concentrations, and previously identified tolerance thresholds of corals to 13 metals, 18 pesticides, 5 polycyclic aromatic hydrocarbons (PAHs), a polychlorinated biphenyl (PCB), and a pharmaceutical. For data-rich contaminants, we make more robust threshold estimates by adapting models for Bayesian hierarchical meta-analysis that were originally developed for biopharmaceutical application. These models use information from multiple studies to characterize the dose-response relationships (i.e., E_{max} curves) between a pollutant's concentration and various measures of coral health. Metals used in antifouling paints, especially copper, have received a great deal of attention to-date, thus enabling us to estimate the cumulative impact of copper across coral's early life-history. The effects of other land-based pollutants on corals are comparatively understudied, which precludes more quantitative analysis. We discuss opportunities to improve future research so that it can be better integrated into quantitative assessments of the effects of more pollutant types on sublethal coral stress-responses. We also recommend that managers use this information to establish more conservative water quality thresholds

* Corresponding author.
E-mail address: enalley@hawaii.edu (E.M. Nalley).

https://doi.org/10.1016/j.scitotenv.2021.148632

that account for the synergistic effects of multiple pollutants on coral reefs. Ultimately, active remediation of local stressors will improve the resistance, resilience, and recovery of individual reefs and reef ecosystems facing the global threat of climate change.

Contents

1. Introduction

Coral reefs are some of the most diverse and productive ecosystems on the planet (Reaka-Kudla, 1997). They provide coastal protection, tourism, and ecological benefits for communities in over 100 countries globally, but despite their importance, coral reefs are threatened by the compound effects of anthropogenic disturbances on global and local scales (Bishop et al., 2011; Bryant et al., 1998; Spalding et al., 2001). Over 60% of coral reefs are threatened by local stressors, which can include pollutants from terrestrial runoff (e.g., sedimentation, increased nutrients, pathogens, and toxins) and overfishing (Burke et al., 2011; Richmond and Wolanski, 2011). The impacts of local stressors can be exacerbated by global stressors such as ocean warming and acidification (Hughes et al., 2010). Though mitigating global stressors remains a priority for resource managers nationally and internationally, coral-reef managers often seek to control local stressors to increase reef resilience and recovery. Runoff and groundwater collectively transport nutrients, sediment, and pollutants onto reefs (Fabricius, 2005; Silbiger et al., 2020; Tuttle and Donahue, 2020; Zhao et al., 2021), but the impacts of pollutant transport have received less attention and are consequently less understood (van Dam et al., 2011). As such, we present a systematic, quantitative review and meta-analysis that addresses this knowledge gap and focuses on studies that have examined the physiological responses of scleractinian corals following direct exposure to chemical toxicants.

Coral reefs near the shoreline are more vulnerable to land-based runoff and submarine groundwater discharge, and they degrade faster than reefs farther offshore (Rodgers et al., 2015; Silbiger et al., 2020; Wenger et al., 2016). The persistence and dispersion of pollutants depend on their chemical composition and environmental conditions, such as water residence time and flushing rate, so corals downstream of watersheds in high retention bays are also more likely to be impacted by runoff from land-based activities (Wolanski et al., 2009). This gradient of decreasing water quality closer to land can lead to lasting changes at reefs closer to the shoreline, such as reduced coral genetic diversity (Tisthammer et al., 2020). Anthropogenic pollutants, such as pesticides, metals, pharmaceuticals, and sewage, can enter reef ecosystems through point sources (e.g., sewage outfall) or nonpoint sources. In many places, onsite waste disposal, leaking septic tanks, and other improper sewage disposal techniques also pose a risk to coastal reefs (Abaya et al., 2018). In areas with harbors, the surrounding reef may be additionally exposed to pollutants associated with boats, such as anti-fouling paints and polycyclic aromatic hydrocarbons (PAHs) (Sheikh et al., 2009).

In addition, pollutants of concern in developed industrial or residential areas and agricultural chemicals can enter marine ecosystems. Highly soluble contaminants have the potential to be carried far offshore, and some pollutants may also be transported through the atmosphere and redeposited, impacting areas far from the site of application (Nash and Hill, 1990). Because many of these compounds, especially herbicides, are designed to inhibit photosynthesis in plants, they can negatively impact the photosynthetic capacity of the algal symbionts in corals that provide up to 90% of coral energy (Muscatine, 1990). Glyphosate, atrazine, diuron, and other active ingredients in herbicides and insecticides have been found in water, sediment, and biological samples from streams that drain to the ocean in Hawaiʻi and in the coastal coral reef ecosystems of the Great Barrier Reef, Hong Kong, and French Polynesia, indicating the widespread presence of these pesticides and their degradates in coral reef ecosystems (Roche et al., 2011; Shaw et al., 2008; Shaw et al., 2010; Hawaiʻi State Dept. of Health and Ag., 2014; Spengler et al., 2019).

Sediment and freshwater directly and indirectly impact corals and other reef organisms while transporting chemical pollutants, which also affect corals (Table 1) (Tuttle and Donahue, 2020; Rodgers et al., 2021). Biological processes of early life stages of corals, including gamete fertilization, larval settlement, and recruit survival, are chemically mediated and therefore often more sensitive to xenobiotics, or chemicals that are not naturally found within the organism (Richmond et al., 1998; Richmond et al., 2018). Certain pollutants are also known to impact early life stages and processes more than others. For example, copper can reduce fertilization success at lower concentrations than zinc or cadmium and is likely more toxic than these other metals at early life stages (Reichelt-Brushett and Harrison, 1999).

Exposure to toxicants can also impact corals at later life stages, causing them to expel their algal symbionts, which are necessary for autotrophic feeding, and in some cases, the corals may also produce increased amounts of mucus, which can affect their ability to feed heterotrophically (Markey et al., 2007; Renegar et al., 2017). While hormone function in corals is still unclear, previous research has shown that corals contain many of the same steroidal hormones involved in reproduction as in other species such as estradiol, estrone, and testosterone (Tarrant et al., 2003). Herbicides that are designed to inhibit photosynthesis, such as atrazine and diuron (Table 1), will impact adult corals that rely on photosynthetic symbionts differently than earlier life stages that do not yet have symbionts. However, pesticides including atrazine and diuron have also been shown to be endocrine disruptors, which can have lasting impacts on organisms and their reproductive capacity (Boscolo et al., 2018; Hayes et al., 2003). Corals also show stress at the molecular level after exposure to chemicals. For example, *Pocillopora damicornis* exposed to insecticides and microplastics increased expression of detoxification enzymes and antioxidant enzymes, respectively (Tang et al., 2018; Wecker et al., 2018).

With this systematic, quantitative review and meta-analysis, we aimed to determine (1) the scope of existing research on the effects of chemical pollutants on scleractinian corals, (2) the concentrations at which marine pollutants elicit adverse physiological responses in corals, (3) the relative impact of different pollutants on coral health, and (4) the areas in need of additional study. Herein, we systematically review the effects on scleractinian corals of a comprehensive list of marine pollutants grouped into five categories: metals, pesticides (herbicide, insecticide, fungicide), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and other. This quantitative review and meta-analysis offers a detailed analytical assessment of stressor thresholds, when possible, and provides insight into the gaps that remain. We conclude with recommendations for future studies to address the current knowledge gaps, including critical data gaps in characterizing stressor-response relationships. This information is essential to managers as they aim to develop guidelines and policies to mitigate the impacts of pollutants on coral reef ecosystems.

2. Methods

2.1. Systematic literature review

2.1.1. Article searches

The systematic review began with previously published reviews on the effects of various pollutants on stony corals (Johnston and Roberts, 2009; Kroon et al., 2014; Mayer-Pinto et al., 2020; Pastorok and Bilyard, 1985; Richmond et al., 2018; van Dam et al., 2011), which were used to develop a list of benchmark studies to be included. The aim of the following literature search was to collect and synthesize all available evidence on the effects of select pollutant classes on hard corals. The search included peer-reviewed, public, and/or 'gray' literature to quantify pollutant-related stress responses in all life stages of all shallow (photic zone, ≤80 m depth), scleractinian corals in all warm-water ocean basins (20–30 °C).

The search engines and databases described and justified in Tuttle et al. (2020) were used in this study and can be found in the Supplementary materials (Table S1). An exhaustive list of potential pollutants and additional characteristic terms was compiled through reference to existing reviews and consultation with experts. Search terms were refined by recording the number and accuracy of results produced in Web of Science searches of the format ([search term]* AND coral), where "*" is a wildcard and "AND" is a Boolean operator. Terms that resulted in double counting of results such as pesticid* and *icid* were refined to only include the term which produced the most results and was, therefore, more comprehensive. Focused searches were included for the following genera due to their listing as endangered or threatened under the U.S. Endangered Species Act (ESA): *Acropora, Anacropora, Cantharellus, Dendrogyra, Euphyllia, Isopora, Montastraea, Montipora, Mycetophyllia, Orbicella, Pavona, Porites, Seriatopora, Siderastrea,* and *Tubastraea*. The genera list was expanded to include those genera of particular importance to the Pacific Island Region: *Alveopora, Astreopora, Favia, Favites, Goniastrea, Goniopora, Leptastrea, Leptoria, Lobophyllia, Millepora, Platygyra, Pocillopora,* and *Turbinaria*. A full list of search terms can be found in Text S1. Possible limitations of this search include regional or language biases and the exclusion of some journals or conference proceedings from sampled database archives.

2.1.2. Article screening and eligibility criteria

The search results were evaluated according to the methods and procedures described previously (Tuttle et al., 2020). After searches were completed, the resulting Bibtex and RIS files were imported to Mendeley, an open-source reference manager (Mendeley, 2020). Duplicate files were combined via Mendeley's duplicate merger tool. The unique citations ($n = 9332$) were then imported into Abstrackr, a free web-based application for screening and organizing literature search results (Abstrackr, 2020), and abstracts were independently screened by at least two reviewers, with each classifying the titles as 'relevant' ($n = 315$), 'not-relevant' ($n = 8885$), or 'maybe-relevant' ($n = 132$) to the research questions. Discrepancies in the classifications were addressed and resolved by a third reviewer.

The full texts for all 'relevant' sources were collected and screened by independent reviewers for each of the pollutant categories based upon the eligibility criteria from the PECO (Population, Exposure, Comparison, Outcome) framework (Morgan et al., 2018), which are described in the Supplementary materials (Text S2). All sources that passed the full-text screening ($n = 140$) were appraised for internal and external validity following the detailed criteria within Tuttle et al. (2020). Articles that did not include coral responses that could be compared across studies were omitted at this step, leaving 127 studies that were considered for the quantitative review and meta-analysis. Studies focusing on oil and oil dispersants were excluded because several recent reviews and meta-analyses provide a thorough summary of the effects of oil and dispersants on corals and other marine organisms (Bejarano, 2018; Bejarano et al., 2016; NAS, 2020; Turner and Renegar, 2017). Microplastics were also excluded as a pollutant from this quantitative review because the described response to microplastics was typically related to a reduced capacity for heterotrophic feeding rather than an adverse physiological response to the stressor. A recent review (Huang et al., 2021) describes the impacts of microplastics on corals and notes that associations between microplastics and other toxins may increase the susceptibility of corals to disease, which is a response with physiological complexity that is beyond the scope of this study.

2.1.3. Data extraction

Each article remaining in the "relevant" category that passed the study validity assessment ($n = 55$) had data extracted by a single

Table 1
Focal pollutants of this review that may elicit negative physiological responses in corals, grouped by class, industrial use/source, and mode of action.

Pollutant class	Pollutant	Industrial use/source	Mode of action
Metal	Aluminum	Naturally occurring but also distributed in the environment through fossil fuel combustion, agricultural spray drift, and runoff or leaching from resource extraction and wastewater treatment (EPA, 2018).	Disrupts osmoregulation at gill surface in fish, leading to cell death (Exley et al., 1991). May disrupt concentrations of specific ions, primarily resulting in a loss of sodium in invertebrates (Hornstrom et al., 1984).
	Cadmium	Naturally occurring but is also used for batteries, pigments, paints, stabilizers and coatings, and alloys (ATSDR, 2012).	Disrupts lipid composition and depletes antioxidant enzymes. Alters metabolism of other metals (e.g., zinc, iron, and copper) and can disrupt DNA transcription (ATSDR, 2012).
	Cobalt	Naturally occurring but also used to form alloys for industrial and military applications, as a colorant in dyes, and as an additive in agricultural applications (ATSDR, 2004).	Generates oxidants and causes lipid peroxidation, inducing nitric oxide synthase as a response to oxidant stress and free radical DNA damage. Can block calcium channels in mammals. Increased damage documented in combination with other stressors, like UV radiation (ATSDR, 2004).
	Copper	Used as a biocide in antifouling paints (Jones and Kerswell, 2003).	Forms reactive oxygen radicals that damage cells and proteins, and also denature enzymes (Boone et al., 2012; Yruela, 2009).
	Gallium	Naturally occurring but generated as a byproduct of aluminum manufacturing and used to make semiconductors and light-emitting diodes (Yu and Liao, 2010).	Can replace iron in iron transport proteins, disrupting the synthesis of DNA and proteins (Yu and Liao, 2010).
	Iron	Naturally occurring and required by plants and animals, but used in many manufacturing processes (US EPA, 1988).	Causes cellular oxidative stress by inhibiting antioxidants (e.g., glutathione) and increasing lipid peroxidation (Vijayavel et al., 2012).
	Lead	Naturally occurring but was widely distributed in the environment through combustion of leaded gasoline. Also occurs in paints, pesticides, pipes, and can be released through waste incineration (ATSDR, 2020).	Disrupts ion homeostasis by taking the place of metal ions (e.g., iron, calcium, zinc, magnesium, selenium, and manganese) interrupting biological processes requiring these ions or dependent enzymes and proteins (ATSDR, 2020).
	Manganese	Naturally occurring but produced through smelting, fertilizer, and gasoline (US EPA, 2003).	In mammalian studies, primarily targets the nervous system (US EPA, 2003).
	Mercury	Naturally occurring but released through burning waste and fossil fuels. Used in gold mining and as a wood preservative, fungicide, and in electrical equipment. Microorganisms convert into toxic methylmercury (ATSDR, 1999; US EPA, 2021a).	Accumulates in zooxanthellae symbionts responsible for photosynthesis, potentially leading to the expulsion of symbionts (Bastidas and Garcia, 2004).
	Nickel	Naturally occurring but found at increased concentrations due to industrial pollution (e.g., production of stainless steel) (Brix et al., 2017).	Reduces calcium available for growth, affects respiration, and can causes cytotoxicity and lead to tumor formation (Brix et al., 2017).
	Tin	Inorganic: occurs naturally in Earth's crust, also found in dyes and additives Organic: found in plastics, packaging, pipes, pesticides, paint, preservatives, & rodent repellants (ATSDR, 2005b).	Not well studied in invertebrates. In mammals builds up in the pancreas (ATSDR, 2005b).
	Vanadium	Naturally occurring but typically released through combustion of fossil fuels or via runoff (Beusen and Neven, 1987).	Inhibits ATPase, phosphotransferase, nuclease, and kinase. Also interferes with cell growth (Fichet and Miramand, 1998).
	Zinc	Naturally occurring but used to create metal alloys, pigments, and as a fungicide. Released through fossil fuel combustion and road runoff (Eisler, 1993).	Required for function, but excess concentrations can be toxic. Impacts zinc-dependent enzymes that regulate RNA/DNA. Interacts with other compounds (e.g., copper, lead), compounding effects (Eisler, 1993).
Herbicide	2,4-D	Used to control broadleaf weeds and regulate citrus growth (US EPA, 2021b).	Mimics plant growth hormone auxin leading to unregulated, disorganized cell growth (Song, 2014).
	Ametryn	Used as an herbicide to control pre- and post-emergence broadleaf weeds and grasses in pineapple, sugarcane, and banana crops (US EPA, 1984).	Photosystem II inhibitor: inhibits photosynthesis by blocking electron transfer from QA to QB (Jones, 2005).
	Atrazine	Used as a herbicide to control pre- and post-emergence broadleaf weeds and grasses in corn, sorghum, and sugarcane (US EPA, 2021c).	Photosystem II inhibitor as above.
	Diuron	Used to control weeds pre- and post-emergence (Råberg et al., 2003). Used in antifouling paints (Jones and Kerswell, 2003).	Photosystem II inhibitor as above.
	Glyphosate	Used to control broadleaf weeds and grasses (US EPA, 2021d).	Inhibits the enzyme 5-enolpyruvylshikimate-3- phosphate (EPSP) synthase and prevents creation of proteins (Shaner, 2006).
	Hexazinone	Used on broadleaf weeds and woody plants (US EPA, 2008).	Photosystem II inhibitor as above.
	Ioxynil	Used as an herbicide.	Photosystem II inhibitor as above.
	Irgarol	Used in antifouling paints (Jones and Kerswell, 2003).	Photosystem II inhibitor as above.
	Simazine	Used to control broadleaf and grassy weeds (US EPA, 2020).	Photosystem II inhibitor as above.
	Tebuthiuron	Used to control broadleaf and woody weeds, grasses, and brush (US EPA, 1994).	Photosystem II inhibitor as above.
Insecticide	1-Naphthol	Breakdown product of carbaryl (Acevedo, 1991).	Inhibits cholinesterase, affecting the nervous system leading to paralysis (Acevedo, 1991).
	Carbaryl	Used on sugarcane, cotton, fruits, vegetables, grains, and for termite and domestic pest control (Markey et al., 2007).	Inhibits acetylcholinesterase (AChE), which leads to constant stimulation of nervous system (Markey et al., 2007).
	Chlorpyrifos	Used on sugarcane, cotton, fruits, vegetables, grains, and for termite, mosquito, and domestic pest control (Markey et al., 2007).	Inhibits AChE as above (Markey et al., 2007).
	Endosulfan	Used on cotton, fruits, vegetables, and grains (Markey et al., 2007).	Suppresses function of neurotransmitter GABA, resulting in unchecked stimulation of neurons (Markey et al., 2007).
	Naled	Used primarily for mosquito control (US EPA, 2021e).	Inhibits AChE as above (Markey et al., 2007).
	Permethrin	Used on cotton, fruits, vegetables, grains, and for mosquito and domestic pest control (Markey et al., 2007).	Inactivates nerve junctions (Markey et al., 2007).
	Profenofos	Used on cotton (Markey et al., 2007).	Inhibits AChE as above (Markey et al., 2007).
Fungicide	MEMC	Used in seed protectants and paints (Roberts and Reigard, 2013).	Denatures proteins and inactivates enzymes (Markey et al., 2007).
PAH	1-methyl-naphthalene	Generated by burning fossil fuels, wood, or tobacco. Used in dyes and resins (ATSDR, 2005a).	In mammalian studies, primarily targets alveolar pneumocytes and bronchial cells (ATSDR, 2005a).
	Anthracene	Generated in volcanoes and forest fires but also found in dyes, plastics, and pesticides. Also found in fossil fuels and released during combustion (MN Dept. of Health, 2019).	Causes inflammation and buildup of fluid in tissues and can also causes tumors, reproductive issues, and damage to immune system (US EPA, 2009).
	Benzo(*a*) pyrene	Generated in volcanoes and forest fires but also generated through burning fossil fuels, waste, and wood (ATSDR, 1995).	Lipophilic compounds that transform to reactive intermediates which bind to DNA, causing mutation (ASTDR, 1995). Causes oxidative stress

Table 1 (*continued*)

Pollutant class	Pollutant	Industrial use/source	Mode of action
			in larvae (Farina et al., 2008).
	Fluoranthene	Generated in volcanoes and forest fires but also generated through burning fossil fuels, waste, and wood (ATSDR, 1995).	Lipophilic compounds that transform to reactive intermediates which can bind to DNA, causing mutation (ASTDR, 1995).
	Phenanthrene	Generated in volcanoes and forest fires but also generated through burning fossil fuels, waste, and wood (ATSDR, 1995).	Lipophilic compounds that transform to reactive intermediates which can bind to DNA, causing mutation (ASTDR, 1995).
PCB	Aroclor 1254	Used in transformers, electrical equipment, heat transfer material, insulation, and adhesives (US EPA, 2021f).	PCBs interact with the 2,3,7,8-TCDD receptor protein, inhibit intercellular communication, and induce cytochrome P450c dependent monooxygenase (Eisler and Belisle, 1996).
Pharmaceutical	Estrone	Produced in vertebrates and used in human hormone therapy. Released through untreated wastewater and sewage effluent (Atkinson et al., 2003).	Vertebrate hormone involved in female sexual development. Hypothesized to play a role in regulating reproductive process in corals, though the mechanisms are unknown (Tarrant et al., 2004).

reviewer. A complete list of studies can be found in the Supplementary Materials (Text S3). All methodology-related information on the study species, location and collection site, pollutant and concentration levels, and additional factors were recorded for each article (Table S2). Coral response data found in article figures (most commonly as treatment means +/− error) were extracted using tools such as Web Plot Digitizer (Rohatgi, 2020). When possible, reported no- and lowest-observed adverse effect levels (NOAEL, LOAEL) and half maximal effective concentrations (EC_{50}) were also extracted from the papers (Table S3). Many pollutant-response combinations did not have sufficient replication to be included in the meta-analysis (at least 3 independent, comparable articles), so they were assessed in the quantitative review only. We define an 'article' as a unique publication, and an 'experiment' as a unique set of related treatments, including both control and exposure conditions. Thus, an article could contain the results of multiple experiments.

In the extraction of data for meta-analysis of the effects of pollutants on photosynthetic efficiency, we focused on maximum quantum yield (MQY) instead of effective quantum yield (EQY). MQY is represented by F_v (= F_m - F_0) / F_m, where F_m is maximal fluorescence and F_0 is background fluorescence (Osinga et al., 2012). MQY is measured after the coral has been dark-adapted, meaning a complete relaxation of photochemical quenching activity (Osinga et al., 2012). EQY is measured under steady but illuminated conditions and can therefore be more variable (Enríquez and Borowitzka, 2010). Measurements can be affected by variable light intensity, driven in some cases by shading, which can be very important in measurements from corals where light is scattered throughout the skeletal matrix (Enríquez et al., 2017; Enríquez and Borowitzka, 2010). MQY was thus considered a more stable measurement of photosynthetic efficiency in response to stressors than EQY.

2.2. Meta-analysis

For each stressor-coral response combination that met the standards for inclusion in the meta-analysis, we fit a dose-response curve using a Bayesian, inhibitory log-logistic (E_{max}) model, adapted from models used in biopharmaceutical research (Thomas et al., 2014; Wu et al., 2018), with a Gaussian distribution using *brms*, v2.14.0 (Bürkner, 2017; Bürkner, 2018) and *rstan*, v2.21.2 (Stan Development Team, 2020) packages within the *R* statistical software, v4.0.1 (R Core Team, 2020). Data were fit to a four-parameter model (Eq. (1)), with parameters E_0, E_{max}, EC_{50} and the Hill coefficient (λ, curve steepness):

$$(Response\ Level \mid Standard\ Error) \sim E_0 \times \left(1 - \frac{E_{max} \times Concentration^{\lambda}}{EC_{50}{}^{\lambda} + Concentration^{\lambda}}\right) \quad (1)$$

Response level was conditioned on standard error because each datapoint represented the mean (+/− standard error) response of an experimental control/treatment group at a corresponding pollutant concentration. Within the hierarchical Bayesian model framework, we allowed random intercepts for the four parameters and compared model fits (using Bayesian R^2 and posterior distributions) with parameter slopes allowed to vary by experiment or experiment nested within article. The Bayesian priors for the four parameters were normally distributed, with E_{max} constrained between 0 and 1 and the Hill coefficient constrained as non-negative. The model specifications – including hierarchical structure, prior distributions, iterations, and convergence criteria – are described in Table S4.

To test specifically for the effect of Diuron exposure duration on adult corals, we conducted a multiple linear regression in the *R* statistical software, v4.0.1 for which we regressed MQY by duration (in days, $\log_{10}$-transformed; continuous variable) and concentration at three levels: 0, 1, and 10 μg L^{-1} (categorical variable). We used analysis of variance to choose the best-fit of three models: (1) equal slopes and intercepts (simple linear regression), (2) equal slopes and different intercepts, and (3) different slopes and intercepts. We visually inspected residuals of the best-fit model (2) to check that it met assumptions.

2.3. Quantitative review

Stressor-response combinations that did not have sufficient data for meta-analysis were assessed in a quantitative review. For each stressor-coral response combination, we report the range of pollutant concentrations examined across all studies, the no- and lowest-observed adverse effect levels (NOAEL and LOAEL), and corresponding references were compiled and synthesized by coral life history stage. Further, we aggregated the most conservative thresholds reported for each stressor-response combination to inform management strategies in data limited scenarios.

3. Results

3.1. Meta-analysis

Copper, nickel, and diuron were the only pollutants matched with coral responses that had sufficiently comparable data for inclusion in the meta-analysis. For copper, we examined four separate coral responses: gamete fertilization success ($n = 9$ articles with 17 experiments therein), larval settlement ($n = 3$ articles with 4 experiments therein), larval survival (n = 3 articles with 6 experiments therein), and adult photosynthetic efficiency ($n = 4$ articles with 11 experiments therein) (Table 2). Diuron had enough articles ($n = 5$ with 25 experiments therein) to assess its effect on adult photosynthetic efficiency. While there were at least three independent, comparable articles that examined the effects of nickel on fertilization success and copper on chlorophyll concentration, these stressor-response combinations did not exhibit a dose-response relationship that could be accurately modeled with an inhibitory log-logistic (E_{max}) model.

3.1.1. Coral gametes

Coral gametes are particularly vulnerable to copper exposure, with the rate of fertilization inhibited by 5% at 22.6 μg L^{-1} and by 50% at 48.6 μg L^{-1} (Table 2; Fig. 1A). Thresholds were estimated from inhibition curves for 9 articles that tested the effects of copper concentrations across 5 orders of magnitude (Fig. 1A) on corals from 12 species within

Table 2
Bayesian hierarchical dose-response meta-analysis results for the stressor-response pairs with sufficient data to be included in the meta-analysis. EC_x refers to the effective concentration of copper (μg L^{-1}), as derived from the meta-analytical model, that inhibited the coral response by 5%,10%, 20%, or 50%, with model average estimates and lower (Q2.5) and upper (Q97.5) Bayesian credible intervals.

