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15 Effects of sedimentation, eutrophication, and chemical pollution on coral reef fishes

Amelia S. Wenger, Katharina E. Fabricius, Geoffrey P. Jones, and Jon E. Brodie

Increasing exposure to sediment, nutrients and chemical pollutants are threatening an estimated 25% of the world's coral reefs. This chapter reviews the direct and indirect effects of these three forms of marine pollution on the behavior, physiology, life histories, and communities of coral reef fishes, and the potential consequences of altered fish abundances for the ecology of coral reefs. Increased sediment, both in suspension and settled, can directly affect reef fishes by reducing visual and chemical cues, disrupting the feeding of planktivores and herbivores, and altering predator–prey interactions. Sublethal effects on physiological performance, including gill damage, impaired osmoregulation, and larval development may also have long-term ecological consequences for coral reef fish communities. Increased sediment and nutrient loads can also lead to algal blooms and the proliferation of macroalgae, exposing coral reef fishes to hypoxia, toxins, and degrading habitat quality. Pesticides, heavy metals and other chemical contaminants can accumulate in coral reef fishes, with as yet unknown ecological consequences. Finally, pharmaceuticals and personal care products can act as endocrine disrupters and alter behavior, and can be vectors for antibiotic-resistant bacteria. The documented effects of pollution on reef fishes suggest the potential for feedback loops, with altered fish behavior and abundances detrimentally affecting reef health. Given the rapid spread of coastal pollution, field studies on their multi-facetted effects on ecological processes in coral reefs deserve a high priority.

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Coral reefs are increasingly subject to the effects of sedimentation, eutrophication, and chemical pollution [717,783,2493]. Currently, 275 million people worldwide reside within 30 km of coral reefs [380]. Some of the greatest increases in population density and coastal development are occurring in emerging tropical economies, including those in the Coral Triangle – the global biodiversity hotspot for coral reef ecosystems [1138]. The main types of pollutants delivered into coral reefs are sediments, nutrients, pesticides (herbicides and insecticides), heavy metals, and industrial and pharmaceutical contaminants [346,380]. These pollutants can have serious consequences for coastal marine systems, already threatening an estimated 25% of the world's coral reefs [380]. Agriculture, deforestation, urbanization, port development, dredging, and mining are all contributing to coastal pollution, and all pollutant types affect at least some coral reefs globally, including coral reefs in remote locations (Table 15.1).

The direct effects of reduced water quality on the benthic communities within coral reefs have been investigated since the 1970s [e.g. 681,1535]. Nutrient enrichment from fertilizers and sewage can facilitate the spread of macroalgae and other organisms that compete with corals [786]. This has been linked to reduced coral calcification and declining coral diversity and cover [1537,2330]. Additionally, there is evidence to suggest that nutrient enrichment may enhance population outbreaks of the coral predator *Acanthaster planci* (crown of thorns) [344,785]. These outbreaks are responsible for a large proportion of coral cover loss on many Pacific reefs, including the Great Barrier Reef [632]. An increase in sediment supply can lead to increased turbidity and light attenuation, and hence reduced photosynthesis and calcification rates, and a shallower depth limit for coral reef development [783,1356]. Sedimentation can also increase the metabolic costs for mucus production and sediment removal in corals [2470], and can suppress coral recruitment and survival [117]. Herbicides from agricultural run-off can cause reduced photosynthesis and bleaching in corals [1838]. Finally, some insecticides, and heavy metals including those commonly found in antifoulants, can result in acute or chronic toxicity causing

Table 15.1 A small subsection of examples to exemplify the prevalence of pollutants on nearshore coral reefs

Suspended sediment	**Domestic and industrial run-off**
Australia [360,2721]	Indonesia [739]
Bahrain [2706]	New Caledonia [624]
United States [1871]	Sri Lanka [2061]
Deposited sediment	Zanzibar [1277]
Bahrain [2706]	**Heavy metals**
Costa Rica [559]	Australia [771]
Honduras [55]	Bermuda [1301]
Indonesia [739]	China [446]
Japan [2330]	Costa Rica [1010]
New Caledonia [624]	Cuba [950]
Sri Lanka [2061]	Fiji [1827]
Turbidity	Hong Kong [1956]
Australia [552,787]	Indonesia [2690]
Fiji [1827]	Malaysia [2504]
Thailand [2096]	Mexico [1677]
Nutrients	Micronesia [1209]
Barbados [1163]	Panama [251]
Fiji [1827]	St. Croix [682]
Honduras [55]	Thailand [445,2504]
Indonesia [739]	Venezuela [151]
Japan [2330]	**TBT**
Philippines [949]	Fiji [2756]
Thailand [2096]	Indonesia [2504]
Tonga [2756]	Malaysia [2504]
United States [1204]	Singapore [2504]
Sewage	Thailand [2453]
Belize [932]	**PAHs**
Indonesia [739]	Bermuda [1301]
Nicaragua [55]	China [2767]
Thailand [445]	Wider Caribbean Region [107]
Tonga [2756]	**Petroleum**
Zanzibar [1277]	Bermuda [1301]
Pesticides	Jamaica [2593]
Bermuda [1301]	Southeastern Caribbean Sea [1947]
China [2766]	Sri Lanka [2061]
French Polynesia [2154]	**PCBs**
Singapore [2744]	Bermuda [1301]
Zanzibar [1277]	China [2766]
	Singapore [2744]

lethal effects or long-term impacts to key biological processes of corals, such as fertilization and metamorphosis [1582,1836,1837].

The effects of reduced water quality on live corals have been used to infer indirect effects on coral-associated reef fishes, via declining habitat [1292,2160]. The link between declining coral cover and the abundance and diversity of coral-associated reef fishes has been well-studied [1288,2023,2707]. However, strong evidence from other aquatic systems points to serious direct effects of reduced water quality on fishes [558,1676,2544]. These potential direct effects have been largely ignored in the literature on coral reef fishes, yet may compound the indirect effects of habitat loss. Our understanding of these direct effects is still in its infancy, but recent studies on the effects of sediment and turbidity on reef fishes [e.g. 203,2646] raise serious concerns. To date there is very little information on the effects of sedimentation, nutrient enrichment, or chemical pollution on coral reef fishes or on the effects of simultaneous multiple stressors.

This chapter reviews the effects that arise from exposure to reduced water quality on the behavior, physiology, and populations of coral reef fishes. While there is limited data on pollutant effects on coral reef fishes, the chapter reviews studies from other aquatic environments to make predictions about the potential effects on coral reef fishes. Although this chapter reviews the effects of individual pollutants, they rarely occur alone and there will no doubt be additive, and possibly synergistic impacts resulting from exposure to multiple pollutants. This review shows the pervasiveness of pollutants in the coastal marine environment in which coral reef fishes reside, and the consequences of elevated pollutant loads on coral reef fishes. In addition, it highlights the knowledge gaps that exist in this emerging field.

FLOW ON EFFECTS OF WATER QUALITY AND HABITAT CHANGE IN STRUCTURING FISH COMMUNITIES

River loads of sediments and nutrients have increased several-fold compared to pre-industrial times in many places including the Great Barrier Reef [1389]. Increasing pollutant loads result in steeper gradients in pollutant concentrations from coastal to offshore environments [348,380]. However, rivers have always discharged sediments and nutrients into coastal marine environments, leading to natural gradients in coral reef population structures from coastal to offshore reefs. The effects of poor water quality on coral reefs and their fishes can therefore be difficult to distinguish from natural gradients or other impacts, especially where historic data are missing, making it hard to establish when coral reefs are being affected by reduced water quality.