Coral age class	Coral response	Pollutant	Bayesian model R^2	EC_x	Estimate	Q2.5	Q97.5
Gametes	Fertilization success rate	Copper	0.932	EC_5	22.6	8.7	40.9
				EC_{10}	27.5	12.3	45.7
				EC_{20}	33.9	17.8	51.7
				EC_{50}	48.6	33.4	63.7
Larvae	Settlement rate	Copper	0.844	EC_5	27.7	11.2	50.5
				EC_{10}	31.3	13.4	54.4
				EC_{20}	35.7	16.4	59.0
				EC_{50}	44.8	23.1	67.7
	Survival rate	Copper	0.973	EC_5	44.7	15.9	86.9
				EC_{10}	55.0	23.8	95.0
				EC_{20}	68.8	37.0	104.7
				EC_{50}	101.0	78.6	123.6
Adults	Photosynthetic efficiency (MQY)	Copper	0.717	EC_5	285.5	156.9	351.5
				EC_{10}	303.9	188.0	362.5
				EC_{20}	325.3	228.9	374.9
				EC_{50}	365.3	320.3	397.0
		Diuron	0.853	EC_5	2.5	0.6	8.0
				EC_{10}	5.1	1.5	13.8
				EC_{20}	11.3	4.1	24.9
				EC_{50}	43.7	24.0	68.5

5 genera: *Acropora*, *Coelastrea*, *Goniastrea*, *Montipora*, and *Platygyra*. Coral gametes were less susceptible to exposure to other metals. We conducted a joint meta-analysis for the 10 metals for which there was an apparent log-linear decline in fertilization rate with increasing metal molar concentration (in μmol L^{-1}). Relative susceptibility to these metals, ranked from most to least susceptible in terms of estimated EC_{50} values, is as follows: copper, tin, zinc, lead, vanadium, gallium, nickel, aluminum, cadmium, and iron (Fig. 2). The posterior distributions of EC_{50} values are wide (Fig. 2B) indicating the relative paucity of data available to estimate the dose-response curves for most metals, with the notable exception of copper.

3.1.2. Coral larvae

Coral larvae were also relatively vulnerable to copper exposure. Settlement (i.e., metamorphosis) rates were inhibited by 5% at 27.7 μg L^{-1} and by 50% at 44.8 μg L^{-1} copper (Table 2; Fig. 1C). Thresholds were estimated from inhibition curves for 3 articles that tested the effects of copper concentrations across 5 orders of magnitude (Fig. 1C) on corals from 2 species: *Acropora millepora* and *Acropora tenuis*. Survival rates of pre-settlement coral larvae were inhibited by 5% at 44.7 μg L^{-1} and by 50% at 101.0 μg L^{-1} copper (Table 2; Fig. 1B). These thresholds were estimated from inhibition curves for 3 articles that tested the effects of copper concentrations across 3 orders of magnitude (Fig. 1B) on corals from 2 species: *Coelastrea aspera* and *Platygyra acuta*.

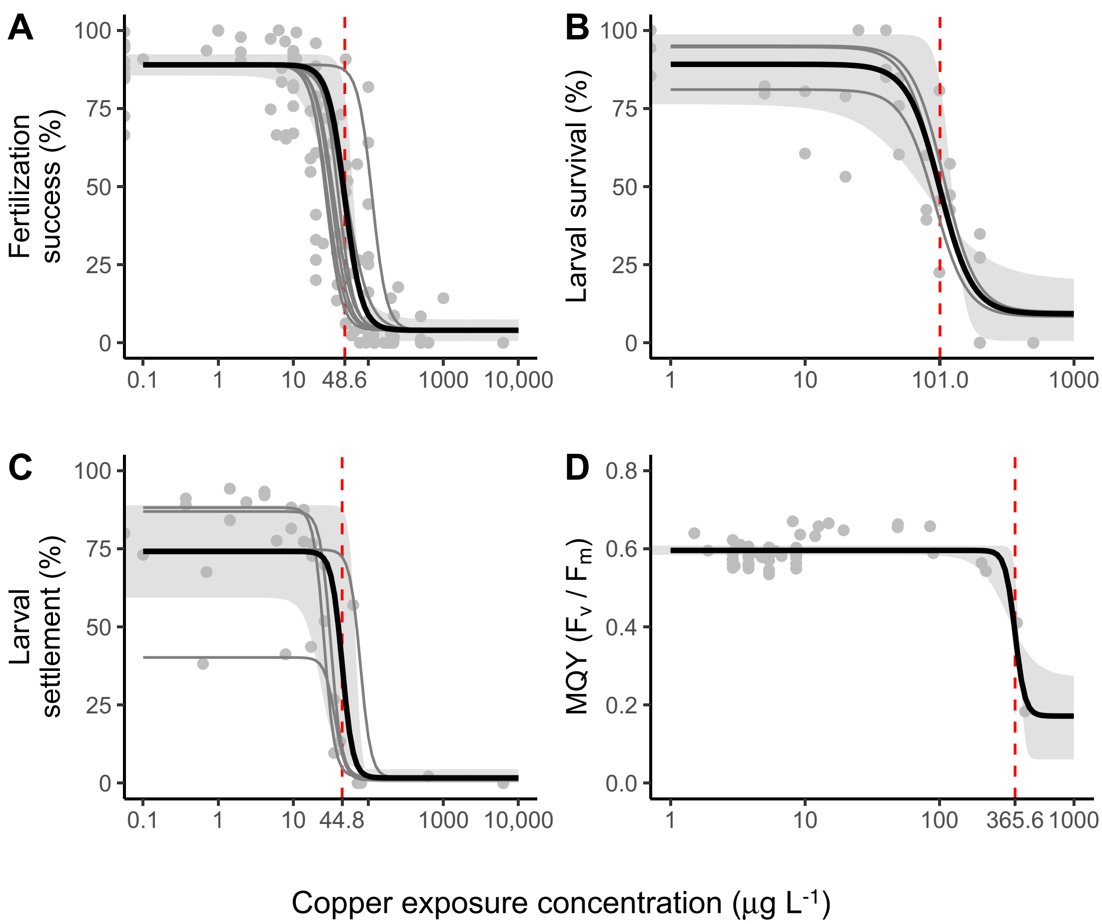


Fig. 1. Inhibitory dose-response curves for the effects of copper on coral fertilization success ($n = 9$ articles with 17 experiments therein) (A), larval survival ($n = 3$ articles with 6 experiments therein) (B), larval settlement (n = 3 articles with 4 experiments therein) (C), and adult maximum quantum yield ($n = 4$ articles with 11 experiments therein) (D). Each point represents a raw mean from an experimental control/treatment group included in the meta-analysis. Bayesian model results are shown as lines: the bold black lines represent the models' average curves (with 95% credible intervals as gray-shaded regions) across all studies, and the gray lines represent the model-estimated curve for each article/experiment (all lines in D converged along the average). The red dashed lines and corresponding numbers along the x-axis indicate the EC_{50} parameter estimate for the average curve. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

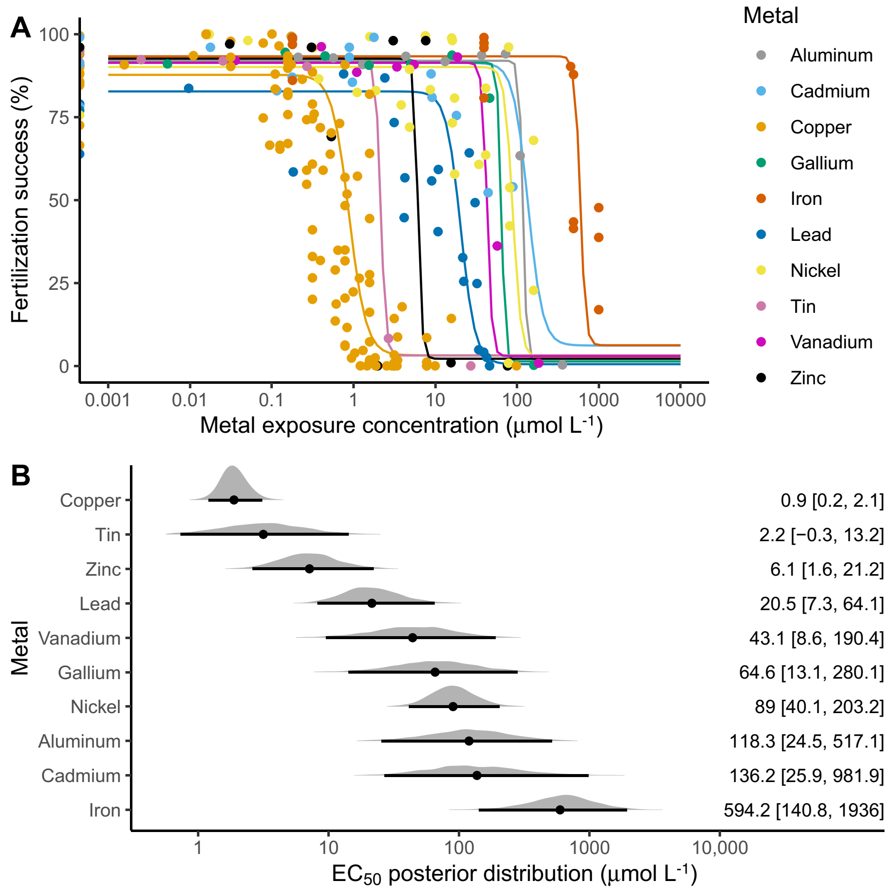


Fig. 2. The relative effects of different metal concentrations (in μmol L^{-1}) on coral fertilization success, shown as Bayesian-modeled inhibitory dose-response curves (A) and as EC_{50} posterior distributions and estimates (points) +/− Bayesian 95% credible intervals (dark lines) (B). Points and lines in (A) are color-coded by metal as indicated in the key. The following metals were included: cadmium ($n = 2$ articles with 3 experiments therein); copper ($n = 9$ articles with 17 experiments therein); iron ($n = 1$ article with 4 experiments therein); lead ($n = 1$ article with 3 experiments therein); manganese ($n = 1$ article with 4 experiments therein); nickel ($n = 3$ articles with 5 experiments therein); zinc ($n = 2$ articles with 2 experiments therein); and aluminum, cobalt, gallium, tin, and vanadium (all with $n = 1$ experiment in 1 article).

3.1.3. Coral adults

The only response of coral adults that was adequately comparable for meta-analysis across studies was photosynthetic efficiency measured as maximum quantum yield (MQY, F_v/F_m). Adult coral photosynthetic efficiency was relatively insensitive to copper exposure, with MQY inhibited by 5% at 285.5 μg L^{-1} and by 50% at 365.3 μg L^{-1} (Table 2; Fig. 1D). Thresholds were estimated from inhibition curves for 4 articles that tested the effects of copper concentrations across 3 orders of magnitude on corals from 2 species: *Mussismilia harttii* and *Pocillopora damicornis*.

Adult coral photosynthetic efficiency was much more sensitive to diuron exposure as compared to copper exposure, with MQY inhibited by 5% at just 2.5 μg L^{-1} and by 50% at 43.7 μg L^{-1} (Table 2; Fig. 3A). Thresholds were estimated from inhibition curves for 5 articles that tested the effects of diuron concentrations across 4 orders of magnitude (Fig. 3A) on corals from 5 species and genera: *A. millepora*, *Montipora digitata*, *P. damicornis*, *Porites cylindrica*, and *Seriatopora hystrix*. The effect of diuron exposure duration on MQY was slight but significant. A ten-fold increase in duration (in days) was associated with a decline in mean MQY of 0.03 (95% confidence interval: 0.01, 0.06; multiple linear regression $p = 0.019$; Fig. 3B).

3.2. Quantitative review

Stressor-response combinations with fewer than three independent and comparable articles were excluded from the meta-analysis but were included in the quantitative review (Tables 3; S3). Metals tended to affect coral responses at a range of concentrations that varied by metal, as seen with fertilization success (Fig. 2), which in general was more impacted by metals than by the pesticides examined. Considering all pollutants, larval survival and settlement were typically affected at low concentrations or were not affected at all until extremely high concentrations were applied. Juvenile survival was examined in response to a limited range of pollutants but appeared more affected by the metal examined than by the pesticides. In adult corals, the growth rate was impacted at lower pollutant concentrations than the mortality rate across a range of pollutants. Coral responses related to symbiotic zooxanthellae (e.g., bleaching, chlorophyll content, MQY) varied by pollutant.

3.2.1. Coral gametes

Fertilization success was examined in response to twelve metals and eight pesticides. The effect of metals on fertilization can be grouped into three broad categories: no impact at high concentrations, decreased fertilization at relatively high concentrations, and decreased fertilization at relatively low concentrations. Cobalt, iron, and manganese had no significant impact on fertilization at concentrations up to 2357 μg L^{-1}, 25,300 μg L^{-1}, and 71,200 μg L^{-1} respectively. Cadmium, gallium, vanadium, and aluminum impacted fertilization success at relatively high concentrations (5000 μg L^{-1}, 3230 μg L^{-1}, 2920 μg L^{-1}, and 2950 μg L^{-1} respectively). Tin, nickel, zinc, and copper had significant impacts on fertilization success at the comparatively low concentrations of 318 μg L^{-1}, 100 μg L^{-1}, 10 μg L^{-1}, and 6 μg L^{-1}, respectively. Of the eight pesticides examined, only the fungicide MEMC

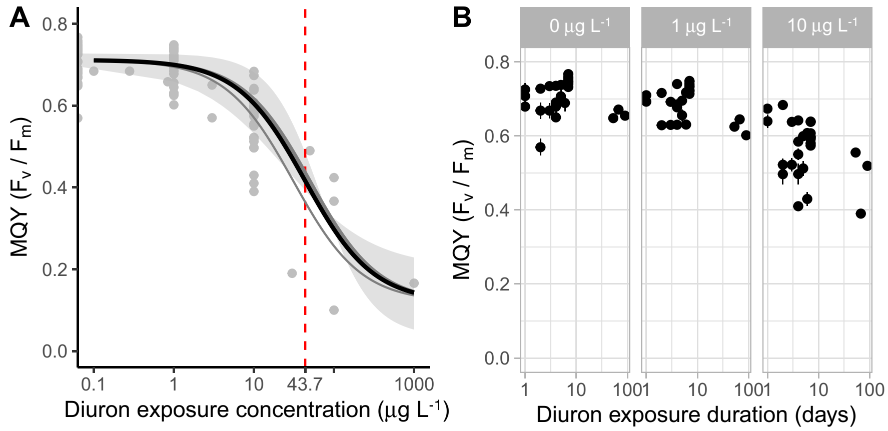


Fig. 3. Coral maximum quantum yield as a function of diuron exposure concentration (A) and duration (B) ($n = 5$ with 25 experiments therein). Each point represents a raw mean (+/− standard error, shown in B only) from an experimental control/treatment group included in the meta-analysis. Bayesian model results are shown in (A) as lines: the bold black line represents the model's average curve (with 95% credible intervals as gray-shaded region) across all studies, and the gray lines represent the model-estimated curve for each article/experiment. The red dashed line and corresponding number along the x-axis indicate the EC_{50} parameter estimate for the average curve. (B) Shows data for three exposure concentrations across two orders of magnitude of diuron exposure duration (1–100 days), and indicates a relatively weak relationship between duration and MQY, especially at 0 and 1 μg L^{-1}.
(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(2-methoxyethylmercuric chloride) had an impact on fertilization at 1 μg L^{-1}. The insecticides carbaryl, chlorpyrifos, chlorpyrifos-oxon, endosulfan, permethrin, and profenofos had no significant effect on fertilization success at concentrations up to 30 μg L^{-1}, and the herbicide diuron had no significant effect at concentrations up to 1000 μg L^{-1}.

3.2.2. Coral larvae

Survival rates of pre-settlement coral larvae were examined in response to exposure to five metals, five pesticides (all insecticides), and three PAHs. The impacts of metals on larval survival were variable by metal. Mercury had no impact on larval survival at concentrations up to 10 μg L^{-1}, though higher concentrations were not examined. Iron and manganese had significant negative effects at concentrations of 27,200 μg L^{-1} and 17,000 μg L^{-1}, respectively. Lead had a significant negative impact at 640 μg L^{-1}, and copper had a significant negative impact at concentrations as low as 10 μg L^{-1}. Copper also affected larval development and swimming velocity at 50 μg L^{-1}, and lead impacted swimming velocity at concentrations of 1000 μg L^{-1}.

Among pesticides, the insecticides naled (0.56 μg L^{-1}) and permethrin (1.0 μg L^{-1}) had significant negative impacts on larval survival at very low concentrations, but chlorpyrifos (1000 μg L^{-1}), 1-naphthol (1000 μg L^{-1}), and carbaryl (10,000 μg L^{-1}) did not have measurable effects until applied at much higher concentrations. PAHs appear to have negative effects on larval survival at relatively low concentrations. Benzo(*a*)pyrene had significant negative effects at 10 μg L^{-1}, which was the only concentration examined, and anthracene and phenanthrene negatively impacted larval survival and settlement at 9.4 μg L^{-1} and 56.3 μg L^{-1}, respectively.

Larval settlement success (i.e., metamorphosis) was examined in response to five metals, nine pesticides, and two PAHs. Metals either impacted settlement at relatively low concentrations (i.e., copper at 24 μg L^{-1} and tin at 10 μg L^{-1}), or they did not have any impact until applied at very high concentrations (i.e., gallium at 2150 μg L^{-1}, aluminum at 1960 μg L^{-1}, and vanadium at 564 μg L^{-1}). Similarly, pesticides either affected settlement at low concentrations or did not have an apparent effect until they were applied at high concentrations. Naled, an insecticide, had no significant impacts on settlement at the concentrations examined, and diuron, a herbicide, had negative effects at concentrations of 300 μg L^{-1}. Carbaryl, an insecticide, negatively impacted settlement at 3.0 μg L^{-1}, while the insecticides chlorpyrifos, endosulfan, and permethrin all had negative impacts at 1.0 μg L^{-1}, as did the fungicide MEMC. Chlorpyrifos-oxon and profenofos (both insecticides) showed negative effects on settlement at concentrations as low as 0.3 μg L^{-1}.

3.2.3. Coral juveniles

The only response examined for juvenile, post-settlement corals (i.e., recruits) was survival, which was assessed after exposure to tin, diuron, naled, and permethrin. Tin significantly decreased the likelihood of juvenile survival at 2.5 μg L^{-1}. The insecticides naled and permethrin did not have any significant effect on juvenile survival at the maximum concentrations examined, 9.59 μg L^{-1} and 6.04 μg L^{-1}, respectively. Diuron had no effect on juvenile survival at concentrations up to 1000 μg L^{-1}.

3.2.4. Coral adults

Tissue loss, growth rates, and adult mortality were examined in response to four metals, eight pesticides, two PAHs, and a PCB. Mortality increased following exposure to low concentrations of some pollutants (e.g., copper) and higher concentrations of others (e.g., manganese), but growth rates typically declined at much lower concentrations. Copper reduced growth rates at 4 μg L^{-1} and increased adult mortality at concentrations as low as 40 μg L^{-1}. Coral growth rates also declined at low concentrations of nickel (3.52 μg L^{-1} when combined with temperature stress), tin (0.4 μg L^{-1}), and cobalt (0.22 μg L^{-1}). Mortality increased after exposure to higher concentrations of lead (320 μg L^{-1}), and tissue loss and mortality increased at even higher concentrations of manganese (1000 μg L^{-1} and 5000 μg L^{-1}, respectively).

Diuron decreased growth rates at 1 μg L^{-1} and caused tissue loss and adult coral mortality at 10 μg L^{-1}, while another herbicide, 2,4-D, caused mortality at 19,300 μg L^{-1}. None of the fungicides or insecticides (i.e., MEMC, carbaryl, chlorpyrifos, endosulfan, permethrin, and profenofos) caused tissue mortality at the maximum concentration examined, 10 μg L^{-1}, but profenofos and MEMC reduced tentacular activity at 10 μg L^{-1}. Fluoranthene, a PAH, increased tissue mortality at low concentrations, while 1-methylnaphthalene increased tissue mortality and decreased tentacular activity at much higher concentrations (5427 μg L^{-1} and above). Aroclor 1254, a PCB, did not affect mortality or growth at the concentration examined, 0.29 μg L^{-1}. Estrone, which is a naturally produced hormone used in pharmaceutical applications, decreased coral growth rates at concentrations as low as 0.002 μg L^{-1}, but mortality rates were not reported.

Bleaching was also examined as a stress response to two metals, eight pesticides, two PAHs, and one PCB. No bleaching was seen in

Table 3
Quantitative review of pollutants, coral responses, range of concentrations examined (not including control levels at 0 μg L^{-1}), and lowest-observed adverse effect levels (LOAEL) from the corresponding article(s). A LOAEL is the lowest pollutant concentration experimentally tested at which a coral adversely responded. If more than one article is listed, then the LOAEL is the most conservative (i.e., lowest) value from among the articles. See Table S3 for more details concerning species, region, NOAEL, and reported EC_{50} values from each article. Abbreviations: EQY = effective quantum yield; MQY = maximum quantum yield; P/R = production to respiration ratio.

Pollutant class	Pollutant	Coral response	Range of concentrations examined (μg L^{-1})	LOAEL (μg L^{-1})	Article
METAL	Aluminum	Fertilization success	5.5–9700	2950	Negri et al., 2011b
		Settlement	15.3–9700	1960	Negri et al., 2011b
	Cadmium	Fertilization success	2–10,000	5000	Reichelt-Brushett and Harrison, 1999, 2005
		Bleaching	5–50	None	Mitchelmore et al., 2007
		Chlorophyll concentration	5–50	None	Mitchelmore et al., 2007
		Symbiont density	5–50	None	Mitchelmore et al., 2007
		Tissue mortality	5–50	50	Mitchelmore et al., 2007
	Cobalt	Fertilization success	9.5–2357	None	Reichelt-Brushett and Hudspith, 2016
		Growth	0.03–0.2	0.2	Biscéré et al., 2015
		MQY	0.03–0.2	None	Biscéré et al., 2015
	Copper	Fertilization success	0.1–6263	6	Gissi et al., 2017; Kwok et al., 2016; Reichelt-Brushett and Hudspith, 2016; Puisay et al., 2015; Hédouin and Gates, 2013; Reichelt-Brushett and Harrison, 1999, 2005; Victor and Richmond, 2005; Negri and Heyward, 2001
		Abnormal larval development	10–220	50	Puisay et al., 2015
		Larval survival	5–611	10	Hédouin et al., 2016; Kwok et al., 2016; Kwok and Ang, 2013; Reichelt-Brushett and Harrison, 2004
		Larval swimming velocity	10–200	50	Kwok et al., 2016; Kwok and Ang, 2013; Reichelt-Brushett and Harrison, 2004
		Settlement	0.1–6263	24	Kwok et al., 2016; Negri and Hoogenboom, 2011; Negri and Heyward, 2001; Reichelt-Brushett and Harrison, 2000
		Adult mortality	5–434	40	Hédouin et al., 2016; Jones, 1997
		Bleaching	5–80	30	Bielmyer et al., 2010; Mitchelmore et al., 2007; Muhaemin, 2007; Jones, 1997, 2004
		Chlorophyll concentration	3.8–434	5	Fonseca et al., 2017; Hédouin et al., 2016; Jones, 1997; Mitchelmore et al., 2007; Yost et al., 2010
		EQY	4–20.3	4	Bielmyer et al., 2010
		Growth	4–200	4	Kwok et al., 2016; Bielmyer et al., 2010
		MQY	1–434	1	Banc-Prandi and Fine, 2019; Fonseca et al., 2017, 2019; de Barros Marangoni et al., 2017; Hédouin et al., 2016
		Production	10–30	30	Muhaemin, 2007; Alutoin et al., 2001; Nyström et al., 2001
		Symbiont density	5–434	12.6	Hédouin et al., 2016; Jones, 1997, 2004; Mitchelmore et al., 2007; Yost et al., 2010
		Tissue mortality	5–50	50	Mitchelmore et al., 2007
	Gallium	Fertilization success	10.2–11,200	3230	Negri et al., 2011b
		Settlement	10.2–11,200	2150	Negri et al., 2011b
	Iron	Fertilization success	10–55,800	25,300	Leigh-Smith et al., 2018
		Larval survival	10–55,800	27,200	Leigh-Smith et al., 2018
		Symbiont density	5–50	10	Harland and Brown, 1989
	Lead	Fertilization success	2–9577	855	Reichelt-Brushett and Harrison, 2005
		Larval survival	100–20,000	640	Hédouin et al., 2016; Reichelt-Brushett and Harrison, 2004
		Larval swimming velocity	7.7–20,000	828	Reichelt-Brushett and Harrison, 2004
		Adult mortality	68–1200	320	Hédouin et al., 2016
		Chlorophyll concentration	68–1200	75.6	Hédouin et al., 2016
		MQY	68–1200	320	Hédouin et al., 2016
		Symbiont density	68–1200	75.6	Hédouin et al., 2016
	Manganese	Fertilization success	800–161,100	71,200	Summer et al., 2019
		Larval survival	17,000–163,800	17,000	Summer et al., 2019
		Adult colony mortality	1000–50,000	10,000	Summer et al., 2019
		Tissue mortality	1000–50,000	5000	Summer et al., 2019
	Mercury	Larval survival	10	None	Farina et al., 2008
		Chlorophyll concentration	4–180	180	Bastidas and Garcia, 2004
		Symbiont density	4–180	180	Bastidas and Garcia, 2004
	Nickel	Fertilization success	5–9090	100	Gissi et al., 2017; Reichelt-Brushett and Hudspith, 2016; Reichelt-Brushett and Harrison, 2005
		Chlorophyll concentration	3.5	None	Biscéré et al., 2017, 2018
		Growth	2.7–3.5	3.5[a]b	Biscéré et al., 2017, 2018
		MQY	3.5	None	Biscéré et al., 2017, 2018
		P/R	3.5	None	Biscéré et al., 2018
		Production	2.7–3.5	None	Biscéré et al., 2017
		Respiration	2.7–3.5	None	Biscéré et al., 2017
		Symbiont density	3.5	3.5[b]	Biscéré et al., 2017, 2018
	Tin	Fertilization success	0.3–3228	318	Negri and Heyward, 2001
		Settlement	0.3–3228	3	Negri and Heyward, 2001
		Juvenile survival	0.1–2.5	2.5	Watanabe et al., 2007
		Growth	0.1–0.4	0.4	Watanabe et al., 2007
	Vanadium	Fertilization success	20.6–9380	2920	Watanabe et al., 2007
		Settlement	20.6–9380	564	Negri et al., 2011b
	Zinc	Fertilization success	2–5000	10	Reichelt-Brushett and Harrison, 1999, 2005