Studies on spatial gradients in coral reef communities can contribute to our understanding of how reduced water quality can affect coral reefs, by documenting differences in cross-shelf gradients and between regions that are and are not influenced by coastal pollution (i.e. space-for-time substitution; [1957]). Several studies have shown that fish abundance, biomass, and species diversity are lower on nearshore compared to offshore sites [654,1479,2682]; and on turbid reefs compared to non-turbid reefs [444,1569]. Other fish species may increase in abundance as turbidity increases (e.g. the yellowtail hamlet *Hypoplectrus chlorurus* and sharknose goby *Elacatinus evelynae*; [170]). Fabricius *et al*. [784] reported different suites of fish species among nearshore sites with little adjacent land use when compared to sites exposed to run-off from developed catchments in the Great Barrier Reef. The study showed that almost twice as many species were likely to occur at the low impacted sites, including more coral-dependent species. Similarly, Rodgers *et al*. [2157] observed a higher diversity, abundance, and biomass of fishes on reefs adjacent to healthier watersheds. However, although these studies attribute the observed gradients in large part to water quality gradients, other environmental changes may also be important. Hence, it is difficult to disentangle natural patterns from anthropogenic effects and the indirect effects of water quality due to habitat changes from the direct effects of water quality on fishes.

SEDIMENT

Sediment input to reef environments has increased worldwide and is now a major cause of concern on many nearshore coral reefs [198,783,1389,1563]. Sediments are either suspended in the water column where they increase turbidity, or they are deposited on the substrata. In shallow waters, rates of resuspension are determined by wind and tidal forcing [1421,2721], and by the new supply of terrestrial sediments after run-off events [787]. The following sections document how suspended and deposited sediments can profoundly affect many aspects of the biology and ecology of coral reef fishes.

Suspended sediment

Suspended sediment is a major agent altering the behavior, life histories and ecology of reef fishes. Most studies on the effects of suspended sediment on coral reef fishes have focused on early life history stages of fish, which are considered particularly vulnerable [61,1178]. Wenger *et al*. [2651] experimentally established that increasing suspended sediments extended larval development time up to two-fold in the clownfish *Amphiprion percula*. In both the Caribbean [760,2387] and the Great Barrier Reef [345,1651], fish recruitment peaks during the wet season, exposing the pelagic larval stage for coastal fishes to high turbidity during sediment run-off events. Fish larvae have extremely high mortality rates [254,1178], and a prolonged pelagic larval stage may lower their recruitment success [226,1442]. Suspended sediment can also impair the ability of reef fish to find suitable habitat at settlement, through a reduced ability to detect visual and chemical cues [2646]. Settlement on unsuitable habitat has been linked to reduced fitness and increased mortality, which could lead to demographic changes [1287,1657,1787,1796].

Suspended sediment can also chronically affect coral reef fishes by impairing daily activities such as home range movement or foraging [2647,2648]. Elevated concentrations of suspended sediment, at concentrations that are regularly experienced on nearshore coral reefs, appear to reduce home range size [2648], which could lead to reduced growth, condition and survivorship through an inability to fully exploit resources [516,888,1490,1865]. Wenger *et al*. [2647] demonstrated that increased suspended sediment also reduced foraging success, growth rates, and body condition, and increased mortality in juvenile damselfish *Acanthochromis polyacanthus*. Any reduction in the visual field due to suspended sediment also has the potential to impair prey intake and growth in planktivorous fishes. One of the caveats to this study is that it did not test fish that originated in nearshore environments, and one would expect a certain level of adaptation in nearshore populations to higher concentrations of suspended sediment. Indeed, Johansen and Jones [1265] found that *Neopomacentrus bankieri*, a nearshore coral reef fish species on the Great Barrier Reef that frequently experiences elevated turbidity levels, had higher foraging success in turbid environments in comparison to species from offshore reefs. However, *N. bankieri* lost this advantage as turbidity increased even at levels that were still within the range of the turbidity it naturally experiences. The results of Johansen and Jones [1265] suggest that although nearshore coral reef fishes may be more adapted to turbid environments than their offshore counterparts, they can encounter turbidity levels that exceed their tolerance limits.

Coral reef fishes also rely heavily on chemoreception as well as visual cues for predator avoidance, so there is the potential that individuals may compensate for reduced visibility by utilizing chemical cues associated with a predator [1049]. Leahy *et al*. [1431] tested the response of *A. polyacanthus* to chemical predator cues and found the strongest anti-predator response in high turbidity conditions. In comparison, Wenger *et al*. [2649] found that when a predator can access their prey in turbid conditions, predation rates increase in moderate turbidity. This result is important as it shows that suspended sediment can lead to significant changes in mortality rates for juveniles that are already extremely vulnerable to predation [61]. Predator–prey interactions are critical in shaping the demography and community structure of coral reef fishes, therefore relatively small changes in mortality rates can lead to large differences in the number of prey individuals that reach maturity [1114,1165].