(continued on next page)

Table 3 (*continued*)

Pollutant class	Pollutant	Coral response	Range of concentrations examined (μg L^{-1})	LOAEL (μg L^{-1})	Article
INSECTICIDE	1-Naphthol	Larval survival	10–100,000	1000	Acevedo, 1991
	Carbaryl	Fertilization success	0.3–30	None	Markey et al., 2007
		Larval survival	10–100,000	10,000	Acevedo, 1991
		Settlement	0.1–300	3	Markey et al., 2007
		Bleaching	1–10	None	Markey et al., 2007
		EQY	1–10	None	Markey et al., 2007
		Symbiont density	10	None	Markey et al., 2007
		Tentacular activity	1–10	None	Markey et al., 2007
		Tissue mortality	1–10	None	Markey et al., 2007
	Chlorpyrifos	Fertilization success	0.3–30	None	Markey et al., 2007
		Larval survival	10–100,000	1000	Acevedo, 1991
		Settlement	0.1–300	1	Markey et al., 2007
		Bleaching	1–10	10	Markey et al., 2007
		EQY	1–10	10	Markey et al., 2007
		Symbiont density	10	None	Markey et al., 2007
		Tentacular activity	1–10	None	Markey et al., 2007
		Tissue mortality	1–10	None	Markey et al., 2007
	Chlorpyrifos-oxon	Fertilization success	0.3–30	None	Markey et al., 2007
		Settlement	0.1–300	0.3	Markey et al., 2007
	Endosulfan	Fertilization success	0.3–30	None	Markey et al., 2007
		Settlement	0.1–300	1	Markey et al., 2007
		Bleaching	1–10	10	Markey et al., 2007
		EQY	1–10	10	Markey et al., 2007
		Symbiont density	10	None	Markey et al., 2007
		Tentacular activity	1–10	None	Markey et al., 2007
		Tissue mortality	1–10	None	Markey et al., 2007
	Glyphosate	Bleaching	108–10,800	10,800[a]	Amid et al., 2018
		Chlorophyll concentration	108–10,800	10,800[a]	Amid et al., 2018
	Naled		0.6–9.6	0.6	Ross et al., 2015
		Settlement	0.6–9.6	None	Ross et al., 2015
		Juvenile survival	0.6–9.6	None	Ross et al., 2015
		Symbiont density	0.6–9.6	None	Ross et al., 2015
	Permethrin	Fertilization success	0.3–30	None	Markey et al., 2007
		Larval survival	0.4–6	1	Ross et al., 2015
		Settlement	0.1–300	1	Ross et al., 2015; Markey et al., 2007
		Juvenile survival	0.4–6	None	Ross et al., 2015
		Bleaching	1–10	10	Markey et al., 2007
		EQY	1–10	None	Markey et al., 2007
		Symbiont density	0.4–10	None	Ross et al., 2015; Markey et al., 2007
		Tentacular activity	1–10	None	Markey et al., 2007
		Tissue mortality	1–10	None	Markey et al., 2007
	Profenofos	Fertilization success	0.3–30	None	Markey et al., 2007
		Settlement	0.1–300	0.3	Markey et al., 2007
		Bleaching	1–10	10	Markey et al., 2007
		EQY	1–10	None	Markey et al., 2007
		Symbiont density	10	10	Markey et al., 2007
		Tentacular activity	1–10	10	Markey et al., 2007
		Tissue mortality	1–10	None	Markey et al., 2007
HERBICIDE	2,4-D	Adult colony mortality	50–1,000,000	19,300	Sabdono et al., 1998; Glynn et al., 1984
		EQY	10,000–100,000	100,000	Råberg et al., 2003
		MQY	10,000–100,000	None	Råberg et al., 2003
		Mucus production	100–1,000,000	1000[c]	Sabdono et al., 1998
		P/R	10,000–100,000	10,000	Råberg et al., 2003
		Production	10,000–100,000	10,000	Råberg et al., 2003
		Symbiont density	100–1,000,000	19,300	Sabdono et al., 1998
		Tentacular activity	50–1,000,000	1000 [c]	Sabdono et al., 1998; Glynn et al., 1984
		Tissue mortality	50–1,000,000	100,000 [c]	Sabdono et al., 1998; Glynn et al., 1984
	Ametryn	EQY	0.3–1000	0.3	Jones and Kerswell, 2003
	Atrazine	Chlorophyll concentration	12	None	Negri et al., 2011a
		EQY	0.3–1000	3	Negri et al., 2011a; Jones and Kerswell, 2003; Jones et al., 2003
		MQY	0.3–1000	100	Negri et al., 2011a; Jones et al., 2003
		Fertilization success	0.1–1000	None	Negri et al., 2005
		Settlement	0.1–1000	300	Negri et al., 2005
		Juvenile survival	0.1–1000	None	Negri et al., 2005
	Diuron	Adult colony mortality	1–10	10	Cantin et al., 2007
		Bleaching	0.1–1000	10	Cantin et al., 2007; Negri et al., 2005; Jones, 2004
		Chlorophyll concentration	0.8	None	Negri et al., 2011a
		EQY	0.1–1000	0.3	Negri et al., 2005, 2011a; Cantin et al., 2007; Jones, 2004; Jones and Kerswell, 2003; Jones et al., 2003; Råberg et al., 2003
		Growth	0.3–10	1	Watanabe et al., 2007
		MQY	0.1–1000	1	Negri et al., 2005, 2011a; Cantin et al., 2007; Jones, 2004; Jones et al., 2003; Råberg et al., 2003
		P/R	10–100	10	Råberg et al., 2003

Table 3 (*continued*)

Pollutant class	Pollutant	Coral response	Range of concentrations examined (μg L^{-1})	LOAEL (μg L^{-1})	Article
		Symbiont density	0.1–1000	10	Negri et al., 2005; Jones, 2004
		Tissue mortality	1–10	10	Cantin et al., 2007
		Chlorophyll concentration	3.8	None	Negri et al., 2011a
	Hexazinone	EQY	0.3–1000	3	Negri et al., 2011a; Jones and Kerswell, 2003
		MQY	0.3–1000	3	Negri et al., 2011a
	Ionynil	EQY	0.3–1000	None	Jones and Kerswell, 2003
	Irgarol	EQY	0.3–1000	0.3	Jones and Kerswell, 2003
	Simazine	EQY	0.3–1000	30	Jones and Kerswell, 2003
	Tebuthiuron	EQY	0.3–1000	10	Jones and Kerswell, 2003
FUNGICIDE	2-Methoxy-ethylmercuric chloride (MEMC)	Fertilization success	0.3–30	1	Markey et al., 2007
		Settlement	0.1–300	1	Markey et al., 2007
		Bleaching	1–10	1	Markey et al., 2007
		EQY	1–10	1	Markey et al., 2007
		Symbiont density	10	10	Markey et al., 2007
		Tentacular activity	1–10	1	Markey et al., 2007
		Tissue mortality	1–10	1	Markey et al., 2007
PAH	1-Methyl-naphthalene	EQY	640–25,095	None	Renegar et al., 2017
		Adult mortality	640–25,095	None	Renegar et al., 2017
	Anthracene	Larval survival	9.4–600	9.4[d]	Overmans et al., 2018
		Settlement	9.4–600	9.4[d]	Overmans et al., 2018
	Benzo(a)-pyrene	Larval survival	10	10	Farina et al., 2008
		Bleaching	10–100	None	Ramos and Garcia, 2007
		Chlorophyll concentration	9–100	9	Xiang et al., 2019; Ramos and Garcia, 2007
		Symbiont density	10–100	100	Ramos and Garcia, 2007
	Fluoranthene	Bleaching	15–60	15	Martínez et al., 2007
		Tissue mortality	15–60	15	Martínez et al., 2007
	Phenanthrene	Larval survival	14.1–900	56.3[d]	Overmans et al., 2018
		Settlement	14.1–900	56.3[d]	Overmans et al., 2018
PCB	Aroclor 1254	Adult colony mortality	0.3	None	Chen et al., 2012
		Bleaching	0.3	None	Chen et al., 2012
		Growth	0.3	None	Chen et al., 2012
		MQY	0.3	None	Chen et al., 2012
PHARMACEUTICAL	Estrone	Growth	0.002	0.002	Tarrant et al., 2004

[a] When combined with temperature stress.
[b] When combined with urea enrichment.
[c] Qualitative description.
[d] When combined with UVA.

response to cadmium at concentrations up to 50 μg L^{-1}, but bleaching was seen after exposure to copper concentrations of 30 μg L^{-1}. Aroclor 1254, a PCB, did not cause bleaching at the concentration examined (0.29 μg L^{-1}). Bleaching after exposure to PAHs and pesticides was variable. Bleaching occurred at 15 μg L^{-1} of fluoranthene but not at concentrations of up to 100 μg L^{-1} of benzo(*a*)pyrene. Bleaching also occurred in response to four pesticides at 10 μg L^{-1}: the fungicide MEMC; the herbicide diuron; and the insecticides permethrin and profenofos. No bleaching response was seen, however, after exposure to 10 μg L^{-1} of the insecticides carbaryl, chlorpyrifos, or endosulfan, and even when combined with temperature stress, bleaching was only seen after exposure to very high concentrations of the herbicide glyphosate (10,800 μg L^{-1}).

Symbiont density was also measured in response to six metals, nine pesticides, and one PAH. As seen with other coral responses, symbiont density decreased with exposure to metals at a range of concentrations that varied by metal. Cadmium had no significant effect on symbiont density at the maximum concentrations examined, 5 μg L^{-1}, while nickel decreased symbiont density at 3.5 μg L^{-1} when combined with temperature stress. Symbiont density decreased with exposure to mercury (180 μg L^{-1}), lead (75.6 μg L^{-1}), copper (12.6 μg L^{-1}), iron (10 μg L^{-1}), and benzo(*a*)pyrene, a PAH, (100 μg L^{-1}). Symbiont density decreased following exposure to 10 μg L^{-1} of profenofos (insecticide), MEMC (fungicide), and diuron (herbicide), but there was no significant change in symbiont density following exposure to the same concentration of the insecticides carbaryl, chlorpyrifos, endosulfan, naled, and permethrin. Symbiont density also decreased after exposure to very high (19,300 μg L^{-1}) concentrations of the herbicide 2,4-D.

The impact of pollutants on chlorophyll content was also examined. This assessment included studies focusing on five metals, four pesticides, and one PAH. As seen in other coral responses, chlorophyll content decreased after exposure to metals at a range of concentrations that varied by metal. Cadmium had no significant impact on chlorophyll at concentrations up to 50 μg L^{-1}, but chlorophyll content decreased with exposure to mercury (180 μg L^{-1}), lead (75.6 μg L^{-1}), and copper (5 μg L^{-1}). Benzo(*a*)pyrene, a PAH, reduced chlorophyll content at 9.02 μg L^{-1}, and when combined with temperature stress, the herbicide glyphosate decreased chlorophyll content at 10,800 μg L^{-1}. Atrazine, diuron, and hexazinone, all herbicides that inhibit photosystem II (Table 1), did not significantly impact chlorophyll content at the maximum concentrations examined (12.0 μg L^{-1}, 0.84 μg L^{-1}, and 3.8 μg L^{-1}, respectively).

Effective quantum yield (EQY) was measured as a response in studies that focused on the effects of copper, 1-methyl-naphthalene (a PAH), and fifteen pesticides (Table 3). However, maximum quantum yield (MQY) is the primary photosynthetic response considered herein (see Methods). MQY was examined in response to copper (see meta-analysis), cobalt, lead, nickel, Aroclor 1254 (PCB), and four herbicides. Cobalt and nickel had no significant impact on MQY at the highest concentrations examined, 0.22 μg L^{-1} and 3.52 μg L^{-1}, respectively. Copper had negative effects on MQY at concentrations as low as 1 μg L^{-1}, and lead also affected MQY at higher concentrations of 320 μg L^{-1}. Aroclor 1254 had no significant impact on MQY at the highest concentration examined, 0.29 μg L^{-1}. The herbicide, 2,4-D, similarly had no effect on MQY at 100,000 μg L^{-1}, the highest concentration examined. Atrazine and diuron did have negative effects on MQY at 3 μg L^{-1} and 1 μg L^{-1}, respectively.

4. Discussion

Reduced water quality can be a root cause of extended and extensive coral-reef loss. Pollutants are major components of water quality, and as reviewed herein and elsewhere (Cooper et al., 2009; Fabricius, 2005; Gregg, 2013; Shaw et al., 2010), can cause reductions in coral reproductive function, recruitment, growth rates, and survivorship of both larvae and adults, while increasing disease susceptibility. Cumulatively, these effects diminish coral populations' persistence and replenishment capacity. To address this concern, we estimated thresholds of coral health in response to pollutants using a meta-analytical approach (Table 2). This required adapting Bayesian hierarchical dose-response meta-analysis models, originally developed for biopharmaceutical research (Thomas et al., 2014; Wu et al., 2018), for use with complex ecological datasets. Given the diversity of pollutants, coral responses, and experimental approaches, however, thresholds could not be estimated for most combinations of pollutants and responses (Table 4). Some pollutants, such as copper, have 14 different responses examined with up to 9 papers examining a single pollutant-response pair. Other pollutants and pollutant classes have received far less attention, which limits the capacity for meta-analysis to be used to develop more robust guidelines for these stressors. This is a particularly urgent need for pollutants with known impacts in other systems, such as estrogenic compounds and pesticides (Hayes and Hansen, 2017). In contrast to the coverage for copper, the three most widely used herbicides – 2,4-D, atrazine, and glyphosate – have only 7 studies among them included in this quantitative review (Table 3) (Hayes and Hansen, 2017).

Our study highlights the need to reassess the way in which pollution thresholds are examined on coral reefs and in other systems. Typically, the responses measured during early coral life-history are 'terminal' in that failure to fertilize or survive to the settlement-stage effectively precludes the capacity of a coral population to persist and rebound after stressful events, but these impacts can also compound through the life stages of a coral and affect various life stages differently. The varied and in some cases cumulative impacts of pollutants at different life stages have been demonstrated in other organisms such as Chinese cabbage (Luo et al., 2019), zebrafish (Brion et al., 2004), and albatross (Goutte et al., 2014). Understanding how these potentially additive impacts manifest is important in identifying high risk time periods or locations for management. This is especially important in corals which have unique, complex life cycles that are intimately linked to the health of their holobiont (i.e., associated symbionts, bacteria, fungi) (Vega-Thurber et al., 2009).

One example of the compounding effect of pollutant exposure specific to this study is illustrated in Fig. 4, in which exposure to just 40 μg L^{-1} copper during the first week post-fertilization leads to less than half the number of coral recruits, as compared to uncontaminated conditions (27% vs. 59% of starting gametes). Copper exposure at 100 μg L^{-1} effectively eliminates all coral larvae from settling to the reef. Thus, assigning a management threshold at EC_{50} values for responses of immature corals will likely be inadequate to prevent reef decline. A greater diversity of responses to stressors is measured for adult corals, which offers an opportunity to consider sublethal effects when estimating pollution thresholds that are more conservative than those estimated from lethal effects only. Regardless, additional studies are needed that evaluate the effect of more pollutants across the coral life cycle before truly effective management thresholds can be assigned. In the meantime, a conservative approach should be adopted when data suggest that a pollutant adversely affects corals at any stage.

Our quantitative review indicates that some pollutants impact corals more than other pollutants, which can offer insight and guidance into mitigating the risks of multiple, co-occurring chemicals (see Table 3). For example, the lowest concentrations (LOAELs) at which copper adversely affected fertilization was 6 μg L^{-1}, while settlement was impacted at 24 μg L^{-1} and adult survival at 40 μg L^{-1}. Zinc similarly affects fertilization at just 10 μg L^{-1}. Conversely, tin does not impact fertilization at concentrations up to 318 μg L^{-1}, but does negatively affect settlement and juvenile survival at much lower concentrations of 10 μg L^{-1} and 2.5 μg L^{-1}, respectively. Other metals, such as cadmium, only reduce fertilization at much higher concentrations (5000 μg L^{-1}). Different classes of pollutants, such as herbicides that inhibit photosystem II (e.g., diuron), may differentially impact coral life stages (Table 1). Diuron has a LOAEL for larval settlement of 300 μg L^{-1}, but negatively impacts photosynthesis at concentrations as low as 0.3 μg L^{-1} (Negri et al., 2005). Conversely, another herbicide, chlorpyrifos (an acetylcholinesterase-inhibitor), does not inhibit fertilization or adult coral function at the concentrations measured, but does impact larval settlement at just 1 μg L^{-1} (Table 3). Compared to metals and pesticides, the impacts of PAHs, PCBs, and pharmaceuticals on corals are understudied. However, within those studies that do exist, there is variability in the impacts among life stages. These differences highlight the importance of examining impacts at different life stages to understand the breadth of potential effects and develop management strategies that specifically target the greatest threats at the most vulnerable stages.

Many pollutants also degrade in the environment and in organisms, yielding a myriad of different breakdown products that may be harmful to corals and other animals (ATSDR, 1995). However, breakdown products present in the environment are not well documented for many pollutants, making it difficult to assess their potential impact (Hayes and Hansen, 2017). Further, most studies examine one pollutant at varying concentrations and then measure a single biological response. In the environment, however, corals and other organisms are exposed to a diverse array of pollutants that may be found in combination with other stressors such as fluctuations in sediment, freshwater, temperature, and pH (Banc-Prandi and Fine, 2019; Donovan et al., 2020; Hédouin et al., 2016; Negri et al., 2011a). These combinations may produce synergistic and additive effects that are difficult to isolate, quantify, and manage. For example, zinc can be harmful to corals and other organisms in isolation, but it is also known to interact with other metals, such as lead and copper, exacerbating negative impacts (Eisler, 1993). This further highlights the need for conservative guidelines that account for multiple stressors, sublethal impacts, and compounding effects throughout the life cycle of an organism.

Future studies examining the impacts of pollutants on corals and other marine organisms should consider environmentally relevant concentrations of pollutants, which means including ambient, background levels as well as those that are enhanced significantly by human activity. For example, nickel is found at high concentrations in the environment from natural sources such as volcanic rock, but it is found in unnaturally high levels on coral reefs adjacent to locations with land use that causes runoff of nickel-rich sediments (Hédouin et al., 2009). Environmentally relevant concentrations may also lend insight into the importance of exposure duration in experimental studies. For instance, we found that diuron may have impacts that vary depending on exposure duration (Fig. 3). This may be of particular importance in areas with limited water flow to flush out pollutants, such as enclosed bays. Understanding the relative importance of exposure concentration, duration, and frequency is important for local management strategies. Thus, increasing the number of studies that examine the impacts of acute vs. chronic pollutant exposures will increase the capacity to compare across stressors and more accurately model their interactions on reefs.

The difference between acute exposure and chronic impacts is often considered in the development of consumption limits in the context of human health (e.g., ATSDR Minimal Risk Levels or US EPA Reference Doses), so these guidelines may offer insight into how to more effectively develop thresholds for pollutant impacts on wildlife. In the human health context, 'Reference Doses' are developed by taking the highest concentration at which there is no observable adverse effect (NOAEL) in response to a pollutant and dividing it by an uncertainty factor, which can range from 10 to 3000 (US EPA, 1993, 2009). Resource

Table 4
Relative amounts of data available (i.e., gap analysis) that address different combinations of pollutants (left two columns) with coral responses, organized by life-history stage (top). The number in each cell indicates the number of articles that examine the pollutant-response pair, and the shade of the cell is scaled to the relative number of articles, with darker shades indicating more articles. Empty cells indicate no (zero) articles found in our systematic review that adequately address the pollutant-response pair.

		GAMETE	LARVAE				JUVENILE	ADULT										
		Fertilization Success	Survival	Abnormal Development	Swimming velocity	Settlement	Survival	Mortality	Tissue Mortality	Tentacular Activity	Mucus Production	Bleaching	Growth	Symbiont Density	Chlorophyll Concentration	Production/ Respiration	EQY	MQY
METALS	Aluminum	1				1												
	Cadmium	2							1			1		1	1			
	Cobalt	1											1					1
	Copper	9	4	1	3	4		2	1			5	2	5	5	3	1	5
	Gallium	1				1												
	Iron	1	1											1				
	Lead	1	2		1			1						1	1			1
	Manganese	1	1					1	1									
	Mercury		1											1	1			
	Nickel	3											2	2	2	2		2
	Tin	1	1			1							1					
	Vanadium	1				1												
	Zinc	2																
INSECTICIDES	1-Naphthol		1															
	Carbaryl	1	1			1			1	1		1		1			1	
	Chlorpyrifos	1	1			1			1	1		1		1			1	
	Chlorpyrifos-oxon	1				1												
	Endosulfan	1				1			1	1		1		1			1	
	Naled		1			1	1							1				
	Permethrin	1	1			2	1		1	1		1		2			1	
	Profenofos	1				1			1	1		1		1			1	
HERBICIDES	2,4-D							2	2	2	1			1		1	1	1
	Ametryn																1	
	Atrazine														1		3	2
	Diuron	1				1	1	1	1			3	1	2	1	1	7	6
	Glyphosate											1			1			
	Hexazinone														1		2	1
	Ionynil																1	
	Irgarol																1	
	Simazine																1	
	Tebuthiuron																1	
FUNGICIDES	MEMC	1				1			1	1		1		1			1	
PAHs	Anthracene		1			1												
	1-methylnaphthalene								1	1	1						1	
	Benzo(a)pyrene		1									1		1	2			
	Flouranthene								1			1						
	Phenanthrene		1			1												
PCBs	Aroclor 1254							1				1	1					1
PHARM.	Estrone												1					

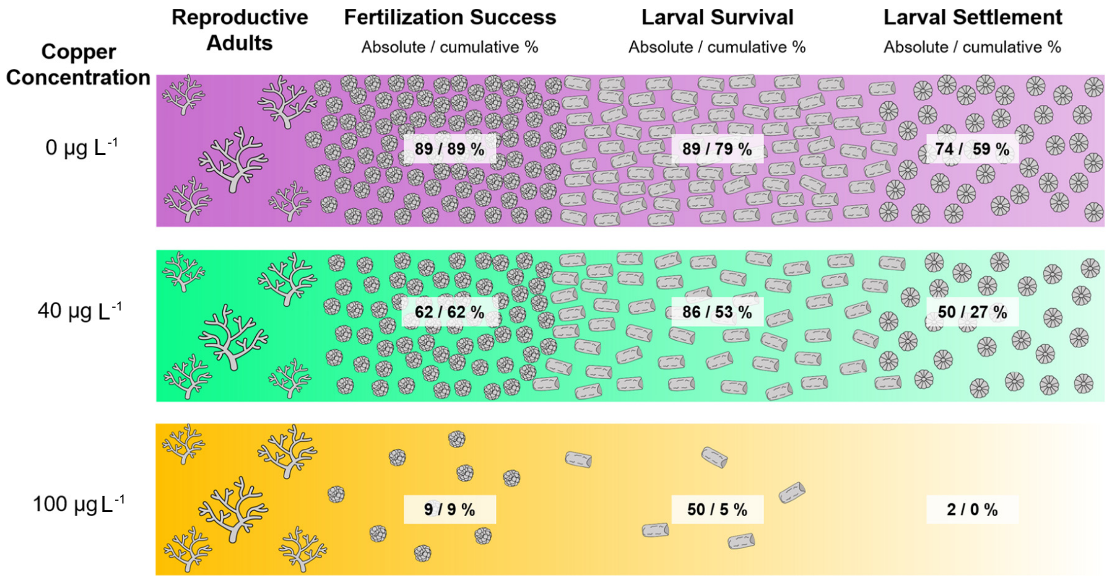


Fig. 4. Illustrative representation of the compounding effects of copper during the early life stages of a coral in a simplified, closed system where only reproductive adults contribute to the population. The horizontal, colored bands correspond to systems with 0, 40, and 100 μg L^{-1} copper, respectively. "Absolute" numbers are the Bayesian model average estimates for the corresponding copper concentration and coral response. "Cumulative" numbers are the absolute percent listed at a stage multiplied by the cumulative percent from the previous stage (assuming 100% for reproductive adults). Thus, it represents the percent of individuals remaining since release of gametes by adults. Absolute estimates (with Bayesian 95% credible intervals) at 0 μg L^{-1} are 89.0% (85.5, 92.3) for fertilization success, 89.1% (76.3, 98.7) for larval survival, and 74.1% (59.3, 88.9) for larval settlement. At 40 μg L^{-1}, the same estimates are 61.7% (38.8, 88.3), 86.4% (63.7, 98.7), and 50.0% (9.8, 88.5), respectively. At 100 μg L^{-1}, the same estimates are 9.0% (4.9, 13.9), 49.9% (42.0, 84.4), and 2.2% (1.8, 4.5), respectively.

managers may want to model habitat conservation guidelines off of this approach to account for the sublethal, synergistic, and compounding impacts of pollutant stressors on corals and other marine organisms. Further, this would aid in addressing the often undocumented differences in responses between species and morphology, where some taxa are better equipped than others to manage exposure to certain stressors. In many cases, we do not have species-specific guidelines, and this is an area that is ripe for additional research, especially in locations where resource managers seek to develop place-based strategies. In the meantime, however, setting conservative limits modeled after human health approaches would ensure that the most vulnerable taxa are better protected, even in cases where their responses are not well documented.