Although most studies on the effects of suspended sediment have focused on small coral reef fishes, impacts on a single species of a large-sized coral reef fish have been documented. In one experimental study, suspended sediment was found to have little impact on the food intake or growth of the grouper *Epinephelus coiodes* [108]. However, 50 mg l^{-1} of suspended sediment caused significant damage to the gill structures, including increased hyperplasia and reduced epithelium volume, which would impair oxygen uptake and cause osmoregulatory stress [108,2724]. The reduced functionality of the gills, possibly through mechanical abrasion and clogging of the gills, underscores the significance of chronically reduced water clarity for a large benthic coral reef fish. Fishes living in reduced water clarity may experience sublethal effects such as reduced gill function that may ultimately have major consequences to population function and persistence.

Deposited sediment

Although sedimentation is one of the main stressors on corals in nearshore environments, little research has been conducted on how deposited sediments interact with the ecology of coral reef fishes. Bellwood and Fulton [203] found that sediment embedded in algal turfs suppresses herbivory around Lizard Island (Great Barrier Reef), with sediment removal resulting in a 225% increase in herbivory by the five most abundant herbivorous fish species. Even slight reductions of sediment in areas with generally very little sediment caused a massive increase in feeding rates of herbivores [943]. Although these studies were conducted on coral reefs that do not experience land-based runoff, they suggest a potential ecological mechanism behind the gradient in herbivore abundances from nearshore to offshore reefs [444]. It may be that on nearshore reefs with higher levels of sedimentation, the suppression of feeding via sedimentation could result in reduced growth rates of herbivorous fishes that feed on algal turfs. In contrast, Ceccarelli *et al*. [430] found that territorial herbivorous damselfish were actually able to control the levels of sediment in their territories, thereby ensuring growth of their desired food source. It may be that sedimentation will more strongly affect roving herbivores that opportunistically discover and feed on algal turfs, whereas territorial herbivores may be more shielded due to a mechanism for removing sediment. However, if sedimentation rates are high, there could be an energetic trade-off for territorial herbivores, whereby they need to spend more energy maintaining low sedimentation rates to grow their algal farms. Much more research is needed to understand the interplay between natural and anthropogenic sedimentation rates, and their effect on foraging in herbivorous fish populations to determine if certain functional groups are more sensitive to increased sedimentation.

NUTRIENTS

Globally, the use of nitrogen and phosphorus based fertilizers has increased by more than eight- and three-fold, respectively, since 1960 and is expected to further increase two- to three-fold over the next 30 years [2493]. Nitrogen and phosphorus run-off, primarily from agriculture, has increased 6- and 8-fold since the mid-nineteenth century in the Great Barrier Reef [1389]. In Indonesia, organic pollution discharge into the South China Sea more than doubled between 1980 and 1993 [470]. The rapid growth of coastal regions has also resulted in increased discharges of sewage and effluents from animal husbandry into coastal waters. In Southeast Asia, up to 80% of the sewage enters the marine environment untreated [949]. There has also been an increasing reliance on aquaculture industry as wild fish stocks continue to decline. Aquaculture facilities tend to expose relatively small areas to high concentrations of waste and fecal matter, as up to 95% of nitrogen and 85% of phosphorus from fish feed are lost into the marine environment [2504].

Coral reefs are naturally oligotrophic environments that rapidly take up nutrients, and studies have observed a positive correlation between low levels of nutrient enrichment and fish larvae populations [410,2481]. Thorrold and McKinnon [2481] found an increase in zooplankton and ichthyoplankton associated with nutrient enriched river plumes in the Great Barrier Reef. Similarly, zooplankton increased with particulate organic matter as a result of proximity to the coast in New Caledonia [410]. The assumption in both of these studies is that the increased production of zooplankton, which is the prey item for larval fishes, will enhance survivorship of fish larvae, and subsequently boost recruitment rates. However, these studies have not established whether terrestrial run-off simply creates an ephemeral community within the river plume, or if the increased density of larval fish translates into greater adult numbers on the reef.