Tools that identify sublethal stress in corals, including molecular techniques such as proteomics, genomics, and transcriptomics, also allow for both the diagnosis and evaluation of the effectiveness of management interventions at both individual and population levels. These molecular biomarkers can be used to identify those specific toxicants that affect homeostasis, metabolic condition, reproductive function, and DNA integrity, potentially before declining coral health is evident (Cantin et al., 2007; Parkinson et al., 2019; Tisthammer et al., 2021). When such molecular data are evaluated and applied, interventions can be designed, implemented and evaluated in periods of weeks to months, rather than years to decades, as is done with ecological indicators such as percent coral cover (Cooper et al., 2009). These qualitative and quantitative tools can identify key stressors of biological relevance, threshold levels at which effects occur, and antagonisms/synergisms with other stressors. Furthermore, research frameworks exist for the discovery, validation, and implementation of molecular biomarker tools in corals (Parkinson et al., 2019).

These molecular tools now allow researchers and managers to rapidly identify the biological relevance of chemical contaminants, not just their presence and concentration, which when measured in the field are ephemeral and change with tides, wind, rainfall, and water characteristics such as flushing and residence times. Corals and other reef organisms serve as sensitive and accurate integrators of toxicant exposure in the field. For example, coral lipids can act as living semipermeable membrane devices for accumulating lipophilic/hydrophobic substances, such as PAHs and pesticides (Caroselli et al., 2020; Porter et al., 2018). Additionally, molecular tools allow managers to identify both sensitive and resistant genotypes, and of critical importance to reef resilience, genotypic diversity within coral populations (Tisthammer et al., 2021). This is a very important indicator of impending local extinction events in which specific stressor thresholds are exceeded and genotypic diversity is lost.

Based on apparent gaps in our understanding and approach-to-date, we recommend that researchers target a broader set of pollutant types. We also recommend defining critical threshold values for toxicants on coral reefs by targeting a broad range of stressor concentrations that reflect toxicant levels seen in the environment and elicit sublethal (e.g., physiological, behavioral, molecular, or microbial) responses in corals, so that stress can be quantified and mitigated before corals experience mortality. We also encourage experimental designs that result in a dose-response curve to enable estimation of the inhibitory concentration thresholds (EC_x). Furthermore, we recommend that researchers attempt to standardize the units in which they report both toxicant levels (e.g., μg L^{-1}) and coral responses (e.g., bleaching, see Grottoli et al., 2020), and that raw data is made available whenever possible. These efforts will improve our ability to synthesize comparable information across studies, locations, species, and stressors, thus resulting in data-rich meta-analyses that better inform management decisions.

As the availability of data that addresses a range of pollutants at environmentally relevant concentrations over the complete life cycle of corals becomes available, it is important to update and adapt management strategies as appropriate. In the cases where sufficient data do not exist to inform management and policy decisions, the approach of public health officials should be followed to develop guidelines that employ the precautionary principle. Many pollutants are co-occurring and are present in combination with other environmental stressors, such as increased temperature or ocean acidification, that may also have synergistic or additive effects (Biscéré et al., 2015; Cabral et al., 2019; Fujita et al., 2014; Kwok and Ang, 2013). With this in mind, it must be acknowledged that guidelines based on NOAEL/LOAELs or EC_{50} values are not necessarily conservative enough to protect foundational species, like reef-building corals. In addition, adopting truly conservative guidelines will better address the potential variability in the effects of exposure duration on the stress response.

Basing guidelines on the maximum concentrations present in water quality monitoring as well as those seen in extreme events, rather than the mean, is one way that resource managers can work to enact more conservative management strategies. In addition, resource managers can also take proactive steps to collaboratively work with other agencies to address pollution before it reaches the coastal zone. As an example, some pollutants are broken down by bacteria and fungi (Ceci et al., 2019), so comprehensive ridge-to-reef management strategies may consider these active remediation strategies to reduce land-based pollutant inputs. Finally, climate change impacts pose a clear threat to reefs globally, so as managers develop strategies to mitigate the risks associated with increased temperatures, bleaching events, ocean acidification, and increased storm frequency, it is important to also consider the reduced capacity for resilience and recovery in corals that are already experiencing physiological stress as a result of toxicant exposure.

5. Conclusions

When sufficient data are available, Bayesian dose-response meta-analysis provides a robust way of examining the relationship between pollutant concentrations and subsequent coral responses. The impacts of copper on fertilization are well studied and offer an example of the type of data that would be desirable for all stressor-response combinations. Because there are so few studies, it is not yet possible to disentangle the effects of species, morphology, or location, but these are important considerations for the development of place-based management strategies. In the absence of robust reference data for most pollutants, it is important to create management guidelines that are conservative and abide by the precautionary principle. Pollutants on reefs do not act in isolation. Instead, they are typically combined with other toxins and environmental stressors associated with climate change (Cabral et al., 2019; Fujita et al., 2014), and negative impacts likely compound throughout the different life stages (Fig. 4). In combination with more conservative guidelines that account for the known and unknown variability in these systems, coordinated strategies that include active remediation will also reduce impacts on reefs. Finally, it is also important to move beyond considering just lethal coral responses at single life-history stages as indicators of stress. Developing standardized approaches to measure sublethal responses will offer resources for the development of targeted, proactive interventions.

Global climate change – with the associated problems of elevated seawater temperatures and regional mass coral bleaching events, ocean acidification affecting calcification rates, enhanced tropical storm frequency and severity, and sea level rise – is clearly the major cause of coral-reef loss at the global scale. From a management perspective, however, it is strategic and essential to address local stressors now to buy time to tackle the challenge of climate change. Reducing local stressors, such as chemical pollutants, can improve resistance, resilience, and recovery for individual reefs and reef ecosystems.

Funding

This work was funded by the U.S. National Oceanic and Atmospheric Administration [grant number NA19NMF4540068], which had no role in study design, writing, or the collection, analysis, or interpretation of data.

Data statement

All data generated during this study, along with code used to analyze data and generate figures, are shared in the public repository: https://github.com/ljtuttle/coral_pollutant_thresholds

CRediT authorship contribution statement

Eileen M. Nalley: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. **Lillian J. Tuttle:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Alexandria L. Barkman:** Investigation, Methodology, Visualization, Writing – review & editing. **Emily E. Conklin:** Investigation, Methodology, Visualization, Writing – review & editing. **Devynn M. Wulstein:** Investigation, Methodology, Visualization, Writing – review & editing. **Robert H. Richmond:** Writing – original draft, Writing – review & editing. **Megan J. Donahue:** Conceptualization, Formal analysis, Funding acquisition, Software, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to thank Malia Chow, Anne Chung, Gerry Davis, and Stu Goldberg, all of the NOAA Pacific Islands Regional Office (PIRO) Habitat Conservation Division, who gave feedback and organizational support throughout the project.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148632.

References

Abaya, L.M., Wiegner, T.N., Beets, J.P., Colbert, S.L., Carlson, K.M., Kramer, K.L., 2018. Spatial distribution of sewage pollution on a Hawaiian coral reef. Mar. Pollut. Bull. 130, 335–347. https://doi.org/10.1016/j.marpolbul.2018.03.028.

Abstrackr, 2020. Brown University http://abstrackr.cebm.brown.edu.

Acevedo, R., 1991. Preliminary observations on effects of pesticides carbaryl, naphthol, and chlorpyrifos on planulae of the hermatypic coral *Pocillopora damicornis*. Pac. Sci. 45, 287–289.

Agency for Toxic Substances and Disease Registry (ATSDR), 1995. Toxicological Profile for Polycyclic Aromatic Hydrocarbons. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR), 1999. Toxicological Profile for Mercury. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR), 2004. Toxicological Profile for Cobalt. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR), 2005a. Toxicological Profile for Naphthalene, 1-Methylnaphthalene, and 2-Methylnaphthalene. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR), 2005b. Toxicological Profile for Tin. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR), 2012. Toxicological Profile for Cadmium. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Agency for Toxic Substances and Disease Registry (ATSDR), 2020. Toxicological Profile for Lead. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA.

Alutoin, S., Boberg, J., Nyström, M., Tedengren, M., 2001. Effects of the multiple stressors copper and reduced salinity on the metabolism of the hermatypic coral *Porites lutea*. Mar. Environ. Res. 52, 289–299. https://doi.org/10.1016/S0141-1136(01)00105-2.

Amid, C., Olstedt, M., Gunnarsson, J.S., Le Lan, H., Tran Thi Minh, H., den Brink, P.J., Hellstrom, M., Tedengren, M., 2018. Additive effects of the herbicide glyphosate and elevated temperature on the branched coral *Acropora formosa* in Nha Trang, Vietnam. Environ. Sci. Pollut. Res. 25, 13360–13372. https://doi.org/10.1007/s11356-016-8320-7.

Atkinson, S., Atkinson, M.J., Tarrant, A.M., 2003. Estrogens from sewage in coastal marine environments. Environ. Health Perspect. 111, 531–535. https://doi.org/10.1289/ehp.5233.

Banc-Prandi, G., Fine, M., 2019. Copper enrichment reduces thermal tolerance of the highly resistant Red Sea coral *Stylophora pistillata*. Coral Reefs 38, 285–296. https://doi.org/10.1007/s00338-019-01774-z.

Bastidas, C., Garcia, E.M., 2004. Sublethal effects of mercury and its distribution in the coral *Porites astreoides*. Mar. Ecol. Prog. Ser. 267, 133–143. https://doi.org/10.3354/meps267133.

Bejarano, A.C., 2018. Critical review and analysis of aquatic toxicity data on oil spill dispersants. Environ. Toxicol. Chem. 37, 2989–3001. https://doi.org/10.1002/etc.4254.

Bejarano, A.C., Farr, J.K., Jenne, P., Chu, V., Hielscher, A., 2016. The chemical aquatic fate and effects database (CAFE), a tool that supports assessments of chemical spills in aquatic environments. Environ. Toxicol. Chem. 35, 1576–1586. https://doi.org/10.1002/etc.3289.

Beusen, J.-M., Neven, B., 1987. Toxicity of vanadium to different freshwater organisms. Bull. Environ. Contam. Toxicol. 39, 194–201.

Bielmyer, G.K., Grosell, M., Bhagooli, R., Baker, A.C., Langdon, C., Gillette, P., Capo, T.R., 2010. Differential effects of copper on three species of scleractinian corals and their algal symbionts (*Symbiodinium* spp.). Aquat. Toxicol. 97, 125–133. https://doi.org/10.1016/j.aquatox.2009.12.021.

Biscéré, T., Rodolfo-Metalpa, R., Lorrain, A., Chauvaud, L., Thébault, J., Clavier, J., Houlbrèque, F., 2015. Responses of two scleractinian corals to cobalt pollution and ocean acidification. PLoS One 10, 1–18. https://doi.org/10.1371/journal.pone.0122898.

Biscéré, T., Lorrain, A., Rodolfo-Metalpa, R., Gilbert, A., Wright, A., Devissi, C., Peignon, C., Farman, R., Duvieilbourg, E., Payri, C., Houlbrèque, F., 2017. Nickel and ocean warming affect scleractinian coral growth. Mar. Pollut. Bull. 120, 250–258. https://doi.org/10.1016/j.marpolbul.2017.05.025.

Biscéré, T., Ferrier-Pagès, C., Grover, R., Gilbert, A., Rottier, C., Wright, A., Payri, C., Houlbrèque, F., 2018. Enhancement of coral calcification via the interplay of nickel and urease. Aquat. Toxicol. 200, 247–256. https://doi.org/10.1016/j.aquatox.2018.05.013.

Bishop, R.C., Chapman, D.J., Kanninen, B.J., Krosnick, J.A., Leeworthy, B., Meade, N.F., 2011. Total economic value for protecting and restoring Hawaiian coral reef ecosystems. Final Report, NOAA Technical Memorandum CRCP 16. Silver Spring, MD.

Boone, C., Gervais, J., Luukinen, B., Buhl, K., Stone, D., 2012. Copper Sulfate Technical Fact Sheet. https://doi.org/10.1007/978-3-540-71095-0_2413.

Boscolo, C.N.P., Pereira, T.S.B., Batalhão, I.G., Dourado, P.L.R., Schlenk, D., de Almeida, E.A., 2018. Diuron metabolites act as endocrine disruptors and alter aggressive behavior in Nile tilapia (*Oreochromis niloticus*). Chemosphere 191, 832–838. https://doi.org/10.1016/j.chemosphere.2017.10.009.

Brion, F., Tyler, C.R., Palazzi, X., Laillet, B., Porcher, J.M., Garric, J., Flammarion, P., 2004. Impacts of 17β-estradiol, including environmentally relevant concentrations, on reproduction after exposure during embryo-larval-, juvenile- and adult-life stages in zebrafish (*Danio rerio*). Aquat. Toxicol. 68, 193–217. https://doi.org/10.1016/j.aquatox.2004.01.022.

Brix, K.V., Schlekat, C.E., Garman, E.R., 2017. The mechanisms of nickel toxicity in aquatic environments: an adverse outcome pathway analysis. Environ. Toxicol. Chem. 36, 1128–1137. https://doi.org/10.1002/etc.3706.

Bryant, D., Burke, L., McManus, J., Spalding, M., 1998. Reefs at Risk: A Map-based Indicator of Threats to the Worlds Coral Reefs. World Resources Institute, Washington, D.C.

Burke, L., Reytar, K., Spalding, M., Perry, A.L., 2011. Reefs at Risk: Revisited. World Resources Institute, Washington, D.C.

Bürkner, P.-C., 2017. *brms*: an R package for Bayesian multilevel models using Stan. J. Stat. Softw. 80 (1), 1–28.

Bürkner, P.-C., 2018. Advanced Bayesian multilevel modeling with the R package *brms*. The R Journal 10 (1), 395–411.

Cabral, H., Fonseca, V., Sousa, T., Leal, M.C., 2019. Synergistic effects of climate change and marine pollution: an overlooked interaction in coastal and estuarine areas. Int. J. Envir. Research and Public Health 16, 2737. https://doi.org/10.3390/ijerph16152737.

Cantin, N.E., Negri, A.P., Willis, B.L., 2007. Photoinhibition from chronic herbicide exposure reduces reproductive output of reef-building corals. Mar. Ecol. Prog. Ser. 344, 81–93. https://doi.org/10.3354/meps07059.

Caroselli, E., Frapiccini, E., Franzellitti, S., Palazzo, Q., Prada, F., Betti, M., Goffredo, S., Marini, M., 2020. Accumulation of PAHs in the tissues and algal symbionts of a common Mediterranean coral: skeletal storage relates to population age structure. Sci. Total Environ. 743, 140781. https://doi.org/10.1016/j.scitotenv.2020.140781.

Ceci, A., Pinzari, F., Russo, F., Persiani, A.M., Gadd, G.M., 2019. Roles of saprotrophic fungi in biodegradation or transformation of organic and inorganic pollutants in co-contaminated sites. Appl. Microbiol. Biotechnol. 103, 53–68. https://doi.org/10.1007/s00253-018-9451-1.

Chen, T.H., Cheng, Y.M., Cheng, J.O., Ko, F.C., 2012. Assessing the effects of polychlorinated biphenyls (Aroclor 1254) on a scleractinian coral (*Stylophora pistillata*) at organism, physiological, and molecular levels. Ecotoxicol. Environ. Saf. 75, 207–212. https://doi.org/10.1016/j.ecoenv.2011.09.001.

Cooper, T.F., Gilmour, J.P., Fabricius, K.E., 2009. Bioindicators of changes in water quality on coral reefs: review and recommendations for monitoring programmes. Coral Reefs 28, 589–606. https://doi.org/10.1007/s00338-009-0512-x.

de Barros Marangoni, L.F., Marques, J.A., Duarte, G.A.S., Pereira, C.M., Calderon, E.N., Castro, C.B.E., Bianchini, A., 2017. Copper effects on biomarkers associated with photosynthesis, oxidative status and calcification in the Brazilian coral *Mussismilia harttii* (Scleractinia, Mussidae). Mar. Environ. Res. 130, 248–257. https://doi.org/10.1016/j.marenvres.2017.08.002.

Donovan, M.K., Adam, T.C., Shantz, A.A., Speare, K.E., Munsterman, K.S., Rice, M.M., Schmitt, R.J., Holbrook, S.J., Burkepile, D.E., 2020. Nitrogen pollution interacts with heat stress to increase coral bleaching across the seascape. Proc. Natl. Acad. Sci. U. S. A. 117, 5351–5357. https://doi.org/10.1073/pnas.1915395117.

Eisler, R., 1993. Zinc Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review. U.S. Fish and Wildlife Service Contaminant Hazard Reviews, Report 26.

Eisler, R., Belisle, A.A., 1996. Planar PCB hazards to fish, wildlife, and invertebrates: a synoptic review. Contaminant Hazards Reviews Report No. 31. U.S. National Biological Service.

Enríquez, S., Borowitzka, M.A., 2010. Chlorophyll a fluorescence in aquatic sciences: methods and applications, in: Suggett, D.J. (Ed.), Chlorophyll a Fluorescence in Aquatic Sciences: Methods and Applications. Springer Science+Business Media B.V, pp. 187–208. doi:https://doi.org/10.1007/978-90-481-9268-7.

Enríquez, S., Méndez, E.R., Hoegh-Guldberg, O., Iglesias-Prieto, R., 2017. Key functional role of the optical properties of coral skeletons in coral ecology and evolution. Proc. R. Soc. B Biol. Sci. 284. https://doi.org/10.1098/rspb.2016.1667.

Exley, C., Chappell, J.S., Birchall, J.D., 1991. A mechanism for acute aluminium toxicity in fish. J. Theor. Biol. 151, 417–428. https://doi.org/10.1016/S0022-5193(05)80389-3.

Fabricius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Mar. Pollut. Bull. 50, 125–146. https://doi.org/10.1016/j.marpolbul.2004.11.028.

Farina, O., Ramos, R., Bastidas, C., García, E., 2008. Biochemical responses of cnidarian larvae to mercury and benzo(a)pyrene exposure. Bull. Environ. Contam. Toxicol. 81, 553–557. https://doi.org/10.1007/s00128-008-9534-2.

Fichet, D., Miramand, P., 1998. Vanadium toxicity to three marine invertebrates larvae: *Crassostrea gigas*, *Paracentrotus lividus* and *Artemia salina*. Chemosphere 37, 1363–1368. https://doi.org/10.1016/S0045-6535(98)00118-0.

Fonseca, J. da S., de Barros Marangoni, L.F., Marques, J.A., Bianchini, A., 2017. Effects of increasing temperature alone and combined with copper exposure on biochemical and physiological parameters in the zooxanthellate scleractinian coral *Mussismilia harttii*. Aquat. Toxicol. 190, 121–132. https://doi.org/10.1016/j.aquatox.2017.07.002.

Fonseca, J. da S., de Barros Marangoni, L.F., Marques, J.A., Bianchini, A., 2019. Carbonic anhydrase activity as a potential biomarker for acute exposure to copper in corals. Chemosphere 227, 598–605. https://doi.org/10.1016/j.chemosphere.2019.04.089.

Fujita, M., Ide, Y., Sato, D., Kench, P.S., Kuwahara, Y., Yokoki, H., Kayanne, H., 2014. Heavy metal contamination of coastal lagoon sediments: Fongafale Islet, Funafuti Atoll, Tuvalu. Chemosphere 95, 628–634. https://doi.org/10.1016/j.chemosphere.2013.10.023.

Gissi, F., Stauber, J., Reichelt-Brushett, A., Harrison, P.L., Jolley, D.F., 2017. Inhibition in fertilisation of coral gametes following exposure to nickel and copper. Ecotoxicol. Environ. Saf. 145, 32–41. https://doi.org/10.1016/j.ecoenv.2017.07.009.

Glynn, P.W., Howard, L.S., Corcoran, E., Freay, A.D., 1984. The occurrence and toxicity of herbicides in reef building corals. Mar. Pollut. Bull. 15, 370–374.

Goutte, A., Barbraud, C., Meillère, A., Carravieri, A., Bustamente, P., Labadie, P., Budzinski, H., Delord, K., Cherel, Y., Weimerskirch, H., Chastel, O., 2014. Demographic consequences of heavy metals and persistent organic pollutants in a vulnerable long-lived bird, the wandering albatross. Proc. R. Soc. B 281, 20133313. https://doi.org/10.1098/rspb.2013.3313.

Gregg, K., 2013. Literature Review and Synthesis of Land-Based Sources of Pollution Affecting Essential Fish Habitats in Southeast Florida. West Palm Beach, Florida, USA.

Grottoli, A.G., Toonen, R.J., van Woesik, R., Vega Thurber, R., Warner, M.E., McLachlan, R.H., Price, J.T., Bahr, K.D., Baums, I.B., Castillo, K., Coffroth, M.A., Cunning, R., Dobson, K., Donahue, M., Hench, J.L., Iglesias-Prieto, R., Kemp, D.W., Kenkel, C.D., Kline, D.I., Kuffner, I.B., Matthews, J.L., Mayfield, A., Padilla-Gamino, J., Palumbi, S., Voolstra, C.R., Weis, V.M., Wu, H.C., 2020. Increasing comparability among coral bleaching experiments. Ecol. Appl., e2262 https://doi.org/10.1002/eap.2262.

Harland, A.D., Brown, B.E., 1989. Metal tolerance in the scleractinian coral *Porites lutea*. Mar. Pollut. Bull. 20, 353–357. https://doi.org/10.1016/0025-326X(89)90159-8.

Hawaii State Departments of Health and Agriculture, 2014. 2013-14 State Wide Pesticide Sampling Pilot Project Water Quality Findings: Draft. Honolulu, Hawai'i, USA.

Hayes, T., Haston, K., Tsui, M., Hoang, A., Haeffele, C., Vonk, A., 2003. Atrazine-induced hermaphroditism at 0.1 ppb in American leopard frogs (*Rana pipiens*): laboratory and field evidence. Environ. Health Perspect. 111, 568–575. https://doi.org/10.1289/ehp.5932.

Hayes, T.B., Hansen, M., 2017. From silent spring to silent night: agrochemicals and the anthropocene. Elementa 5. https://doi.org/10.1525/elementa.246.

Hédouin, L., Gates, R.D., 2013. Assessing fertilization success of the coral *Montipora capitata* under copper exposure: does the night of spawning matter? Mar. Pollut. Bull. 66, 221–224. https://doi.org/10.1016/j.marpolbul.2012.11.020.

Hédouin, L., Reichelt-Brushett, A.J., Gates, R.D., 2009. Assessment of metals and a metalloid in sediments from Hawaiian coral reef ecosystems. Mar. Pollut. Bull. 58, 1759–1765.

Hédouin, L.S., Wolf, R.E., Phillips, J., Gates, R.D., 2016. Improving the ecological relevance of toxicity tests on scleractinian corals: influence of season, life stage, and seawater temperature. Environ. Pollut. 213, 240–253. https://doi.org/10.1016/j.envpol.2016.01.086.

Hornstrom, E., Ekstroem, C., Duraini, M., 1984. Effects of pH and Different Levels of Aluminium on Lake Plankton in the Swedish West Coast Area. Report - Institute of Freshwater Research, Drottningholm (Sweden), p. 61.

Huang, W., Chen, M., Song, B., Deng, J., Shen, M., Chen, Q., Zeng, G., Liang, J., 2021. Microplastics in the coral reefs and their potential impacts on corals: a mini-review. Sci. Total Environ. 762, 143112. https://doi.org/10.1016/j.scitotenv.2020.143112.

Hughes, T.P., Graham, N.A.J., Jackson, J.B.C., Mumby, P.J., Steneck, R.S., 2010. Rising to the challenge of sustaining coral reef resilience. Trends Ecol. Evol. 25, 633–642. https://doi.org/10.1016/j.tree.2010.07.011.

Johnston, E.L., Roberts, D.A., 2009. Contaminants reduce the richness and evenness of marine communities: a review and meta-analysis. Environ. Pollut. 157, 1745–1752. https://doi.org/10.1016/j.envpol.2009.02.017.

Jones, R., 2005. The ecotoxicological effects of photosystem II herbicides on corals. Mar. Pollut. Bull. 51, 495–506. https://doi.org/10.1016/j.marpolbul.2005.06.027.

Jones, R.J., 1997. Zooxanthellae loss as a bioassay for assessing stress in corals. Mar. Ecol. Prog. Ser. 149, 163–171. https://doi.org/10.3354/meps149163.

Jones, R.J., 2004. Testing the 'photoinhibition' model of coral bleaching using chemical inhibitors. Mar. Ecol. Prog. Ser. 284, 133–145. https://doi.org/10.3354/meps284133.

Jones, R.J., Kerswell, A.P., 2003. Phytotoxicity of photosystem II (PSII) herbicides to coral. Mar. Ecol. Prog. Ser. 261, 149–159. https://doi.org/10.3354/meps261149.

Jones, R.J., Muller, J., Haynes, D., Schreiber, U., 2003. Effects of herbicides diuron and atrazine on corals of the Great Barrier Reef, Australia. Mar. Ecol. Prog. Ser. 251, 153–167. https://doi.org/10.3354/meps251153.

Kroon, F.J., Schaffelke, B., Bartley, R., 2014. Informing policy to protect coastal coral reefs: insight from a global review of reducing agricultural pollution to coastal ecosystems. Mar. Pollut. Bull. 85, 33–41. https://doi.org/10.1016/j.marpolbul.2014.06.003.

Kwok, C.K., Ang, P.O.J., 2013. Inhibition of larval swimming activity of the coral (*Platygyra acuta*) by interactive thermal and chemical stresses. Mar. Pollut. Bull. 74, 264–273. https://doi.org/10.1016/j.marpolbul.2013.06.048.

Kwok, C.K., Lam, K.Y., Leung, S.M., Chui, A.P.Y., Ang, P.O., 2016. Copper and thermal perturbations on the early life processes of the hard coral *Platygyra acuta*. Coral Reefs 35, 827–838. https://doi.org/10.1007/s00338-016-1432-1.

Leigh-Smith, J., Reichelt-Brushett, A., Rose, A.L., 2018. The characterization of iron (III) in seawater and related toxicity to early life stages of scleractinian corals. Environ. Toxicol. Chem. 37, 1104–1114. https://doi.org/10.1002/etc.4043.

Luo, Y., Liang, J., Zeng, G., Li, X., Chen, M., Jiang, L., Xing, W., Tang, N., Fang, Y., Chen, X., 2019. Evaluation of tetracycline phytotoxicity by seed germination stage and radicle elongation stage tests: a comparison of two typical methods for analysis. Environ. Pollut. 251, 257–263. https://doi.org/10.1016/j.envpol.2019.05.005.

Markey, K.L., Baird, A.H., Humphrey, C., Negri, A.P., 2007. Insecticides and a fungicide affect multiple coral life stages. Mar. Ecol. Prog. Ser. 330, 127–137. https://doi.org/10.3354/meps330127.

Martinez, M.D.C.G., Romero, P.R., Banaszak, A.T., 2007. Photoinduced toxicity of the polycyclic aromatic hydrocarbon, fluoranthene, on the coral, *Porites divaricata*. J. Environ. Sci. Heal. Part A-Toxic/Hazardous Subst. Environ. Eng. 42, 1495–1502. https://doi.org/10.1080/10934520701480946.

Mayer-Pinto, M., Ledet, J., Crowe, T.P., Johnston, E.L., 2020. Sublethal effects of contaminants on marine habitat-forming species: a review and meta-analysis. Biol. Rev. 95, 1554–1573. https://doi.org/10.1111/brv.12630.

Mendeley Reference Manager, 2020. Elsevier. https://mendeley.com.

Minnesota Department of Health, 2019. Anthracene and Groundwater. Minnesota Department of Health, Health Risk Assessment Unit www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/anthraceneinfo.pdf.

Mitchelmore, C.L., Verde, E.A., Weis, V.M., 2007. Uptake and partitioning of copper and cadmium in the coral *Pocillopora damicornis*. Aquat. Toxicol. 85, 48–56. https://doi.org/10.1016/j.aquatox.2007.07.015.

Morgan, R.L., Whaley, P., Thayer, K.A., Schünemann, H.J., 2018. Identifying the PECO: a framework for formulating good questions to explore the association of environmental and other exposures with health outcomes. Environ. Int. 121, 1027–1031. https://doi.org/10.1016/j.envint.2018.07.015.

Muhaemin, M., 2007. The copper and reduced salinity effects on metabolism of hermatypic coral *Fungia* sp. J. Coast. Dev 11, 14–19.

Muscatine, L., 1990. The role of symbiotic algae in carbon and energy flux in coral reefs. Coral Reefs 25, 75–87.

NAS (National Academies of Sciences, Engineering, and Medicine), 2020. The Use of Dispersants in Marine Oil Spill Response. The National Academies Press, Washington, D.C., USA https://doi.org/10.17226/25161.

Nash, R.G., Hill, B.D., 1990. Modeling pesticide volatilization and soil decline under controlled conditions, in: Kurtz, D.A. (Ed.), Long Range Transport of Pesticides. Lewis Publishers, Inc., Chelsea, Michigan, USA.

Negri, A., Vollhardt, C., Humphrey, C., Heyward, A., Jones, R., Eaglesham, G., Fabricius, K., 2005. Effects of the herbicide diuron on the early life history stages of coral. Mar. Pollut. Bull. 51, 370–383. https://doi.org/10.1016/j.marpolbul.2004.10.053.

Negri, A.P., Heyward, A.J., 2001. Inhibition of coral fertilisation and larval metamorphosis by tributyltin and copper. Mar. Environ. Res. 51, 17–27. https://doi.org/10.1016/S0141-1136(00)00029-5.

Negri, A.P., Hoogenboom, M.O., 2011. Water contamination reduces the tolerance of coral larvae to thermal stress. PLoS One 6. https://doi.org/10.1371/journal.pone.0019703.

Negri, A.P., Flores, F., Roethig, T., Uthicke, S., 2011a. Herbicides increase the vulnerability of corals to rising sea surface temperature. Limnol. Oceanogr. 56, 471–485. https://doi.org/10.4319/lo.2011.56.2.0471.

Negri, A.P., Harford, A.J., Parry, D.L., van Dam, R.A., 2011b. Effects of alumina refinery wastewater and signature metal constituents at the upper thermal tolerance of: 2. The early life stages of the coral *Acropora tenuis*. Mar. Pollut. Bull. 62, 474–482. https://doi.org/10.1016/j.marpolbul.2011.01.011.

Nyström, M., Nordemar, I., Tedengren, M., 2001. Simultaneous and sequential stress from increased temperature and copper on the metabolism of the hermatypic coral *Porites cylindrica*. Mar. Biol. 138, 1225–1231. https://doi.org/10.1007/s002270100549.

Osinga, R., Iglesias-Prieto, R., Enríquez, S., 2012. Measuring photosynthesis in symbiotic invertebrates: a review of methodologies, rates and processes, in: Najafpour, M.M. (Ed.), Applied Photosynthesis. InTech, Rijeka, Croatia, pp. 229–256.

Overmans, S., Nordborg, M., Díaz-Rúa, R., Brinkman, D.L., Negri, A.P., Agustí, S., 2018. Phototoxic effects of PAH and UVA exposure on molecular responses and developmental success in coral larvae. Aquat. Toxicol. 198, 165–174. https://doi.org/10.1016/j.aquatox.2018.03.008.

Parkinson, J.E., Baker, A.C., Baums, I.B., Davies, S.W., Grottoli, A.G., Kitchen, S.A., Matz, M.V., Miller, M.W., Shantz, A.A., Kenkel, C.D., 2019. Molecular tools for coral reef restoration: beyond biomarker discovery. Conserv. Lett., 1–12 https://doi.org/10.1111/conl.12687.

Pastorok, R.A., Bilyard, G.R., 1985. Effects of sewage pollution on coral-reef communities. Mar. Ecol. Prog. Ser. 21, 175–189.

Porter, S.N., Humphries, M.S., Buah-Kwofie, A., Schleyer, M.H., 2018. Accumulation of organochlorine pesticides in reef organisms from marginal coral reefs in South Africa and links with coastal groundwater. Mar. Pollut. Bull. 137, 295–305. https://doi.org/10.1016/j.marpolbul.2018.10.028.

Puisay, A., Pilon, R., Hédouin, L., 2015. High resistance of *Acropora* coral gametes facing copper exposure. Chemosphere 120, 563–567. https://doi.org/10.1016/j.chemosphere.2014.09.041.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria https://www.R-project.org.

Råberg, S., Nyström, M., Erös, M., Plantman, P., 2003. Impact of the herbicides 2,4-D and diuron on the metabolism of the coral *Porites cylindrica*. Mar. Environ. Res. 56, 503–514. https://doi.org/10.1016/S0141-1136(03)00039-4.

Ramos, R., Garcia, E., 2007. Induction of mixed-function oxygenase system and antioxidant enzymes in the coral *Montastraea faveolata* on acute exposure to benzo(a) pyrene. Comp. Biochem. Physiol. C-Toxicology Pharmacol. 144, 348–355. https://doi.org/10.1016/j.cbpc.2006.11.006.

Reaka-Kudla, M.L., 1997. The global biodiversity of coral reefs: a comparison with rain forests. In: Reaka-Kudla, M.L., Wilson, D.E., Wilson, E.O. (Eds.), Biodiversity II: Understanding and Protecting our Biological Resources. Joseph Henry Press, Washington, D.C., pp. 83–108.

Reichelt-Brushett, A., Hudspith, M., 2016. The effects of metals of emerging concern on the fertilization success of gametes of the tropical scleractinian coral *Platygyra daedalea*. Chemosphere 150, 398–406. https://doi.org/10.1016/j.chemosphere.2016.02.048.

Reichelt-Brushett, A.J., Harrison, P.L., 1999. The effect of copper, zinc and cadmium on fertilization success of gametes from scleractinian reef corals. Mar. Pollut. Bull. 38, 182–187. https://doi.org/10.1016/S0025-326X(98)00183-0.

Reichelt-Brushett, A.J., Harrison, P.L., 2000. The effect of copper on the settlement success of larvae from the scleractinian coral *Acropora tenuis*. Mar. Pollut. Bull. 41, 385–391. https://doi.org/10.1016/S0025-326X(00)00131-4.

Reichelt-Brushett, A.J., Harrison, P.L., 2004. Development of a sublethal test to determine the effects of copper, and lead on scleractinian coral larvae. Arch. Environ. Contam. Toxicol. 47, 40–55. https://doi.org/10.1007/s00244-004-3080-7.

Reichelt-Brushett, A.J., Harrison, P.L., 2005. The effect of selected trace metals on the fertilization success of several scleractinian coral species. Coral Reefs 24, 524–534. https://doi.org/10.1007/s00338-005-0013-5.

Turner, N.R., Renegar, D.A., 2017. Petroleum hydrocarbon toxicity to corals: a review. Mar. Pollut. Bull. 119, 1–16. doi:https://doi.org/10.1016/j.marpolbul.2017.04.050.

Renegar, D.A., Turner, N.R., Riegl, B.M., Dodge, R.E., Knap, A.H., Schuler, P.A., 2017. Acute and subacute toxicity of the polycyclic aromatic hydrocarbon 1-methylnaphthalene to the shallow-water coral *Porites divaricata*: application of a novel exposure protocol. Environ. Toxicol. Chem. 36, 212–219. https://doi.org/10.1002/etc.3530.

Richmond, R., Leota, S., Romano, S., MacKenna, S., 1998. The use of coral planula larvae as ecological indicators of pollution effects on coral reefs. Am. Zool. 38 (5).

Richmond, R.H., Wolanski, E., 2011. Coral research: past efforts and future horizons. In: Dubinsky, Z., Stambler, N. (Eds.), Coral Reefs: An Ecosystem in Transition. Springer, Dordrecht, Germany https://doi.org/10.1007/978-94-007-0114-4.

Richmond, R.H., Tisthammer, K.H., Spies, N.P., 2018. The effects of anthropogenic stressors on reproduction and recruitment of corals and reef organisms. Front. Mar. Sci. 5, 1. https://doi.org/10.3389/fmars.2018.00226.

Roberts, J.R., Reigard, J.R., 2013. Recognition and management of pesticide poisonings. United States Environmental Protection Agency Office of Pesticide Programs. EPA 735K13001.

Roche, H., Salvat, B., Ramade, F., 2011. Assessment of the pesticides pollution of coral reefs communities from French Polynesia. Rev. Ecol. (Terre Vie) 66, 3–10.

Rodgers, K.S., Jokiel, P.L., Brown, E.K., Hau, S., Sparks, R., 2015. Over a decade of change in spatial and temporal dynamics of Hawaiian coral reef communities. Pac. Sci. 69, 1–13. https://doi.org/10.2984/69.1.1.

Rodgers, K.S., Stefanek, M.P., Tsang, A.O., Han, J.J., Graham, A.T., Stender, Y.O., 2021. Impact to coral reef populations at Hā'ena and Pila'a, Kaua'i following a record 2018 freshwater flood event. Diversity 13, 66. https://doi.org/10.3390/d13020066.

Rohatgi, A., 2020. WebPlotDigitizer. https://automeris.io/WebPlotDigitizer.

Ross, C., Olsen, K., Henry, M., Pierce, R., 2015. Mosquito control pesticides and sea surface temperatures have differential effects on the survival and oxidative stress response of coral larvae. Ecotoxicology 24, 540–552. https://doi.org/10.1007/s10646-014-1402-8.

Sabdono, A., Joetono Soedarsono, J., Hartiko, H., Artama, W.T., 1998. Preliminary study on the effects of 2,4-D herbicide formulations on reef building corals. J. Coast. Dev. 1, 201–206.

Shaner, D., 2006. An overview of glyphosate mode of action: why is it such a great herbicide? North Cent. Weed Sci. Soc. US Proc. 61, 94.

Shaw, C.M., Lam, P.K.S., Mueller, J.F., 2008. Photosystem II herbicide pollution in Hong Kong and its potential photosynthetic effects on corals. Mar. Pollut. Bull. 57, 473–478. https://doi.org/10.1016/j.marpolbul.2008.04.002.

Shaw, M., Furnas, M.J., Fabricius, K., Haynes, D., Carter, S., Eaglesham, G., Mueller, J.F., 2010. Monitoring pesticides in the Great Barrier Reef. Mar. Pollut. Bull. 60, 113–122. https://doi.org/10.1016/j.marpolbul.2009.08.026.

Sheikh, M.A., Higuchi, T., Fujimura, H., Imo, T.S., Miyagi, T., Oomori, T., 2009. Contamination and impacts of new antifouling biocide Irgarol-1051 on subtropical coral reef waters. Int. J. Environ. Sci. Technol. 6, 353–358. https://doi.org/10.1007/BF03326073.

Silbiger, N.J., Donahue, M.J., Lubarsky, K., 2020. Submarine groundwater discharge alters coral reef ecosystem metabolism. Proc. R. Soc. B 287, 2020743. https://doi.org/10.1098/rspb.2020.2743.

Song, Y., 2014. Insight into the mode of action of 2,4-dichlorophenoxyacetic acid (2,4-D) as an herbicide. J. Integr. Plant Biol. 56, 106–113. https://doi.org/10.1111/jipb.12131.

Spalding, M.D., Ravilious, C., Green, E.P., 2001. World Atlas of Coral Reefs. books.google.com.

Spengler, S.R., Heskett, M.D., Gray, J.I., 2019. Pesticide levels in streams and sediments on the islands of Oahu and Kauai, Hawaii. Int. J. Environ. Impacts Manag. Mitig. Recover. 2, 283–299. https://doi.org/10.2495/ei-v2-n3-283-299.

Stan Development Team, 2020. *RStan*: the R interface to Stan. R package version 2.21.2. http://mc-stan.org/.

Summer, K., Reichelt-Brushett, A., Howe, P., 2019. Toxicity of manganese to various life stages of selected marine cnidarian species. Ecotoxicol. Environ. Saf. 167, 83–94. https://doi.org/10.1016/j.ecoenv.2018.09.116.

Tang, J., Ni, X., Zhou, Z., Wang, L., Lin, S., 2018. Acute microplastic exposure raises stress response and suppresses detoxification and immune capacities in the scleractinian coral *Pocillopora damicornis*. Environ. Pollut. 243, 66–74. https://doi.org/10.1016/j.envpol.2018.08.045.

Tarrant, A.M., Blomquist, C.H., Lima, P.H., Atkinson, M.J., Atkinson, S., 2003. Metabolism of estrogens and androgens by scleractinian corals. Comp. Biochem. Physiol. Part B 236, 473–485. https://doi.org/10.1016/S1096-4959(03)00253-7.

Tarrant, A.M., Atkinson, M.J., Atkinson, S., 2004. Effects of steroidal estrogens on coral growth and reproduction. Mar. Ecol. Prog. Ser. 269, 121–129. https://doi.org/10.3354/meps269121.

Thomas, N., Sweeney, K., Somayaji, V., 2014. Meta-analysis of clinical dose–response in a large drug development portfolio. Stat. Biopharm. Res. 6, 302–317. https://doi.org/10.1080/19466315.2014.924876.

Tisthammer, K.H., Forsman, Z.H., Toonen, R.J., Richmond, R.H., 2020. Genetic structure is stronger across human-impacted habitats than among islands in the coral *Porites lobata*. PeerJ 2020, 1–24. https://doi.org/10.7717/peerj.8550.

Tisthammer, K.H., Timmins-Schiffman, E., Seneca, F.O., Nunn, B.L., Richmond, R.H., 2021. Physiological and molecular responses of lobe coral indicate nearshore adaptations to anthropogenic stressors. Sci. Rep. 11, 1–11. https://doi.org/10.1038/s41598-021-82569-7.

Tuttle, L.J., Donahue, M.J., 2020. Thresholds for Sediment Stress on Corals: A Systematic Review and Meta-analysis. Honolulu, Hawai'i, USA.

Tuttle, L.J., Johnson, C., Kolinski, S., Minton, D., Donahue, M.J., 2020. How does sediment exposure affect corals? A systematic review protocol. Environ. Evid. 9, 1–7. https://doi.org/10.1186/s13750-020-00200-0.

United States Environmental Protection Agency (US EPA), 1984. Health and Environmental Effects Profile for Ametryn. US EPA Environmental Criteria and Assessment Office, Office of Health and Environmental Assessment (Report Number EPA-600-X-84-232).

United States Environmental Protection Agency (US EPA), 1988. Iron. Water Quality Standards Criteria Summaries: A Compilation of State/federal Criteria. Report Number EPA 440–5–88-022.

United States Environmental Protection Agency (US EPA), 1993. Reference Dose (RfD): Description and Use in Human Health Risk Assessments. Background Document 1A.

United States Environmental Protection Agency (US EPA), 1994. Pesticide Registration, R.E.D. Factors: Tebuthiuron. US EPA Prevention, Pesticides and Toxic Substances. Report Number EPA-739-F-94-006.

United States Environmental Protection Agency (US EPA), 2003. Health Effects Support Document for Manganese. Report Number EPA-822-R-03-003.

United States Environmental Protection Agency (US EPA), 2008. Risks of Hexazinone Use to Federally Threatened California Red-legged Frog (*Rana aurora draytonii*). US EPA Environmental Fate and Effects Division.

United States Environmental Protection Agency (US EPA), 2009. Provisional Peer-reviewed Toxicity Values for Anthracene. Report Number EPA-690-R-09-002F.

United States Environmental Protection Agency (US EPA), 2018. Final Aquatic Life Ambient Water Quality Criteria for Aluminum 2018. Report Number EPA-822-R-18-001.

United States Environmental Protection Agency (US EPA), 2020. Simazine: Interim Registration Review Decision. Case Number 0070. Docket Number EPA-HQ-OPP-2013-0251.

United States Environmental Protection Agency (US EPA), 2021a. Basic information about mercury. https://www.epa.gov/mercury/basic-information-about-mercury.

United States Environmental Protection Agency (US EPA), 2021b. Ingredients used in pesticide products: 2,4-D. https://www.epa.gov/ingredients-used-pesticide-products/24-d.

United States Environmental Protection Agency (US EPA), 2021c. Ingredients used in pesticide products: atrazine. https://www.epa.gov/ingredients-used-pesticide-products/atrazine.

United States Environmental Protection Agency (US EPA), 2021d. Ingredients used in pesticide products: glyphosate. https://www.epa.gov/ingredients-used-pesticide-products/glyphosate.

United States Environmental Protection Agency (US EPA), 2021e. Naled for mosquito control. https://www.epa.gov/mosquitocontrol/naled-mosquito-control.

United States Environmental Protection Agency (US EPA), 2021f. Polychlorinated biphenyls. https://www.epa.gov/pcbs/learn-about-polychlorinated-biphenyls-pcbs.

van Dam, J.W., Negri, A.P., Uthicke, S., Mueller, J.F., 2011. Chemical pollution on coral reefs: exposure and ecological effects, in: Sánchez-Bayo, F., van den Brink, P.J., Mann, R.M. (Eds.), Ecological Impacts of Toxic Chemicals. Bentham Science Publishers Ltd., Sharjah, United Arab Emirates, pp. 187–211. doi:https://doi.org/10.2174/978160805121210187.

Vega-Thurber, R., Willner-Hall, D., Rodriguez-Mueller, B., Desnues, C., Edwards, R.A., Angly, F., Dinsdale, E., Kelly, L., Rohwer, F., 2009. Metagenomic analysis of stressed coral holobionts. Environ. Microbiol. 11, 2148–2163. https://doi.org/10.1111/j.1462-2920.2009.01935.x.

Victor, S., Richmond, R.H., 2005. Effect of copper on fertilization success in the reef coral *Acropora surculosa*. Mar. Pollut. Bull. 50, 1448–1451. https://doi.org/10.1016/j.marpolbul.2005.09.004.

Vijayavel, K., Downs, C.A., Ostrander, G.K., Richmond, R.H., 2012. Oxidative DNA damage induced by iron chloride in the larvae of the lace coral *Pocillopora damicornis*. Comparative Biochemistry and Physiology, Part C 155, 275–280. https://doi.org/10.1016/j.cbpc.2011.09.007.

Watanabe, T., Utsunomiya, Y., Yuyama, I., 2007. Long-term laboratory culture of symbiotic coral juveniles and their use in eco-toxicological study. J. Exp. Mar. Biol. Ecol. 352, 177–186. https://doi.org/10.1016/j.jembe.2007.07.022.

Wecker, P., Lecellier, G., Guibert, I., Zhou, Y., Bonnard, I., Berteaux-Lecellier, V., 2018. Exposure to the environmentally-persistent insecticide chlordecone induces detoxification genes and causes polyp bail-out in the coral *P. damicornis*. Chemosphere 195, 190–200. https://doi.org/10.1016/j.chemosphere.2017.12.048.

Wenger, A.S., Williamson, D.H., da Silva, E.T., Ceccarelli, D.M., Browne, N.K., Petus, C., Devlin, M.J., 2016. Effects of reduced water quality on coral reefs in and out of no-take marine reserves. Conserv. Biol. 30, 142–153. https://doi.org/10.1111/cobi.12576.

Wolanski, E., Martinez, J.A., Richmond, R.H., 2009. Quantifying the impact of watershed urbanization on a coral reef: Maunalua Bay, Hawaii. Estuarine 84, 259–268. https://doi.org/10.1016/j.ecss.2009.06.029.

Wu, J., Banerjee, A., Jin, B., Menon, S.M., Martin, S.W., Heatherington, A.C., 2018. Clinical dose–response for a broad set of biological products: a model-based meta-analysis. Stat. Methods Med. Res. 27, 2694–2721. https://doi.org/10.1177/0962280216684528.

Xiang, N., Jiang, C., Huang, W., Nordhaus, I., Zhou, H., Drews, M., Diao, X., 2019. The impact of acute benzo(a)pyrene on antioxidant enzyme and stress-related genes in tropical stony corals (*Acropora* spp.). Sci. Total Environ. 694, 133474. https://doi.org/10.1016/j.scitotenv.2019.07.280.

Yost, D.M., Jones, R.J., Mitchelmore, C.L., 2010. Alterations in dimethylsulfoniopropionate (DMSP) levels in the coral *Montastraea franksi* in response to copper exposure. Aquat. Toxicol. 98, 367–373. https://doi.org/10.1016/j.aquatox.2010.03.005.

Yruela, I., 2009. Copper in plants: acquisition, transport and interactions. Funct. Plant Biol. 36, 409–430. https://doi.org/10.1071/FP08288.

Yu, H.S., Liao, W.T., 2010. Gallium: environmental pollution and health effects. Encycl. Environ. Heal., 829–833 https://doi.org/10.1016/B978-0-444-52272-6.00474-8.

Zhao, H., Yuan, M., Strokal, M., Wu, H.C., Liu, X., Murk, A., Kroeze, C., Osinga, R., 2021. Impacts of nitrogen pollution on corals in the context of global climate change and potential strategies to conserve coral reefs. Sci. Total Environ. 774, 145017. https://doi.org/10.1016/j.scitotenv.2021.145017.

SUPPLEMENTARY MATERIALS

Text S1. Full Search Terms.

The following search was run through each DSE listed in Tuttle et al (2020), and the number of results were recorded and saved as RIS (.ris) or Bibtex (.bib) files: ((pollut* AND Acropora) OR (pollut* AND Anacropora) OR (pollut* AND Cantharellus) OR (pollut* AND Dendrogyra) OR (pollut* AND Euphyllia) OR (pollut* AND Isopora) OR (pollut* AND Montastraea) OR (pollut* AND Montipora) OR (pollut* AND Mycetophyllia) OR (pollut* AND Orbicella) OR (pollut* AND Pavona) OR (pollut* AND Porites) OR (pollut* AND Seriatopora) OR (pollut* AND Siderastrea) OR (pollut* AND Tubastraea) OR (pollut* AND Alveopora) OR (pollut* AND Astreopora) OR (pollut* AND Favia) OR (pollut* AND Favites) OR (pollut* AND Goniastrea) OR (pollut* AND Goniopora) OR (pollut* AND Leptastrea) OR (pollut* AND Leptoria) OR (pollut* AND Lobophyllia) OR (pollut* AND Millepora) OR (pollut* AND Platygyra) OR (pollut* AND Pocillopora) OR (pollut* AND Turbinaria) OR (coral AND toxi*) OR (coral AND toxic*) OR (coral AND *icide*) OR (coral AND metal*) OR (coral AND contamin*) OR (coral AND sewage) OR (coral AND effluent) OR (coral AND dispersant*) OR (coral AND "oil") OR (coral AND anti-foul*) OR (coral AND antifoul*) OR (coral AND pharmaceutic*) OR (coral AND agricultural) OR (coral AND outfall*) OR (coral AND termit*) OR (coral AND creosote) OR (coral AND mercury) OR (coral AND estrog*) OR (coral AND hydrocarbon*) OR (coral AND copper) OR (coral AND iron) OR (coral AND cadmium) OR (coral AND zinc) OR (coral AND arsenic) OR (coral AND "tin") OR (coral AND irgarol) OR (coral AND fuel*) OR (coral AND dioxin*) OR (coral AND PCB*) OR (coral AND *benz*) OR (coral AND *ylene*) OR (coral AND chlori*) OR (coral AND chlord*) OR (coral AND chlorp*) OR (coral AND DDT*) OR (coral AND DDE*) OR (coral AND DDD*) OR (coral AND "PAH*") OR (coral AND PFAS) OR (coral AND glypho*) OR (coral AND aldrin*) OR (coral AND *dieldrin*) OR (coral AND *endrin*) OR (coral AND *sulph*) OR (coral AND discharg*) OR (coral AND sunscreen) OR (coral AND sunblock) OR (coral AND *plastic*) OR (coral AND phthalate*) OR (coral AND wastewater) OR (coral AND bioaccumulat*) OR (coral AND antibiotic*) OR (coral AND flame retard*) OR (coral AND PBB*) OR (coral AND PBDE*) OR (coral AND BOA) OR (coral AND atrazine)).