Although some nutrient enrichment may be beneficial for nearshore coral reef fishes, nutrient enrichment can lead to hypoxia when algal blooms are promoted [666]. Depleted oxygen levels can result in altered behavior, including increased ventilation, which increases energy demands [321]. If hypoxia persists, the abundance and distribution of fishes may change as they emigrate from the low oxygen environment [321]. The effects of hypoxic water may be particularly severe for fish eggs and larvae due to their limited ability to avoid low oxygen water and their relatively high oxygen requirements [321]. Coral reefs may be more susceptible to eutrophication as hypoxia is more prevalent in both warmer water due to elevated rates of organic decomposition and in saltwater, which has a reduced oxygen saturation level [321,435]. Severe eutrophication can lead to anoxia or "dead zones" with high levels of fish mortality [665]. Nutrient enrichment can also lead to blooms of toxic microalgae. Red tides have resulted in extensive fish mortality in Florida [318] and Oman [154]. *Gambierdiscus toxicus* and *Prorocentrum* sp., the dinoflagellates responsible for ciguatera fish poisoning, appears to be increasing, but changing in local dominance, in response to nitrification on the Great Barrier Reef [2365]. While intense algal blooms that cause mortality via anoxia or toxic exposure have obvious immediate effects on the population, chronic hypoxia or low exposure to toxic algal could be equally detrimental. Reduced growth rates from increased ventilation, decreased hatching success and larval survivorship, and the accumulation of toxins from low-level exposure are just some of the ways in which fish communities can be affected by nutrient enrichment, and it may be difficult to observe such insidious impacts [321,435,1213].

An indirect consequence of nutrient enrichment in coral reef waters is the proliferation of macroalgae that compete with corals. Herbivorous fishes are one of the main mechanisms by which macroalgal cover is kept in check, but may not be able to compensate for increased algal proliferation. Lapointe *et al*. [1418] found that nutrient enrichment increased the biomass of macroalgae in the Bahamas, while herbivory only moderated algal species composition. In contrast, Rasher *et al*. [2081] determined that herbivory was the primary mechanism in controlling macroalgal proliferation in Fiji, while nutrient enrichment had little effect. Although different systems may be controlled by herbivory or nutrient enrichment to a greater or lesser extent, there is the potential for a negative feedback loop to exist: nutrient enrichment results in increased macroalgal production, which then outcompete corals, limiting habitat for the recruits of herbivorous fishes [654,1292], which leads to further proliferation of macroalgae. The reported negative correlation between water clarity and the diversity and abundance of herbivorous fishes [444] also suggests reduced herbivory in areas of high turbidity. Evidence is therefore increasing that poor water quality (high nutrients and turbidity are often correlated) can directly affect both macroalgae and herbivorous fishes, thereby simultaneously increasing bottom-up and reducing top-down drivers.

PESTICIDES

Although pesticides have been widely reported on coral reefs (Table 15.1), there is almost no research on the biological uptake of pesticides by coral reef fishes and its ecological consequences. Exposure to pesticides is becoming more widespread in coastal ecosystems as agriculture continues to intensify [2493]. In the Caribbean in the 1990s, up to 90% of pesticides were applied incorrectly, resulting in a high proportion entering the marine environment [2538]. Although many countries have banned the use of certain pesticides such as DDT, they are still commonly used in many Southeast Asian countries [2504]. Roche *et al*. [2154] examined the accumulation of pesticides in two coral reef inhabiting fishes, the parrotfish *Chlorurus sordidus* and grouper *Epinephelus merra* in French Polynesia. They found an accumulation of pesticides in both fish, including DDT and one pesticide not ‘‘officially’’ used in French Polynesia, but the physiological implications of such accumulation remain unknown. There is increasing evidence that pesticides can disrupt reproductive function in fish although few studies have focused on coral reef species (Kroon *et al*. pers. comm.). Pesticides have been shown to inhibit the metabolism of sex hormones and impair gonad development in the freshwater fish *Channa punctata* [264], and sperm development in the freshwater catfish *Heteropneustes fossilis* [2403]. The potentially severe physiological consequences of exposure to pesticides are particularly concerning for site-attached species that may be unable to move away from contaminated environments. Larger, more mobile fish species may be able to swim away from run-off inundated with pesticides, however, a study on the seawater phase of the cutthroat trout *Oncorhynchus clarkii* showed that pesticides rendered the olfactory system unresponsive. They appeared to target acetylcholinesterase (AChE), an enzyme that regulates chemical signaling between cells in fish [1405,2490]. If fish are unable to detect pesticides using their sense of smell, they may not be able to behaviorally avoid contaminated areas, which could lead to increased exposure and risk of uptake of pesticides.