Text S2. PECO Eligibility Criteria.

The following criteria were adapted from criteria described in Tuttle et al (2020):

Population: All life stages of all shallow (photic zone, ≤80 m depth) scleractinian coral genera in all warm-water ocean basins (20°–30 °C).

Exposure: Exposure to concentrations of pollutants (i.e., heavy metals, hydrocarbons, pesticides, herbicides, microplastics, etc.), including experimental application in both short- and long-term exposures in the laboratory.

Comparison: Specimens experimentally exposed to pollutants must be compared to an appropriate experimental control.

Outcome(s): Specific endpoints are all physical, physiological, behavioral, developmental, and ecological responses of corals associated with exposure to pollutants. These may include but are not limited to tissue/colony mortality, bleaching, fertilization success, larval survival and settlement, and changes in rates of growth and photosynthesis. Outcomes will be recorded as binary or continuous data, as reported in the study.

Text S3. List of References Included in the Quantitative Review and Meta-analysis.

Acevedo, R., 1991. Preliminary observations on effects of pesticides carbaryl, naphthol, and chlorpyrifos on planulae of the hermatypic coral *Pocillopora damicornis*. Pacific Sci. 45, 287–289.

Alutoin, S., Boberg, J., Nyström, M., Tedengren, M., 2001. Effects of the multiple stressors copper and reduced salinity on the metabolism of the hermatypic coral *Porites lutea*. Mar. Environ. Res. 52, 289–299. https://doi.org/10.1016/S0141-1136(01)00105-2

Amid, C., Olstedt, M., Gunnarsson, J.S., Le Lan, H., Tran Thi Minh, H., den Brink, P.J., Hellstrom, M., Tedengren, M., 2018. Additive effects of the herbicide glyphosate and elevated temperature on the branched coral *Acropora formosa* in Nha Trang, Vietnam. Environ. Sci. Pollut. Res. 25, 13360–13372. https://doi.org/10.1007/s11356-016-8320-7

Banc-Prandi, G., Fine, M., 2019. Copper enrichment reduces thermal tolerance of the highly resistant Red Sea coral *Stylophora pistillata*. Coral Reefs 38, 285–296. https://doi.org/10.1007/s00338-019-01774-z

Bastidas, C., Garcia, E.M., 2004. Sublethal effects of mercury and its distribution in the coral *Porites astreoides*. Mar. Ecol. Prog. Ser. 267, 133–143. https://doi.org/10.3354/meps267133

Bielmyer, G.K., Grosell, M., Bhagooli, R., Baker, A.C., Langdon, C., Gillette, P., Capo, T.R., 2010. Differential effects of copper on three species of scleractinian corals and their algal symbionts (*Symbiodinium* spp.). Aquat. Toxicol. 97, 125–133. https://doi.org/http://dx.doi.org/10.1016/j.aquatox.2009.12.021

Biscéré, T., Ferrier-Pagès, C., Grover, R., Gilbert, A., Rottier, C., Wright, A., Payri, C., Houlbrèque, F., 2018. Enhancement of coral calcification via the interplay of nickel and urease. Aquat. Toxicol. 200, 247–256. https://doi.org/10.1016/j.aquatox.2018.05.013

Biscéré, T., Lorrain, A., Rodolfo-Metalpa, R., Gilbert, A., Wright, A., Devissi, C., Peignon, C., Farman, R., Duvieilbourg, E., Payri, C., Houlbrèque, F., 2017. Nickel and ocean warming affect scleractinian coral growth. Mar. Pollut. Bull. 120, 250–258. https://doi.org/10.1016/j.marpolbul.2017.05.025

Biscéré, T., Rodolfo-Metalpa, R., Lorrain, A., Chauvaud, L., Thébault, J., Clavier, J., Houlbrèque, F., 2015. Responses of two scleractinian corals to cobalt pollution and ocean acidification. PLoS One 10, 1–18. https://doi.org/10.1371/journal.pone.0122898

Cantin, N.E., Negri, A.P., Willis, B.L., 2007. Photoinhibition from chronic herbicide exposure reduces reproductive output of reef-building corals. Mar. Ecol. Prog. Ser. 344, 81–93. https://doi.org/10.3354/meps07059

Chen, T.H., Cheng, Y.M., Cheng, J.O., Ko, F.C., 2012. Assessing the effects of polychlorinated biphenyls (Aroclor 1254) on a scleractinian coral (*Stylophora pistillata*) at organism, physiological, and molecular levels. Ecotoxicol. Environ. Saf. 75, 207–212. https://doi.org/10.1016/j.ecoenv.2011.09.001

de Barros Marangoni, L.F., Marques, J.A., Duarte, G.A.S., Pereira, C.M., Calderon, E.N., Castro, C.B. e., Bianchini, A., 2017. Copper effects on biomarkers associated with photosynthesis, oxidative status and calcification in the Brazilian coral *Mussismilia harttii* (Scleractinia, Mussidae). Mar. Environ. Res. 130, 248–257. https://doi.org/10.1016/j.marenvres.2017.08.002

Farina, O., Ramos, R., Bastidas, C., García, E., 2008. Biochemical responses of cnidarian larvae to mercury and benzo(a)pyrene exposure. Bull. Environ. Contam. Toxicol. 81, 553–557. https://doi.org/10.1007/s00128-008-9534-2

Fonseca, J. da S., de Barros Marangoni, L.F., Marques, J.A., Bianchini, A., 2019. Carbonic anhydrase activity as a potential biomarker for acute exposure to copper in corals. Chemosphere 227, 598–605. https://doi.org/10.1016/j.chemosphere.2019.04.089

Fonseca, J. da S., de Barros Marangoni, L.F., Marques, J.A., Bianchini, A., 2017. Effects of increasing temperature alone and combined with copper exposure on biochemical and physiological parameters in the zooxanthellate scleractinian coral *Mussismilia harttii*. Aquat. Toxicol. 190, 121–132. https://doi.org/10.1016/j.aquatox.2017.07.002

Gissi, F., Stauber, J., Reichelt-Brushett, A., Harrison, P.L., Jolley, D.F., 2017. Inhibition in fertilisation of coral gametes following exposure to nickel and copper. Ecotoxicol. Environ. Saf. 145, 32–41. https://doi.org/10.1016/j.ecoenv.2017.07.009

Glynn, P.W., Howard, L.S., Corcoran, E., Freay, A.D., 1984. The Occurrence and Toxicity of Herbicides in Reef Building Corals. Mar. Pollut. Bull. 15, 370–374.

Harland, A.D., Brown, B.E., 1989. Metal Tolerance in the Scleractinian Coral *Porites lutea*. Mar. Pollut. Bull. 20, 353–357. https://doi.org/10.1016/0025-326X(89)90159-8

Hédouin, L., Gates, R.D., 2013. Assessing fertilization success of the coral *Montipora capitata* under copper exposure: Does the night of spawning matter? Mar. Pollut. Bull. 66, 221–224. https://doi.org/10.1016/j.marpolbul.2012.11.020

Hédouin, L.S., Wolf, R.E., Phillips, J., Gates, R.D., 2016. Improving the ecological relevance of toxicity tests on scleractinian corals: Influence of season, life stage, and seawater temperature. Environ. Pollut. 213, 240–253. https://doi.org/10.1016/j.envpol.2016.01.086

Jones, R.J., 2004. Testing the 'photoinhibition' model of coral bleaching using chemical inhibitors. Mar. Ecol. Prog. Ser. 284, 133–145. https://doi.org/10.3354/meps284133

Jones, R.J., 1997. Zooxanthellae loss as a bioassay for assessing stress in corals. Mar. Ecol. Prog. Ser. 149, 163–171. https://doi.org/10.3354/meps149163

Jones, R.J., Kerswell, A.P., 2003. Phytotoxicity of Photosystem II (PSII) herbicides to coral. Mar. Ecol. Prog. Ser. 261, 149–159. https://doi.org/10.3354/meps261149

Jones, R.J., Muller, J., Haynes, D., Schreiber, U., 2003. Effects of herbicides diuron and atrazine on corals of the Great Barrier Reef, Australia. Mar. Ecol. Prog. Ser. 251, 153–167.

Kwok, C.K., Ang, P.O.J., 2013. Inhibition of larval swimming activity of the coral (*Platygyra acuta*) by interactive thermal and chemical stresses. Mar. Pollut. Bull. 74, 264–273. https://doi.org/10.1016/j.marpolbul.2013.06.048

Kwok, C.K., Lam, K.Y., Leung, S.M., Chui, A.P.Y., Ang, P.O., 2016. Copper and thermal perturbations on the early life processes of the hard coral *Platygyra acuta*. Coral Reefs 35, 827–838. https://doi.org/10.1007/s00338-016-1432-1

Leigh-Smith, J., Reichelt-Brushett, A., Rose, A.L., 2018. The Characterization of Iron (III) in Seawater and Related Toxicity to Early Life Stages of Scleractinian Corals. Environ. Toxicol. Chem. 37, 1104–1114. https://doi.org/10.1002/etc.4043

Markey, K.L., Baird, A.H., Humphrey, C., Negri, A.P., 2007. Insecticides and a fungicide affect multiple coral life stages. Mar. Ecol. Prog. Ser. 330, 127–137.

Martinez, M.D.C.G., Romero, P.R., Banaszak, A.T., 2007. Photoinduced toxicity of the polycyclic aromatic hydrocarbon, fluoranthene, on the coral, *Porites divaricata*. J. Environ. Sci. Heal. Part A-Toxic/Hazardous Subst. Environ. Eng. 42, 1495–1502. https://doi.org/10.1080/10934520701480946

Mitchelmore, C.L., Verde, E.A., Weis, V.M., 2007. Uptake and partitioning of copper and cadmium in the coral *Pocillopora damicornis*. Aquat. Toxicol. 85, 48–56.

Muhaemin, M., 2007. The Copper and reduced salinity effects on metabolism of hermatypic coral *Fungia* sp. J. Coast. Dev. 11, 14–19.

Negri, A., Vollhardt, C., Humphrey, C., Heyward, A., Jones, R., Eaglesham, G., Fabricius, K., 2005. Effects of the herbicide diuron on the early life history stages of coral. Mar. Pollut. Bull. 51, 370–383. https://doi.org/10.1016/j.marpolbul.2004.10.053

Negri, A.P., Flores, F., Roethig, T., Uthicke, S., 2011a. Herbicides increase the vulnerability of corals to rising sea surface temperature. Limnol. Oceanogr. 56, 471–485. https://doi.org/10.4319/lo.2011.56.2.0471

Negri, A.P., Harford, A.J., Parry, D.L., van Dam, R.A., 2011b. Effects of alumina refinery wastewater and signature metal constituents at the upper thermal tolerance of: 2. The early life stages of the coral *Acropora tenuis*. Mar. Pollut. Bull. 62, 474–482. https://doi.org/10.1016/j.marpolbul.2011.01.011

Negri, A.P., Heyward, A.J., 2001. Inhibition of coral fertilisation and larval metamorphosis by tributyltin and copper. Mar. Environ. Res. 51, 17–27. https://doi.org/10.1016/S0141-1136(00)00029-5

Negri, A.P., Hoogenboom, M.O., 2011. Water Contamination Reduces the Tolerance of Coral Larvae to

Thermal Stress. PLoS One 6. https://doi.org/10.1371/journal.pone.0019703
Nyström, M., Nordemar, I., Tedengren, M., 2001. Simultaneous and sequential stress from increased temperature and copper on the metabolism of the hermatypic coral *Porites cylindrica*. Mar. Biol. 138, 1225–1231. https://doi.org/10.1007/s002270100549
Overmans, S., Nordborg, M., Díaz-Rúa, R., Brinkman, D.L., Negri, A.P., Agustí, S., 2018. Phototoxic effects of PAH and UVA exposure on molecular responses and developmental success in coral larvae. Aquat. Toxicol. 198, 165–174. https://doi.org/10.1016/j.aquatox.2018.03.008
Puisay, A., Pilon, R., Hédouin, L., 2015. High resistance of *Acropora* coral gametes facing copper exposure. Chemosphere 120, 563–567. https://doi.org/10.1016/j.chemosphere.2014.09.041
Råberg, S., Nyström, M., Erös, M., Plantman, P., 2003. Impact of the herbicides 2,4-D and diuron on the metabolism of the coral *Porites cylindrica*. Mar. Environ. Res. 56, 503–514. https://doi.org/10.1016/S0141-1136(03)00039-4
Ramos, R., Garcia, E., 2007. Induction of mixed-function oxygenase system and antioxidant enzymes in the coral *Montastraea faveolata* on acute exposure to benzo(a)pyrene. Comp. Biochem. Physiol. C-Toxicology Pharmacol. 144, 348–355. https://doi.org/10.1016/j.cbpc.2006.11.006
Reichelt-Brushett, A., Hudspith, M., 2016. The effects of metals of emerging concern on the fertilization success of gametes of the tropical scleractinian coral *Platygyra daedalea*. Chemosphere 150, 398–406. https://doi.org/10.1016/j.chemosphere.2016.02.048
Reichelt-Brushett, A.J., Harrison, P.L., 2005. The effect of selected trace metals on the fertilization success of several scleractinian coral species. Coral Reefs 24, 524–534. https://doi.org/10.1007/s00338-005-0013-5
Reichelt-Brushett, A.J., Harrison, P.L., 2004. Development of a sublethal test to determine the effects of copper, and lead on scleractinian coral larvae. Arch. Environ. Contam. Toxicol. 47, 40–55. https://doi.org/10.1007/s00244-004-3080-7
Reichelt-Brushett, A.J., Harrison, P.L., 2000. The effect of copper on the settlement success of larvae from the scleractinian coral *Acropora tenuis*. Mar. Pollut. Bull. 41, 385–391. https://doi.org/10.1016/S0025-326X(00)00131-4
Reichelt-Brushett, A.J., Harrison, P.L., 1999. The effect of copper, zinc and cadmium on fertilization success of gametes from scleractinian reef corals. Mar. Pollut. Bull. 38, 182–187. https://doi.org/10.1016/S0025-326X(98)00183-0
Renegar, D.A., Turner, N.R., Riegl, B.M., Dodge, R.E., Knap, A.H., Schuler, P.A., 2017. Acute and subacute toxicity of the polycyclic aromatic hydrocarbon 1-methylnaphthalene to the shallow-water coral *Porites divaricata*: Application of a novel exposure protocol. Environ. Toxicol. Chem. 36, 212–219. https://doi.org/10.1002/etc.3530
Ross, C., Olsen, K., Henry, M., Pierce, R., 2015. Mosquito control pesticides and sea surface temperatures have differential effects on the survival and oxidative stress response of coral larvae. Ecotoxicology 24, 540–552. https://doi.org/http://dx.doi.org/10.1007/s10646-014-1402-8
Sabdono, A., Joetono, Soedarsono, J., Hartiko, H., Artama, W.T., 1998. Preliminary study on the effects of 2,4-D herbicide formulations on reef building corals. J. Coast. Dev. 1, 201–206.
Summer, K., Reichelt-Brushett, A., Howe, P., 2019. Toxicity of manganese to various life stages of selected marine cnidarian species. Ecotoxicol. Environ. Saf. 167, 83–94. https://doi.org/10.1016/j.ecoenv.2018.09.116
Tarrant, A.M., Atkinson, M.J., Atkinson, S., 2004. Effects of steroidal estrogens on coral growth and reproduction. Mar. Ecol. Prog. Ser. 269, 121–129. https://doi.org/10.3354/meps269121
Victor, S., Richmond, R.H., 2005. Effect of copper on fertilization success in the reef coral *Acropora surculosa*. Mar. Pollut. Bull. 50, 1448–1451. https://doi.org/10.1016/j.marpolbul.2005.09.004
Watanabe, T., Utsunomiya, Y., Yuyama, I., 2007. Long-term laboratory culture of symbiotic coral juveniles and their use in eco-toxicological study. J. Exp. Mar. Bio. Ecol. 352, 177–186. https://doi.org/10.1016/j.jembe.2007.07.022
Xiang, N., Jiang, C., Huang, W., Nordhaus, I., Zhou, H., Drews, M., Diao, X., 2019. The impact of acute benzo(a)pyrene on antioxidant enzyme and stress-related genes in tropical stony corals (*Acropora*

spp.). Sci. Total Environ. 694, 133474. https://doi.org/10.1016/j.scitotenv.2019.07.280
Yost, D.M., Jones, R.J., Mitchelmore, C.L., 2010. Alterations in dimethylsulfoniopropionate (DMSP) levels in the coral *Montastraea franksi* in response to copper exposure. Aquat. Toxicol. 98, 367–373. https://doi.org/10.1016/j.aquatox.2010.03.005

Table S1. Search specifications for each database or search engine (DSE).

DSE Category	DSE Name (Abbreviation)	DSE Scope	Search specification(s)	Search dates
Bibliographic databases:	1) *Web of Science* (WoS)*, All Databases*	General science	Topic (titles, authors, abstracts, keywords); 'All Databases' include: (a) WoS Core Collection (SCI-EXPANDED, ESCI), (b) Biological Abstracts, (c) SciELO Citation Index, & (d) Zoological Record	All years (1950 - present)
	2) *JSTOR*	General academic	Abstract, All content	Any time
	3) *Aquatic Sciences and Fisheries Abstracts* (ASFA)	Aquatic and marine science	Abstract	Any time
	4) *Dissertations & Theses Global* (PQDT)	Global dissertations and theses	Abstract	Any time
Organizational databases:	5) *James Cook University One Search* (JCU)	Australian university dissertations and theses	Abstract, Dissertation/Thesis	Any time
	6) *ReefBase*	Proceedings of the International Coral Reef Symposium	Title; also Keywords for taxon-specific search terms	Any time
	7) *Science.gov*	United States federal government science	Full record (no 'Abstract' option)	Any time
	8) *Great Barrier Reef Marine Park Authority (GBRMPA) Elibrary*	Australian federal government science	All of ELibrary, Type = Report	Any time

Table S2. Example of data extraction sheet used in this quantitative review and meta-analysis that is adapted from Tuttle et al. (2020).

Reference ID	Author(s) Year	Extracted Data
	Experiment Number	
	Exposure Level/Description	
	Exposure Frequency	
	Exposure Duration/ Timepoint	
	Species	
QUICK KEY		
n/a	not applicable	
n/r	not reported	
0	no	
1	yes	
UoM	Unit of Measurement	
s.e.	standard error (of the mean)	
s.d.	standard deviation	
95% CI	95% confidence interval	
GENERAL SPECIFICATIONS		
	Coral age class	
	Community study?	
	Current genus name	
	Current species name	
	Colony form	
	Other forms/morphologies	
	Coral surface direction	
	Ocean	
	Ecoregion number	
	Study location	
	Study site	
	Study type	
	Flow characteristics	
	Light characteristics	
	Other sample characteristics	
STRESSOR SPECIFICATIONS		
	Stressor description	
	Application level (amount)	
	Application level (amount) UoM	
	level converted to µg/L	
	Application level (amount) average type	
	N for computing average	
	N UoM	
	lower error estimate	
	upper error estimate	
	level error type	
	exposure duration in days	
	notes	
RESPONSE 1 SPECIFICATIONS		
	Response type	
	Response level	
	Unit of measurement	
	Average type	
	N for computing average	
	N Unit of measurement	
	Lower error bound, if taken from Figure	
	Upper error bound, if taken from Figure	
	Lower error estimate (= response level - lower error bound)	
	Upper error estimate (= upper error bound - response level)	
	Error type	
	Time to response, numeric	
	Time to response, UoM	
	Duration of response, numeric	
	Duration of response, UoM	
	Source of data	
BINARY RESPONSES		
	High yield/ chlA?	
	Hydrostatic inflation?	
	Tentacular activity?	
	Increased mucus?	
	Congealed sediment?	
	Shift from auto to heterotrophy?	
	Reduced P/R?	
	Reduced photosynthetic efficiency?	
	Reduced growth rate?	
	Reduced fertilization success?	
	Reduced larval survival? (pre-settlement)	
	Limited settlement?	
	Reduced recruit survival? (post-settlement)	
	Local bleaching?	
	Algal overgrowth?	
	Smothering?	
	Small necroses?	
	Large necroses?	
	Death of colonies?	
	Binary Notes	
EXTRACTION COMPLETE?		
	Data extractor initials	
	Date of completion	
	Additional notes on study	

Table S3. Full description of stressor-response combinations included in the quantitative review. Data obtained from each pollutant-response-article combination examined in the quantitative review is outlined within and includes the range of concentrations (conc.) examined, relative exposure duration (short = 7 days or less; long = at least 7 days), no observed adverse effect level (NOAEL), lowest observed adverse effect level (LOAEL), and half maximal effective concentrations (EC_{50}), when reported.

Pollutant Class	Pollutant	Chemical Form of Pollutant	Coral Life Stage	Species	Ocean/ Region	Response	Article	Range of Conc. (µg L^{-1})	Exposure Duration	NOAEL (µg L^{-1})	LOAEL (µg L^{-1}) (^ = qualitative assessment)	EC_{50} (µg L^{-1}) if reported
Metal	Aluminum	$AlCl_3.6H_2O$	egg	*Acropora tenuis*	Pacific/ GBR North-Central	fertilization success	Negri et al. 2011	15.3 - 9,700	short	1960.0	2950.0	2997.0
Metal	Aluminum	$AlCl_3.6H_2O$	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Negri et al. 2011	15.3 - 9,700	short	996.0	1960.0	1945.0
Metal	Cadmium	$CdCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	bleaching	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Cadmium	$CdCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	chlorophyll-a concentration	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Cadmium	$CdCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	chlorophyll-c concentration	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Cadmium	$Cd(NO_3)_2$	egg	*Acropora tenuis*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	13 - 10,000	short	2000.0	5000.0	-
Metal	Cadmium	$Cd(NO_3)_2$	egg	*Coelastrea aspera*	Pacific/ GBR North-Central	fertilization success	Reichelt-Brushett & Harrison 1999	2 - 200	short	200.0	none	-
Metal	Cadmium	$Cd(NO_3)_2$	egg	*Oxypora lacera*	Pacific/ GBR North-Central	fertilization success	Reichelt-Brushett & Harrison 1999	20 - 1,000	short	1000.0	none	-
Metal	Cadmium	$CdCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	symbiont density	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Cadmium	$CdCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	tissue mortality	Mitchelmore et al. 2007	5 - 50	short/ long	5.0	50.0	-
Metal	Cobalt	$CoCl_2$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Hudspith 2016	9.5 - 2,357	short	2357.0	none	-
Metal	Cobalt	$CoNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	growth	Biscéré et al. 2015	0.03 - 0.22	long	-	0.2	-
Metal	Cobalt	$CoNO_3$	adult	*Stylophora pistillata*	Pacific/ New Caledonia	growth	Biscéré et al. 2015	0.03 - 0.22	long	-	0.2	-
Metal	Cobalt	$CoNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	maximum quantum yield	Biscéré et al. 2015	0.03 - 0.22	long	0.2	none	-
Metal	Cobalt	$CoNO_3$	adult	*Stylophora pistillata*	Pacific/ New Caledonia	maximum quantum yield	Biscéré et al. 2015	0.03 - 0.22	long	0.2	none	-
Metal	Copper	$Cu(HNO_3)$	larvae	*Acropora pulchra*	Pacific/ Society Islands	abnormal larval development	Puisay et al. 2015	10 - 220	short	20.0	50.0	-
Metal	Copper	$Cu(HNO_3)$	larvae	*Acropora cytherea*	Pacific/ Society Islands	abnormal larval development	Puisay et al. 2015	10 - 220	short	50.0	100.0	-

Metal	Copper	Cu_2SO_4	adult	*Acropora muricata*	Pacific/ GBR North-Central	adult mortality	Jones 1997	5 - 80	short	20.0	40.0	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	adult mortality	Hédouin et al. 2016	12.6 - 434	short	100.0	250.0	Summer: 175 Winter: 251
Metal	Copper	$CuSO_4$	adult	*Fungia sp.*	Indo-Pacific/ Java South	bleaching	Muhaemin 2007	10 - 30	short	10.0	30.0	-
Metal	Copper	Cu_2SO_4	adult	*Acropora muricata*	Pacific/ GBR North-Central	bleaching	Jones 1997	5 - 80	short	20.0	40.0	-
Metal	Copper	n/r	adult	*Seriatopora hystrix*	Pacific/ GBR South	bleaching	Jones 2004	60	short	-	60.0	-
Metal	Copper	$CuCl_2$	adult	*Orbicella faveolata*	Atlantic /Bahamas and Florida Keys	bleaching	Bielmyer et al. 2010	4.04 - 20.31	long	20.3	-	-
Metal	Copper	$CuCl_2$	adult	*Acropora cervicornis*	Atlantic /Bahamas and Florida Keys	bleaching	Bielmyer et al. 2010	4.04 - 20.31	long	4.0	10.63 ^	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Atlantic /Bahamas and Florida Keys	bleaching	Bielmyer et al. 2010	4.04 - 20.31	long	4.0	10.63 ^	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	bleaching	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Copper	Cu_2SO_4	adult	*Orbicella franksi*	Atlantic/ Bermuda	chlorophyll concentration	Yost et al. 2010	5 - 50	short	-	5	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	chlorophyll concentration	Hédouin et al. 2016	12.6 - 434	short	-	12.6	-
Metal	Copper	Cu_2SO_4	adult	*Acropora muricata*	Pacific/ GBR North-Central	chlorophyll concentration	Jones 1997	5 - 80	short	20.0	40.0	-
Metal	Copper	$CuCl_2$	adult	*Mussismilia harttii*	Atlantic/ Brazil	chlorophyll concentration	Fonseca et al. 2017	3.8 - 8.6	short/long	8.6	-	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	chlorophyll-a concentration	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	chlorophyll-c concentration	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Atlantic /Bahamas and Florida Keys	effective quantum yield	Bielmyer et al. 2010	2.4 - 20.31	long	2.4	2.4	-
Metal	Copper	$CuCl_2$	adult	*Acropora cervicornis*	Atlantic /Bahamas and Florida Keys	effective quantum yield	Bielmyer et al. 2010	2.4 - 20.31	long	10.6	20.3	-
Metal	Copper	$CuCl_2$	adult	*Orbicella faveolata*	Atlantic /Bahamas and Florida Keys	effective quantum yield	Bielmyer et al. 2010	2.4 - 20.31	long	20.3	-	-
Metal	Copper	$CuCl_2$	egg	*Acropora millepora*	Pacific/ Ningaloo Reef	fertilization success	Negri & Heyward 2001	0.1 - 6,263	short	0.7	6.0	17.4 +/- 1.1
Metal	Copper	$CuSO_4$	egg	*Acropora surculosa*	Pacific/ Marianas	fertilization success	Victor & Richmond 2005	10 - 200	short	-	10.0	11.4

Metal	Copper	$Cu(HNO_3)_2$	egg	*Montipora capitata*	Pacific/ Hawai'i East	fertilization success	Hédouin & Gates 2013	10 - 500	short	10.0	20.0	3 diff. EC50 reported: 31.7, 17.5, 16.6
Metal	Copper	$CuCl_2$	egg	*Coelastrea aspera*	Pacific/ GBR North-Central	fertilization success	Reichelt-Brushett & Harrison 1999	2 - 200	short	2.0	20.0	14.5
Metal	Copper	$CuCl_2$	egg	*Goniastrea retiformis*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 250	short	10.0	20.0	24.7
Metal	Copper	$CuCl_2$	egg	*Coelastrea aspera*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 250	short	12.8	20.4	18.5
Metal	Copper	$CuCl_2$	egg	*Acropora longi-cyathus*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 250	short	15.3	23.6	15.2
Metal	Copper	$CuCl_2$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Hudspith 2016	7 - 111	short	21.0	33.0	33.3
Metal	Copper	$CuCl_2$	egg	*Acropora tenuis*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 250	short	33.5	41.9	39.7
Metal	Copper	$Cu(HNO_3)$	egg	*Acropora cytherea*	Pacific/ Society Islands	fertilization success	Puisay et al. 2015	10 - 220	short	20.0	50.0	69.4 +/- 4.8
Metal	Copper	$Cu(HNO_3)$	egg	*Acropora pulchra*	Pacific/ Society Islands	fertilization success	Puisay et al. 2015	10 - 220	short	20.0	50.0	75.4 +/- 6.5
Metal	Copper	$CuCl_2$	egg	*Platygyra acuta*	Pacific/ Hong Kong	fertilization success	Kwok et al. 2016	10 - 1,000	short	-	100.0	92.1
Metal	Copper	$Cu(SO_4)_2$	egg	*Acropora aspera*	Pacific/ GBR South	fertilization success	Gissi et al. 2017	4 - 37	short	<6	-	78.0
Metal	Copper	$Cu(SO_4)_2$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Gissi et al. 2017	3.7 - 35	short	9.0	-	28.0
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Atlantic /Bahamas and Florida Keys	growth	Bielmyer et al. 2010	2.4 - 20.31	long	2.4	4.0	-
Metal	Copper	$CuCl_2$	adult	*Acropora cervicornis*	Atlantic /Bahamas and Florida Keys	growth	Bielmyer et al. 2010	2.4 - 20.31	long	10.6	20.3	-
Metal	Copper	$CuCl_2$	juv.	*Platygyra acuta*	Pacific/ Hong Kong	growth	Kwok et al. 2016	25 - 200	long	200.0	none	-
Metal	Copper	$CuCl_2$	adult	*Coelastrea aspera*	Pacific/ GBR North-Central	larval survival	Reichelt-Brushett & Harrison 2004	5 - 500	short	5.0	10.0	34.0
Metal	Copper	$Cu(NO_3)_2$	larvae	*Platygyra acuta*	Pacific/ Hong Kong	larval survival	Kwok & Ang 2013	40 - 200	short	40.0	80.0	93.3
Metal	Copper	$CuCl_2$	larvae	*Pocillopora damicornis*	Pacific/ Hawai'i East	larval survival	Hédouin et al. 2016	11 - 611	short	50.0	100.0	30 deg. C: 141 27 deg. C: 198

Metal	Copper	$CuCl_2$	larvae	*Platygyra acuta*	Pacific/ Hong Kong	larval survival	Kwok et al. 2016	25 - 200	short	50.0	100.0	101.0
Metal	Copper	$CuCl_2$	larvae	*Platygyra acuta*	Pacific/ Hong Kong	larval swimming velocity	Kwok et al. 2016	25 - 200	short	25.0	50.0	45.4
Metal	Copper	$CuCl_2$	adult	*Platygyra daedalea*	Pacific/ GBR North-Central	larval swimming velocity	Reichelt-Brushett & Harrison 2004	10 - 200	short	20.0	50.0	36.0
Metal	Copper	$Cu(NO_3)_2$	larvae	*Platygyra acuta*	Pacific/ Hong Kong	larval swimming velocity	Kwok & Ang 2013	40 - 200	short	40.0	80.0	46.9
Metal	Copper	$CuCl_2$	adult	*Coelastrea aspera*	Pacific/ GBR North-Central	larval swimming velocity	Reichelt-Brushett & Harrison 2004	3.7 - 178.3	short	50.0	100.0	16.0
Metal	Copper	$CuCl_2$	adult	*Stylophora pistillata*	Indian/ Red Sea North-Central	maximum quantum yield	Banc-Prandi & Fine 2019	1	short/long	0.0	1.0	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	maximum quantum yield	Hédouin et al. 2016	12.6 - 434	short	100.0	250.0	-
Metal	Copper	$CuCl_2$	adult	*Mussismilia harttii*	Atlantic/ Brazil	maximum quantum yield	Fonseca et al. 2019	4.6 - 19.4	short	19.4	-	-
Metal	Copper	$CuCl_2$	adult	*Mussismilia harttii*	Atlantic/ Brazil	maximum quantum yield	Fonseca et al. 2017	3.8 - 8.6	short/long	-	3.8 *when combined with increased temp.	-
Metal	Copper	$CuCl_2$	adult	*Mussismilia harttii*	Atlantic/ Brazil	maximum quantum yield	de Barros Marangoni et al. 2017	3 - 6.7	long	6.7	none	-
Metal	Copper	$CuSO_4$	adult	*Porites lutea*	Pacific/ Gulf of Thailand	production	Alutoin et al. 2001	10 - 30	short	10.0	30.0	-
Metal	Copper	$CuSO_4$	adult	*Fungia sp.*	Indo-Pacific/ Java South	production	Muhaemin 2007	10 - 30	short	10.0	30.0	-
Metal	Copper	$CuSO_4$	adult	*Porites cylindrica*	Pacific/ Philippines North	production	Nyström et al. 2001	11	short	11.0	none	-
Metal	Copper	Cu_2SO_4	adult	*Orbicella franksi*	Atlantic/ Bermuda	protein production	Yost et al. 2010	5 - 50	short	5.0	10.0	-
Metal	Copper	$CuSO_4$	adult	*Porites cylindrica*	Pacific/ Philippines North	respiration	Nyström et al. 2001	11	short	-	11.0	-
Metal	Copper	$CuSO_4$	adult	*Porites lutea*	Pacific/ Gulf of Thailand	respiration	Alutoin et al. 2001	10 - 30	short	30.0	-	-
Metal	Copper	$CuCl_2$	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Negri & Hoogenboom 2011	0.37 - 72	short	16.0	24.0	26.0

Metal	Copper	$CuCl_2$	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Negri & Hoogenboom 2011	0.37 - 72	short	24.0	32.0	32.1
Metal	Copper	$CuCl_2$	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Reichelt-Brushett & Harrison 2000	7.9 - 200	short	20.0	42.0	35.0
Metal	Copper	$CuCl_2$	larvae	*Acropora millepora*	Pacific/ Ningaloo Reef	settlement	Negri & Heyward 2001	0.1 - 6,263	short	6.0	63.0	110 +/- 20
Metal	Copper	$CuCl_2$	larvae	*Platygyra acuta*	Pacific/ Hong Kong	settlement	Kwok et al. 2016	25 - 200	short	200.0	none	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	symbiont density	Hédouin et al. 2016	12.6 - 434	short	-	12.6	-
Metal	Copper	Cu_2SO_4	adult	*Acropora muricata*	Pacific/ GBR North-Central	symbiont density	Jones 1997	5 - 80	short	10.0	20.0	-
Metal	Copper	Cu_2SO_4	adult	*Orbicella franksi*	Atlantic/ Bermuda	symbiont density	Yost et al. 2010	5 - 50	short	10.0	50.0	-
Metal	Copper	n/r	adult	*Seriatopora hystrix*	Pacific/ GBR South	symbiont density	Jones 2004	60	short	-	60.0	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	symbiont density	Mitchelmore et al. 2007	5 - 50	short/ long	50.0	none	-
Metal	Copper	$CuCl_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	tissue mortality	Mitchelmore et al. 2007	5 - 50	short/ long	5.0	50.0	-
Metal	Gallium	$GaCl_3$	egg	*Acropora tenuis*	Pacific/ GBR North-Central	fertilization success	Negri et al. 2011	10.2 - 11,200	short	1120.0	3230.0	3430.0
Metal	Gallium	$GaCl_3$	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Negri et al. 2011	10.2 - 11,200	short	1120.0	2150.0	3566.0
Metal	Iron	$FeCl_3$	egg	*Acropora spathulata*	Pacific/ GBR South	fertilization success	Leigh-Smith et al. 2018	10 - 55,800	short	3000.0	25,300.0	66000.0
Metal	Iron	$FeCl_3$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Leigh-Smith et al. 2018	10 - 55,800	short	2750.0	27,200.0	25000.0
Metal	Iron	$FeCl_3$	larvae	*Platygyra daedalea*	Pacific/ GBR South	larval survival	Leigh-Smith et al. 2018	10 - 55,800	short	2750.0	27,200.0	47000.0
Metal	Iron	$Fe(NO_3)_3$	adult	*Porites lutea*	Indian/ Andaman Sea	symbiont density	Harland & Brown 1989	5 - 50	long	5.0	10.0	-
Metal	Manganese	$MnCl_2 \cdot 4H_2O$	adult	*Acropora spathulata*	Pacific/ GBR South	adult mortality	Summer et al. 2019	1,000 - 50,000	short	5000.0	10,000.0	2700.0
Metal	Manganese	$MnCl_2 \cdot 4H_2O$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Summer et al. 2019	800 - 71,200	short	54,200.0	71,200.0	164000.0
Metal	Manganese	$MnCl_2 \cdot 4H_2O$	egg	*Acropora spathulata*	Pacific/ GBR South	fertilization success	Summer et al. 2019	8,500 - 161,100	short	72,000.0	107,900.0	237000.0
Metal	Manganese	$MnCl_2 \cdot 4H_2O$	larvae	*Acropora spathulata*	Pacific/ GBR South	larval survival	Summer et al. 2019	17,000 - 163,800	short	-	17,000.0	28000.0
Metal	Manganese	$MnCl_2 \cdot 4H_2O$	adult	*Acropora spathulata*	Pacific/ GBR South	tissue mortality	Summer et al. 2019	1,000 - 50,000	short	1,000	5,000.0	700.0
Metal	Mercury	$HgCl_2$	adult	*Porites asteroides*	Atlantic/ South Caribbean	chlorophyll-a concentration	Bastidas & Garcia 2004	4 - 180	long	37.0	180.0	-
Metal	Mercury	$HgCl_2$	adult	*Porites asteroides*	Atlantic/ South Caribbean	chlorophyll-c concentration	Bastidas & Garcia 2004	4 - 180	long	180.0	-	-

Metal	Mercury	$HgCl_2$	larvae	*Porites asteroides*	Atlantic/ South Caribbean	larval survival	Farina et al. 2008	10	short	10.0	none	-
Metal	Mercury	$HgCl_2$	adult	*Porites asteroides*	Atlantic/ South Caribbean	symbiont density	Bastidas & Garcia 2004	4 - 180	long	37.0	180.0	-
Metal	Nickel	$NiCl_2$	adult	*Acropora muricata*	Indian/ Red Sea North-Central	chlorophyll concentration	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	chlorophyll concentration	Biscéré et al. 2017	3.52	long	3.52	none	-
Metal	Nickel	$NiCl_2$	adult	*Pocillopora damicornis*	Indian/ Red Sea North-Central	chlorophyll concentration	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiCl_2$	egg	*Coelastrea aspera*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	5 - 2000	short	5.0	100.0	-
Metal	Nickel	$NiCl_2$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Hudspith 2016	65 - 4,621	short	1014.0	4621.0	1420.0
Metal	Nickel	$NiCl_2.6H_2O$	egg	*Acropora aspera*	Pacific/ GBR South	fertilization success	Gissi et al. 2017	938 - 9090	short	<280	-	>9220
Metal	Nickel	$NiCl_2.6H_2O$	egg	*Acropora digitifera*	Pacific/ GBR South	fertilization success	Gissi et al. 2017	938 - 9090	short	940.0	-	4350.0
Metal	Nickel	$NiCl_2.6H_2O$	egg	*Platygyra daedalea*	Pacific/ GBR South	fertilization success	Gissi et al. 2017	91 - 4,595	short	920.0	-	>4610
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	growth	Biscéré et al. 2017	3.52	long	-	3.52 *when combined with increased temp.	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	growth	Biscéré et al. 2017	2.71	short	2.7	none	-
Metal	Nickel	$NiNO_3$	adult	*Pocillopora damicornis*	Pacific/ New Caledonia	growth	Biscéré et al. 2017	2.71	short	2.7	none	-
Metal	Nickel	$NiCl_2$	adult	*Acropora muricata*	Indian/ Red Sea North-Central	growth	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiCl_2$	adult	*Pocillopora damicornis*	Indian/ Red Sea North-Central	growth	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	maximum quantum yield	Biscéré et al. 2017	3.52	long	3.5	none	-
Metal	Nickel	$NiCl_2$	adult	*Acropora muricata*	Indian/ Red Sea North-Central	maximum quantum yield	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiCl_2$	adult	*Pocillopora damicornis*	Indian/ Red Sea North-Central	maximum quantum yield	Biscéré et al. 2018	3.5	long	3.5	none	-

Metal	Nickel	$NiCl_2$	adult	*Acropora muricata*	Indian/ Red Sea North-Central	P/R	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiCl_2$	adult	*Pocillopora damicornis*	Indian/ Red Sea North-Central	P/R	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	production	Biscéré et al. 2017	2.71	short	2.7	none	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	production	Biscéré et al. 2017	3.52	long	3.5	none	-
Metal	Nickel	$NiNO_3$	adult	*Pocillopora damicornis*	Pacific/ New Caledonia	production	Biscéré et al. 2017	2.71	short	2.7	none	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	respiration	Biscéré et al. 2017	2.71	short	2.7	none	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	respiration	Biscéré et al. 2017	3.52	long	3.5	none	-
Metal	Nickel	$NiNO_3$	adult	*Pocillopora damicornis*	Pacific/ New Caledonia	respiration	Biscéré et al. 2017	2.71	short	2.7	none	-
Metal	Nickel	$NiCl_2$	adult	*Pocillopora damicornis*	Indian/ Red Sea North-Central	symbiont density	Biscéré et al. 2018	3.5	long	-	3.5 *when combined with urea enrichment	-
Metal	Nickel	$NiNO_3$	adult	*Acropora muricata*	Pacific/ New Caledonia	symbiont density	Biscéré et al. 2017	3.52	long	3.5	none	-
Metal	Nickel	$NiCl_2$	adult	*Acropora muricata*	Indian/ Red Sea North-Central	symbiont density	Biscéré et al. 2018	3.5	long	3.5	none	-
Metal	Tin	Tributyltin-Cl_2	egg	*Acropora millepora*	Pacific/ Ningaloo Reef	fertilization success	Negri & Heyward 2001	0.3 - 3,228	short	32.0	318.0	200 +/- 31
Metal	Tin	Tributyltin-Cl_2	juv.	*Acropora tenuis*	Pacific/ Honshu, Japan	growth	Watanabe et al. 2007	0.1 - 0.4	long	0.1	0.4	-
Metal	Tin	Tributyltin-Cl_2	juv.	*Acropora tenuis*	Pacific/ Honshu, Japan	juvenile survival	Watanabe et al. 2007	0.1 - 2.5	long	1.0	2.5	-
Metal	Tin	Tributyltin-Cl_2	larvae	*Acropora millepora*	Pacific/ Ningaloo Reef	settlement	Negri & Heyward 2001	0.3 - 3,228	short	0.3	3.0	2 +/- 0.3
Metal	Zinc	$ZnSO_4$	egg	*Acropora tenuis*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	10 - 5,000	short	-	10.0	-
Metal	Zinc	$ZnSO_4$	egg	*Coelastrea aspera*	Pacific/ GBR North-Central	fertilization success	Reichelt-Brushett & Harrison 1999	2 - 500	short	500	none	-
Metal	Lead	$Pb(NO_3)_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	adult mortality	Hédouin et al. 2016	67.9 - 1200	short	160.0	320.0	Winter: 477 Summer: 742
Metal	Lead	$Pb(NO_3)_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	chlorophyll concentration	Hédouin et al. 2016	67.9 - 1200	short	-	75.6	-
Metal	Lead	$Pb(NO_3)_2$	egg	*Acropora longicyathus*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 9,577	short	451.0	855.0	1453.0

Metal	Lead	$Pb(NO_3)_2$	egg	*Acropora tenuis*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 9,577	short	790.0	1982.0	1801.0
Metal	Lead	$Pb(NO_3)_2$	egg	*Coelastrea aspera*	Pacific/ GBR South	fertilization success	Reichelt-Brushett & Harrison 2005	2 - 9,577	short	5455.0	6409.0	2467.0
Metal	Lead	$Pb(NO_3)_2$	larvae	*Pocillopora damicornis*	Pacific/ Hawai'i East	larval survival	Hédouin et al. 2016	201 - 2,040	short	320.0	640.0	30 deg. C: 681 27 deg. C: 462
Metal	Lead	$Pb(NO_3)_2$	larvae	*Coelastrea aspera*	Pacific/ GBR North-Central	larval survival	Reichelt-Brushett & Harrison 2004	100 - 20,000	short	2500.0	5000.0	9890.0
Metal	Lead	$Pb(NO_3)_2$	larvae	*Platygyra daedalea*	Pacific/ GBR North-Central	larval swimming velocity	Reichelt-Brushett & Harrison 2004	1000 - 20,000	short	-	1000.0	1950.0
Metal	Lead	$Pb(NO_3)_2$	larvae	*Coelastrea aspera*	Pacific/ GBR North-Central	larval swimming velocity	Reichelt-Brushett & Harrison 2004	7.7 - 7114.7	short	2081	4675	2230.0
Metal	Lead	$Pb(NO_3)_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	maximum quantum yield	Hédouin et al. 2016	67.9 - 1200	short	160.0	320.0	-
Metal	Lead	$Pb(NO_3)_2$	adult	*Pocillopora damicornis*	Pacific/ Hawai'i East	symbiont density	Hédouin et al. 2016	67.9 - 1200	short	-	75.6	-
Metal	Vanadium	VCl_3	egg	*Acropora tenuis*	Pacific/ GBR North-Central	fertilization success	Negri et al. 2011	20.6 - 9,380	short	952.0	2920.0	2884.0
Metal	Vanadium	VCl_3	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Negri et al. 2011	20.6 - 9,380	short	280.0	564.0	675.0
PAH	1-methyl-naphthalene	1-methyl-napthalene + CH_3OH	adult	*Porites divaricata*	Atlantic/ Bahamas and Florida Keys	adult mortality	Renegar et al. 2017	639.9 – 25,095	short	25,095	none	12,123.0
PAH	1-methyl-naphthalene	1-methyl-napthalene + CH_3OH	adult	*Porites divaricata*	Atlantic/ Bahamas and Florida Keys	condition score (tissue mortality, mucus production, tentacular activity)	Renegar et al. 2017	639.9 – 25,095	short	640.0	5427.0	7442.0
PAH	1-methyl-naphthalene	1-methyl-napthalene + CH_3OH	adult	*Porites divaricata*	Atlantic/ Bahamas and Florida Keys	effective quantum yield	Renegar et al. 2017	639.9 – 25,095	short	25,095.0	none	-
PAH	Anthracene	Anthracene + DMSO	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	larval survival	Overmans et al. 2018	9.4 - 600	short	-	9.4	18.1
PAH	Anthracene	Anthracene + DMSO	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Overmans et al. 2018	9.4 - 600	short	-	9.4	6.3
PAH	Benzo(a)-pyrene	Benzo(a)-pyrene	adult	*Orbicella faveolata*	Atlantic/ South Caribbean	bleaching	Ramos & Garcia 2007	10 - 100	short	100.0	none	-
PAH	Benzo(a)-pyrene	Benzo(a)-pyrene dissolved in dimethyl-sulfoxide	adult	*Acropora formosa*	Pacific/ Hainan	chlorophyll-a concentration	Xiang et al. 2019	9.02 - 36.27	short	-	9.0	-

PAH	Benzo(a)-pyrene	Benzo(a)-pyrene	adult	*Orbicella faveolata*	Atlantic/ South Caribbean	chlorophyll-a concentration	Ramos & Garcia 2007	10 - 100	short	100.0	none	-
PAH	Benzo(a)-pyrene	Benzo(a)-pyrene dissolved in dimethyl-sulfoxide	adult	*Acropora nasuta*	Pacific/ Hainan	chlorophyll-a concentration	Xiang et al. 2019	9.54 - 37.15	short	37.2	none	-
PAH	Benzo(a)-pyrene	Benzo(a)-pyrene	adult	*Orbicella faveolata*	Atlantic/ South Caribbean	chlorophyll-c concentration	Ramos & Garcia 2007	10 - 100	short	100.0	none	-
PAH	Benzo(a)-pyrene	Benzo(a)-pyrene	larvae	*Porites asteroides*	Atlantic/ South Caribbean	larval survival	Farina et al. 2008	10	short	-	10.0	-
PAH	Benzo(a)-pyrene	Benzo(a)-pyrene	adult	*Orbicella faveolata*	Atlantic/ South Caribbean	symbiont density	Ramos & Garcia 2007	10 - 100	short	10.0	100.0	-
PAH	Fluor-anthene	Fluor-anthene dissolved in acetone	adult	*Porites divaricata*	Atlantic/ Yucatan	bleaching	Martínez et al. 2007	15 - 60	short	-	15.0	-
PAH	Fluor-anthene	Fluor-anthene dissolved in acetone	adult	*Porites divaricata*	Atlantic/ Yucatan	tissue mortality	Martínez et al. 2007	15 - 60	short	15.0	30.0	-
PAH	Phen-anthrene	Phen-anthrene + DMSO	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	larval survival	Overmans et al. 2018	14.1 - 900	short	28.1	56.3	-
PAH	Phen-anthrene	Phen-anthrene + DMSO	larvae	*Acropora tenuis*	Pacific/ GBR North-Central	settlement	Overmans et al. 2018	14.1 - 900	short	28.1	56.3	66.0
PCB	Aroclor 1254	Aroclor 1254	adult	*Stylophora pistillata*	Pacific/ Taiwan	adult mortality	Chen et al. 2012	0.29	short	0.3	none	-
PCB	Aroclor 1254	Aroclor 1254	adult	*Stylophora pistillata*	Pacific/ Taiwan	bleaching	Chen et al. 2012	0.29	short	0.3	none	-
PCB	Aroclor 1254	Aroclor 1254	adult	*Stylophora pistillata*	Pacific/ Taiwan	growth	Chen et al. 2012	0.29	short	0.3	none	-
PCB	Aroclor 1254	Aroclor 1254	adult	*Stylophora pistillata*	Pacific/ Taiwan	maximum quantum yield	Chen et al. 2012	0.29	short	0.3	none	-
Pesticide	1-naphthol	1-naphthol + CH_3OH	larvae	*Pocillopora damicornis*	Pacific/ Hawai‘i East	larval survival	Acevedo 1991	10 - 100,000	short	100.0	1000.0	-
Pesticide	2-methoxy-ethyl-mercuric chloride (MEMC)	2-methoxy-ethyl-mercuric chloride (MEMC)	adult	*Acropora millepora*	Pacific/ GBR North-Central	bleaching	Markey et al. 2007	1 - 10	short	-	1	-
Pesticide	2-methoxy-ethyl-mercuric	2-methoxy-ethyl-mercuric	adult	*Acropora millepora*	Pacific/ GBR North-Central	effective quantum yield	Markey et al. 2007	1 - 10	short	-	1.0	-

	chloride (MEMC)	chloride (MEMC)										
Pesticide	2-methoxy-ethyl-mercuric chloride (MEMC)	2-methoxy-ethyl-mercuric chloride (MEMC)	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	0.3	1.0	1.68 +/- 0.04
Pesticide	2-methoxy-ethyl-mercuric chloride (MEMC)	2-methoxy-ethyl-mercuric chloride (MEMC)	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	0.3	1.0	2.5 +/- 0.03
Pesticide	2-methoxy-ethyl-mercuric chloride (MEMC)	2-methoxy-ethyl-mercuric chloride (MEMC)	adult	*Acropora millepora*	Pacific/ GBR North-Central	symbiont density	Markey et al. 2007	10	short	1	10.0	-
Pesticide	2-methoxy-ethyl-mercuric chloride (MEMC)	2-methoxy-ethyl-mercuric chloride (MEMC)	adult	*Acropora millepora*	Pacific/ GBR North-Central	tentacular activity	Markey et al. 2007	1 - 10	short	-	1	-
Pesticide	2-methoxy-ethyl-mercuric chloride (MEMC)	2-methoxy-ethyl-mercuric chloride (MEMC)	adult	*Acropora millepora*	Pacific/ GBR North-Central	tissue mortality	Markey et al. 2007	1 - 10	short	-	1	-
Pesticide	2,4-D	Weed-B-Gon (Dimethyl-amine salt of 2,4 dichloro-dichloro-phenoxy-acetic acid (0.20%). Dimethyl-amine salt of 2-(2 methyl 4 chloro-phenoxy)-propionic acid (0.20%). Inert ingredients 99.60%)	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	adult mortality	Glynn et al. 1984	100 - 100,000	short	100.0	1000.0^	-

Pesticide	2,4-D	Pure 2,4-D (sodium salt)	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	adult mortality	Glynn et al. 1984	50 - 1,000	short	1,000 ^	-	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Galaxea sp.*	Indo-Pacific/ Java Sea	adult mortality	Sabdono et al. 1998	100 - 1,000,000	short	13,890.0	19,300.0	10260.0
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Porites sp.*	Indo-Pacific/ Java Sea	adult mortality	Sabdono et al. 1998	100 - 1,000,000	short	13,890.0	19,300.0	23200.0
Pesticide	2,4-D	2,4-D	adult	*Porites cylindrica*	Pacific/ Philippines North	effective quantum yield	Råberg et al. 2003	10,000 - 100,000	short	10,000	100,000.0	-
Pesticide	2,4-D	2,4-D	adult	*Porites cylindrica*	Pacific/ Philippines North	maximum quantum yield	Råberg et al. 2003	10,000 - 100,000	short	100,000.0	none	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Galaxea sp.*	Indo-Pacific/ Java Sea	mucus production	Sabdono et al. 1998	100 - 1,000,000	short	1000.0	10,000 ^	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Porites sp.*	Indo-Pacific/ Java Sea	mucus production	Sabdono et al. 1998	100 - 1,000,000	short	100.0	1000 ^	-
Pesticide	2,4-D	2,4-D	adult	*Porites cylindrica*	Pacific/ Philippines North	P/R	Råberg et al. 2003	10,000 - 100,000	short	-	10,000.0	-
Pesticide	2,4-D	2,4-D	adult	*Porites cylindrica*	Pacific/ Philippines North	production	Råberg et al. 2003	10,000 - 100,000	short	-	10,000.0	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Galaxea sp.*	Indo-Pacific/ Java Sea	symbiont density	Sabdono et al. 1998	100 - 1,000,000	short	13,890.0	19,300.0	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Porites sp.*	Indo-Pacific/ Java Sea	symbiont density	Sabdono et al. 1998	100 - 1,000,000	short	19,300.0	26,830.0	-
Pesticide	2,4-D	Weed-B-Gon (Dimethyl-amine salt of 2,4 dichloro-dichloro-phenoxy-acetic acid (0.20%). Dimethyl-amine salt of 2-(2 methyl 4 chloro-phenoxy)-propionic acid (0.20%). Inert ingredients 99.60%)	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	tentacular activity	Glynn et al. 1984	100 - 100,000	short	-	100.0 ^	-

Pesticide	2,4-D	Pure 2,4-D (sodium salt)	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	tentacular activity	Glynn et al. 1984	50 - 1,000	short	1,000 ^	-	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Galaxea sp.*	Indo-Pacific/ Java Sea	tentacular activity	Sabdono et al. 1998	100 - 1,000,000	short	100.0	1000 ^	-
Pesticide	2,4-D	Weed-B-Gon (Dimethyl-amine salt of 2,4 dichloro-dichloro-phenoxy-acetic acid (0.20%). Dimethyl-amine salt of 2-(2 methyl 4 chloro-phenoxy)-propionic acid (0.20%). Inert ingredients 99.60%)	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	tissue mortality	Glynn et al. 1984	100 - 100,000	short	-	100.0 ^	-
Pesticide	2,4-D	Pure 2,4-D (sodium salt)	adult	*Pocillopora damicornis*	Pacific/ Hawai‘i East	tissue mortality	Glynn et al. 1984	50 - 1,000	short	1,000 ^	-	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Galaxea sp.*	Indo-Pacific/ Java Sea	tissue mortality	Sabdono et al. 1998	100 - 1,000,000	short	10,000.0	100,000 ^	-
Pesticide	2,4-D	$C_8H_6Cl_2O_3$ + C_2H_6O	adult	*Porites sp.*	Indo-Pacific/ Java Sea	tissue mortality	Sabdono et al. 1998	100 - 1,000,000	short	10,000.0	100,000 ^	-
Pesticide	Ametryn	*N*-ethyl-*N'*-(1-methylethyl)-6-(methylthio) -1,3,5-triazine-2,4-diamine	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	-	0.3	1.7 +/- 0.1
Pesticide	Atrazine	Atrazine (95%)	adult	*Acropora millepora*	Pacific/ GBR North Central	chlorophyll-a concentration	Negri et al. 2011	12	short	12.0	none	-
Pesticide	Atrazine	6-chloro-N-ethyl-N-[1-methyl-ethyl]-1,3,5-	adult	*Acropora muricata*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	1 - 100	short	1.0	3.0	37.0

		triazine-2,4-diamine										
Pesticide	Atrazine	6-chloro-N-ethyl-N-[1-methyl-ethyl]-1,3,5-triazine-2,4-diamine	adult	*Montipora digitata*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	1 - 100	short	1.0	3.0	88.2
Pesticide	Atrazine	6-chloro-N-ethyl-N-[1-methyl-ethyl]-1,3,5-triazine-2,4-diamine	adult	*Porites cylindrica*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	1 - 100	short	1.0	3.0	67.2
Pesticide	Atrazine	Atrazine (95%)	adult	*Acropora millepora*	Pacific/ GBR North Central	effective quantum yield	Negri et al. 2011	0.3 - 1,000	short	3.0	10.0	47.0
Pesticide	Atrazine	6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	1.0	3.0	45.0 +/- 3.0
Pesticide	Atrazine	Atrazine (95%)	adult	*Acropora millepora*	Pacific/ GBR North Central	maximum quantum yield	Negri et al. 2011	0.3 - 1,000	short	30.0	100.0	- (EC_{10}: 106)
Pesticide	Atrazine	6-chloro-N-ethyl-N-[1-methyl-ethyl]-1,3,5-triazine-2,4-diamine	adult	*Acropora muricata*	Pacific/ GBR South	maximum quantum yield	Jones et al. 2003	1 - 100	short	100.0	none	-
Pesticide	Atrazine	6-chloro-N-ethyl-N-[1-methyl-ethyl]-1,3,5-triazine-2,4-diamine	adult	*Montipora digitata*	Pacific/ GBR South	maximum quantum yield	Jones et al. 2003	1 - 100	short	100.0	none	-
Pesticide	Atrazine	6-chloro-N-ethyl-N-[1-methyl-ethyl]-1,3,5-triazine-2,4-diamine	adult	*Porites cylindrica*	Pacific/ GBR South	maximum quantum yield	Jones et al. 2003	1 - 100	short	100.0	none	-
Pesticide	Carbaryl	Carbaryl	adult	*Acropora millepora*	Pacific/ GBR North-Central	bleaching	Markey et al. 2007	1 - 10	short	10.0	none	-

Pesticide	Carbaryl	Carbaryl	adult	*Acropora millepora*	Pacific/ GBR North-Central	effective quantum yield	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Carbaryl	Carbaryl	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	30.0	none	-
Pesticide	Carbaryl	Carbaryl + CH_3OH	larvae	*Pocillopora damicornis*	Pacific/ Hawai‘i East	larval survival	Acevedo 1991	10 - 100,000	short	1000.0	10,000.0	-
Pesticide	Carbaryl	Carbaryl	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	-	3.0	1 +/- 2
Pesticide	Carbaryl	Carbaryl	adult	*Acropora millepora*	Pacific/ GBR North-Central	symbiont density	Markey et al. 2007	10	short	10.0	none	-
Pesticide	Carbaryl	Carbaryl	adult	*Acropora millepora*	Pacific/ GBR North-Central	tentacular activity	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Carbaryl	Carbaryl	adult	*Acropora millepora*	Pacific/ GBR North-Central	tissue mortality	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	bleaching	Markey et al. 2007	1 - 10	short	1	10	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	effective quantum yield	Markey et al. 2007	1 - 10	short	1	10.0	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	30.0	none	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos + CH_3OH	larvae	*Pocillopora damicornis*	Pacific/ Hawai‘i East	larval survival	Acevedo 1991	10 - 100,000	short	100.0	1000.0	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	-	1.0	1 +/- 2

Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	symbiont density	Markey et al. 2007	10	short	10.0	none	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tentacular activity	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Chlor-pyrifos	Chlor-pyrifos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tissue mortality	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Chlor-pyrifos-oxon	Chlorpyrifos-oxon	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	30.0	none	-
Pesticide	Chlor-pyrifos-oxon	Chlor-pyrifos-oxon	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	0.1	0.3	0.39 +/- 0.01
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora valida*	Pacific/ GBR North Central	adult mortality	Cantin et al. 2007	1 - 10	long	1.0	10.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora tenuis*	Pacific/ GBR North Central	adult mortality	Cantin et al. 2007	1 - 10	long	10.0	none	-
Pesticide	Diuron	lab grade diuron	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	adult mortality	Cantin et al. 2007	1 - 10	long	10.0	none	-

		(98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)										
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora tenuis*	Pacific/ GBR North Central	bleaching	Cantin et al. 2007	1 - 10	long	10.0 ^	none	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora valida*	Pacific/ GBR North Central	bleaching	Cantin et al. 2007	1 - 10	long	-	10.0 ^	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	bleaching	Cantin et al. 2007	1 - 10	long	-	10.0 ^	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU) + $(CH_3)_2CO$	adult	*Seriatopora hystrix*	Pacific/ GBR South	bleaching	Jones 2004	1 - 60	short/long	1.0	10.0	-
Pesticide	Diuron	Diuron + C_2H_6O	juv.	*Pocillopora damicornis*	Pacific/ GBR North Central	bleaching	Negri et al. 2005	0.1 - 1,000	short/long	10.0	100.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-	adult	*Acropora tenuis*	Pacific/ GBR North Central	bleaching	Cantin et al. 2007	1 - 10	long	10.0	none	-

		N,N-dimethyl-urea)										
Pesticide	Diuron	Diuron (98%)	adult	*Acropora millepora*	Pacific/ GBR North Central	chlorophyll-a concentration	Negri et al. 2011	0.84	short	0.8	none	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora tenuis*	Pacific/ GBR North Central	effective quantum yield	Cantin et al. 2007	1 - 10	long	-	1.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora valida*	Pacific/ GBR North Central	effective quantum yield	Cantin et al. 2007	1 - 10	long	-	1.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	effective quantum yield	Cantin et al. 2007	1 - 10	long	-	1.0	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU)	adult	*Acropora muricata*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	0.3 - 30	short	0.3	1.0	5.1
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU)	adult	*Montipora digitata*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	0.3 - 30	short	0.3	1.0	5.9
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-	adult	*Porites cylindrica*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	0.3 - 30	short	0.3	1.0	4.3

		dimethyl-urea (DCMU)										
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU)	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones et al. 2003	0.3 - 30	short	0.3	1.0	3.7
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Acropora millepora*	Pacific/ GBR North Central	effective quantum yield	Negri et al. 2005	0.1 - 1,000	short/long	0.1	1.0	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	effective quantum yield	Negri et al. 2005	0.1 - 1,000	short/long	0.1	1.0	-
Pesticide	Diuron	Diuron + C_2H_6O	juv.	*Pocillopora damicornis*	Pacific/ GBR North Central	effective quantum yield	Negri et al. 2005	0.1 - 1,000	short/long	0.1	1.0	-
Pesticide	Diuron	Diuron (98%)	adult	*Acropora millepora*	Pacific/ GBR North Central	effective quantum yield	Negri et al. 2011	0.3 - 1,000	short	0.3	1.0	2.9
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU) + $(CH_3)_2CO$	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones 2004	1 - 60	short/long	-	30.0	-
Pesticide	Diuron	*N'*-(3,4-dichloro-phenyl)-*N,N*-dimethyl-urea	adult	*Acropora muricata*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	-	0.3	2.7 +/- 0.7
Pesticide	Diuron	*N'*-(3,4-dichloro-phenyl)-*N,N*-dimethyl-urea	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	-	0.3	2.3 +/- 0.04
Pesticide	Diuron	Diuron	adult	*Porites cylindrica*	Pacific/ Philippines North	effective quantum yield	Råberg et al. 2003	10 - 100	short	-	10	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Montipora aequituberc ulata*	Pacific/ GBR North Central	fertilization success	Negri et al. 2005	0.1 - 1,000	short/long	1000.0	none	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Acropora millepora*	Pacific/ GBR North Central	fertilization success	Negri et al. 2005	0.1 - 1,000	short/long	1000.0	none	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-	adult	*Acropora tenuis*	Pacific/ Honshu, Japan	growth	Watanabe et al. 2007	0.3 - 10	long	0.3	1	-

		dimethyl-urea (DCMU)										
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Acropora millepora*	Pacific/ GBR North Central	juvenile survival	Negri et al. 2005	0.1 - 1,000	short/long	1000.0	none	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	juvenile survival	Negri et al. 2005	0.1 - 1,000	short/long	1000.0	none	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU)	adult	*Acropora muricata*	Pacific/ GBR South	maximum quantum yield	Jones et al. 2003	0.3 - 30	short	0.3	1.0	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Acropora millepora*	Pacific/ GBR North Central	maximum quantum yield	Negri et al. 2005	0.1 - 1,000	short/long	0.1	1.0	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	maximum quantum yield	Negri et al. 2005	0.1 - 1,000	short/long	0.1	1.0	-
Pesticide	Diuron	Diuron + C_2H_6O	juv.	*Pocillopora damicornis*	Pacific/ GBR North Central	maximum quantum yield	Negri et al. 2005	0.1 - 1,000	short/long	0.1	1.0	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU)	adult	*Porites cylindrica*	Pacific/ GBR South	maximum quantum yield	Jones et al. 2003	0.3 - 30	short	1.0	3.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora tenuis*	Pacific/ GBR North Central	maximum quantum yield	Cantin et al. 2007	1 - 10	long	1.0	10.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora valida*	Pacific/ GBR North Central	maximum quantum yield	Cantin et al. 2007	1 - 10	long	1.0	10.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	maximum quantum yield	Cantin et al. 2007	1 - 10	long	1.0	10.0	-

		phenyl)-N,N-dimethyl-urea)										
Pesticide	Diuron	Diuron - 98% purity from Sigma-Aldrich	adult	*Acropora millepora*	Pacific/ GBR North Central	maximum quantum yield	Negri et al. 2011	0.3 - 1,000	short	3.0	10.0	- (EC_{10}: 7.5)
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU)	adult	*Montipora digitata*	Pacific/ GBR South	maximum quantum yield	Jones et al. 2003	0.3 - 30	short	10.0	30.0	-
Pesticide	Diuron	Diuron	adult	*Porites cylindrica*	Pacific/ Philippines North	maximum quantum yield	Råberg et al. 2003	10 - 100	short	10	100	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU) + $(CH_3)_2CO$	adult	*Seriatopora hystrix*	Pacific/ GBR South	maximum quantum yield	Jones 2004	1 - 60	short/long	-	30 *when combined with light treatment	-
Pesticide	Diuron	Diuron	adult	*Porites cylindrica*	Pacific/ Philippines North	P/R	Råberg et al. 2003	10 - 100	short	-	10	-
Pesticide	Diuron	Diuron	adult	*Porites cylindrica*	Pacific/ Philippines North	Production	Råberg et al. 2003	10 - 100	short	-	10	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Acropora millepora*	Pacific/ GBR North Central	settlement	Negri et al. 2005	0.1 - 1,000	short/long	100.0	300.0	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	settlement	Negri et al. 2005	0.1 - 1,000	short/long	1000.0	none	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-1,1-dimethyl-urea (DCMU) + $(CH_3)_2CO$	adult	*Seriatopora hystrix*	Pacific/ GBR South	symbiont density	Jones 2004	1 - 60	long	-	10.0	-
Pesticide	Diuron	Diuron + C_2H_6O	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	symbiont density	Negri et al. 2005	0.1 - 1,000	short/long	1.0	10.0	-
Pesticide	Diuron	3-(3,4-dichloro-phenyl)-	adult	*Seriatopora hystrix*	Pacific/ GBR South	symbiont density	Jones 2004	1 - 60	short	-	30.0	-

		1,1-dimethyl-urea (DCMU) + $(CH_3)_2CO$										
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora valida*	Pacific/ GBR North Central	tissue mortality	Cantin et al. 2007	1 - 10	long	1.0	10.0	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Acropora tenuis*	Pacific/ GBR North Central	tissue mortality	Cantin et al. 2007	1 - 10	long	10.0	none	-
Pesticide	Diuron	lab grade diuron (98% N'-(3,4-dichloro-phenyl)-N,N-dimethyl-urea)	adult	*Pocillopora damicornis*	Pacific/ GBR North Central	tissue mortality	Cantin et al. 2007	1 - 10	long	10.0	none	-
Pesticide	Endosulfan	Endosulfan stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	bleaching	Markey et al. 2007	1 - 10	short	1	10	-
Pesticide	Endosulfan	Endosulfan stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	effective quantum yield	Markey et al. 2007	1 - 10	short	1	10.0	-
Pesticide	Endosulfan	Endosulfan stock sol. with filtered	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	30.0	none	-

		seawater using 0.1% acetone										
Pesticide	Endosulfan	Endosulfan stock sol. with filtered seawater using 0.1% acetone	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	0.3	1.0	1 +/- 3
Pesticide	Endosulfan	Endosulfan stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	symbiont density	Markey et al. 2007	10	short	10.0	none	-
Pesticide	Endosulfan	Endosulfan stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tentacular activity	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Endosulfan	Endosulfan stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tissue mortality	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Glyphosate	$C_3H_8NO_5P$	adult	*Acropora muricata*	Pacific/ Vietnam South	bleaching	Amid et al. 2018	108 - 10,800	long	6000.0	10,800 *when combined with temp. stress	-
Pesticide	Glyphosate	$C_3H_8NO_5P$	adult	*Acropora muricata*	Pacific/ Vietnam South	chlorophyll-a concentration	Amid et al. 2018	108 - 10,800	long	6000.0	10,800 *when combined with temp. stress	-
Pesticide	Hexazinone	Hexazinone (99.5%)	adult	*Acropora millepora*	Pacific/ GBR North Central	chlorophyll-a concentration	Negri et al. 2011	3.8	short	3.8	none	-
Pesticide	Hexazinone	Hexazinone (99.5%)	adult	*Acropora millepora*	Pacific/ GBR North Central	effective quantum yield	Negri et al. 2011	0.3 - 1,000	short	1.0	3.0	14.0
Pesticide	Hexazinone	3-cyclohexyl-6-(dimethylamino)-1-	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	1.0	3.0	8.8 +/- 1.0

		methyl-1,3,5-triazine-2,4(1H,3H)-dione										
Pesticide	Hexazinone	Hexazinone (99.5%)	adult	*Acropora millepora*	Pacific/ GBR North Central	maximum quantum yield	Negri et al. 2011	0.3 - 1,000	short	1.0	3.0	- (EC_{10}: 3.1)
Pesticide	Ionynil	4-hydroxy-3,5-diiodo-benzonitrile	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	1000.0	none	>1000
Pesticide	Irgarol 1051	*N*-cyclopropyl-*N'*-(1,1-dimethyl-ethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine	adult	*Acropora muricata*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	-	0.3	0.9 +/- 0.2
Pesticide	Irgarol 1051	*N*-cyclopropyl-*N'*-(1,1-dimethyl-ethyl)-6-(methylthio)-1,3,5-triazine-2,4-diamine	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	-	0.3	0.7 +/- 0.03
Pesticide	Naled	Dibrom conc. (78% naled)	juv.	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	juvenile survival	Ross et al. 2015	0.56 - 9.59	short	9.6	none	-
Pesticide	Naled	Dibrom conc. (78% naled)	larvae	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	larval survival	Ross et al. 2015	0.56 - 9.59	short	-	0.6	-
Pesticide	Naled	Dibrom conc. (78% naled)	larvae	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	settlement	Ross et al. 2015	0.56 - 9.59	short	9.6	none	-
Pesticide	Naled	Dibrom conc. (78% naled)	adult	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	symbiont density	Ross et al. 2015	0.56 - 9.59	short	9.6	none	-
Pesticide	Permethrin	Permethrin stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	bleaching	Markey et al. 2007	1 - 10	short	1	10.0	-
Pesticide	Permethrin	Permethrin stock sol.	adult	*Acropora millepora*	Pacific/ GBR North-Central	effective quantum yield	Markey et al. 2007	1 - 10	short	10.0	none	-

		with filtered seawater using 0.1% acetone										
Pesticide	Permethrin	Permethrin stock sol. with filtered seawater using 0.1% acetone	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	30.0	none	-
Pesticide	Permethrin	Permone 30/30 (30% permethrin with piperonyl butoxide)	juv.	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	juvenile survival	Ross et al. 2015	0.4 - 6.04	short	6.0	none	-
Pesticide	Permethrin	Permone 30/30 (30% permethrin with piperonyl butoxide)	larvae	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	larval survival	Ross et al. 2015	0.4 - 6.04	short	0.40	1.0	-
Pesticide	Permethrin	Permethrin stock sol. with filtered seawater using 0.1% acetone	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	0.3	1.0	1 +/- 1
Pesticide	Permethrin	Permone 30/30 (30% permethrin with piperonyl butoxide)	larvae	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	settlement	Ross et al. 2015	0.4 - 6.04	short	6.0	none	-
Pesticide	Permethrin	Permethrin stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	symbiont density	Markey et al. 2007	10	short	10.0	none	-
Pesticide	Permethrin	Permone 30/30 (30% permethrin with piperonyl butoxide)	adult	*Porites asteroides*	Atlantic/ Bahamas and Florida Keys	symbiont density	Ross et al. 2015	0.4 - 6.04	short	6.0	none	-

Pesticide	Permethrin	Permethrin stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tentacular activity	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Permethrin	Permethrin stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tissue mortality	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	bleaching	Markey et al. 2007	1 - 10	short	1	10.0	-
Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	effective quantum yield	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	egg	*Acropora millepora*	Pacific/ GBR North-Central	fertilization success	Markey et al. 2007	0.3 - 30	short	30.0	none	-
Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	larvae	*Acropora millepora*	Pacific/ GBR North-Central	settlement	Markey et al. 2007	0.1 - 300	short	0.1	0.3	0.6 +/- 2
Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	symbiont density	Markey et al. 2007	10	short	-	10.0	-

Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tentacular activity	Markey et al. 2007	1 - 10	short	-	10.0	-
Pesticide	Profenofos	Profenofos stock sol. with filtered seawater using 0.1% acetone	adult	*Acropora millepora*	Pacific/ GBR North-Central	tissue mortality	Markey et al. 2007	1 - 10	short	10.0	none	-
Pesticide	Simazine	6-chloro-*N,N'*-diethyl-1,3,5-triazine-2,4-diamine	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	10.0	30.0	150.0 +/- 7.0
Pesticide	Tebuthiu-ron	*N*-[5-(1,1-dimethyl-ethyl)-1,3,4-thiadiazol-2-yl]-*N,N'*-dimethyl-urea	adult	*Seriatopora hystrix*	Pacific/ GBR South	effective quantum yield	Jones & Kerswell 2003	0.3 - 1,000	short	3.0	10.0	175.0 +/- 7.0
Pharma-ceutical	Estrone	Estrone	adult	*Porites compressa*	Pacific/ Hawai'i East	growth	Tarrant et al. 2004	0.002	long	-	0.002	-

Table S4. Meta-analysis model specifications. The specifications used in the meta-analysis are described below including the pollutant-response combination, general specifications, model parameters, model structure, and prior distributions.

Pollutant	Coral Response	General Specifications	Model Parameter	Hierarchical Structure	Prior Distribution
Copper	**Fertilization success**	Iterations = 2000	E_0	~ 1	N(100, 10), range: 0-100
(µg L^{-1})		Warmup = 1000	E_{max}	~ 1	N(0.5, 0.2), range: 0-1
		Chains = 4	EC_{50}	~ 1 + (1 | Article / Experiment)	N(50, 10), range: 0-1000
			Lambda	~ 1 + (1 | Article / Experiment)	N(0, 10), range: 0-inf
	Larval survival	Iterations = 2000	E_0	~ 1 + (1 | Article / Experiment)	N(90, 10), range: 0-100
		Warmup = 1000	E_{max}	~ 1	N(0.5, 0.2), range: 0-1
		Chains = 4	EC_{50}	~ 1 + (1 | Article / Experiment)	N(105, 15), range: 1-1000
			Lambda	~ 1	N(0, 10), range: 0-inf
	Larval settlement	Iterations = 2000	E_0	~ 1 + (1 | Article / Experiment)	N(75, 10), range: 0-100
		Warmup = 1000	E_{max}	~ 1	N(0.5, 0.2), range: 0-1
		Chains = 4	EC_{50}	~ 1 + (1 | Article / Experiment)	N(50, 20), range: 0-200
			Lambda	~ 1	N(0, 10), range: 0-inf
	Max. Quantum Yield	Iterations = 2000	E_0	~ 1	N(0.6, 0.1), range: 0-1
		Warmup = 1000	E_{max}	~ 1	N(0.5, 0.2), range: 0-1
		Chains = 4	EC_{50}	~ 1 + (1 | Experiment)	N(350, 25), range: 0-500
			Lambda	~ 1	N(0, 10), range: 0-inf
Diuron	**Max. Quantum Yield**	Iterations = 4000	E_0	~ 1	N(0.7, 0.1), range: 0-1
(µg L^{-1})		Warmup = 1000	E_{max}	~ 1	N(0.5, 0.2), range: 0-1
		Chains = 4	EC_{50}	~ 1 + (1 | Article / Experiment)	N(50, 20), range: 0-1000
			Lambda	~ 1	N(0, 10), range: 0-inf
All Metals	**Fertilization success**	Iterations = 2000	E_0	~ 1 + (1 | Metal Type)	N(100, 10), range: 0-100
(log_{10}(µmol L^{-1}))		Warmup = 1000	E_{max}	~ 1 + (1 | Metal Type)	N(0.5, 0.2), range: 0-1
		Chains = 4	EC_{50}	~ 1 + (1 | Article / Experiment) + (1 | Metal Type)	N(2, 1), range: 0-5
			Lambda	~ 1 + (1 | Metal Type)	N(0, 10), range: 0-inf