TOXIC CHEMICAL POLLUTION

Heavy metals

Heavy metals have become more common in marine environments including coral reefs as a consequence of expanding coastal development and urbanization worldwide (Table 15.1). Heavy metals originate from a variety of sources, including mining, automobile emissions, landfill leaching, manufacturing, and domestic and industrial outflows [70,2318,2504]. For example, pig farm effluents into the coastal environment in west Malaysia were found to be laden with copper and zinc, due to metal contamination of the pigs’ diet [1214]. In populated areas of Malaysia and Thailand, lead has been recorded in high concentrations, originating from leaded fuel and direct dumping of industrial and domestic waste [2318]. In Indonesia, relatively high levels of lead, cadmium, copper, tin, nickel, and iron have also been found in sediments adjacent to industrial outflows [70]. Metals from anti-fouling paints can enter the marine environment through the leaching and chipping of paint [1836,2530]. Metals leaching from anti-fouling paint, including TBT, have been recorded throughout most of Southeast Asia, particularly in areas with intense shipping activity [1308,2453] or near sites of ship groundings [1071].

Few studies exist on the effects of metal pollution on coral reef fishes, but numerous studies have been conducted in other aquatic environments. A common symptom of heavy metal exposure in fishes is immuno-suppression, leading to increased susceptibility to disease [123,1358,2763]. This link may be the main mechanism behind increased fish disease and death rates reported from some dredge sites such as Gladstone Harbour in the Great Barrier Reef World Heritage Area [1416]. Heavy metals may also impair olfaction in fishes, due to a change in the number of ciliated cells in the olfactory epithelium, and disrupt critical behaviors such as predator avoidance, social interactions and reproduction [1030,1717,2295]. Arsenic can also affect the nervous system through interference with the production of acetylcholine [265]. Like other industrial pollutants, heavy metals can disrupt the metabolism of sex hormones [1428]. As with many other pollutants, early life history stages appear to be particularly sensitive. In non-reefal environments, heavy metals have been show to accumulate in fish eggs due to their permeability, to adversely affect embryonic development by changing development rates and causing malformations, and to reduce hatching success [1253]. Although acute heavy metal exposure may have drastic consequences [1213,2490,2504], the effects of chronic exposure to lower levels of heavy metals on coral reef fishes remain to be determined. However, behavioral changes in the Atlantic silverside (*Menidia menidia*) brought on by heavy metal exposure, including unnecessary schooling and hyperactivity in larvae, suggest that low-level exposure to heavy metals may decrease the effectiveness of schooling activity, potentially leaving larvae and new recruits more prone to predation [2295].

Industrial pollutants

Additionally to heavy metals, there is a suite of other chemicals from industrial and domestic effluents that have become increasingly prevalent in the marine environment. These include polycyclic aromatic hydrocarbons (PAHs), phenol, and polychlorinated biphenyls (PCB). PAHs are commonly attributed to fossil fuel and wood combustion, urban run-off, and emissions from motor vehicles [1170,2539]. PAHs are the toxic component of petroleum hydrocarbons, so any area that experiences oil leaking, including from commercial and recreational boats, will be vulnerable to PAH exposure [2466]. Fishes exposed to PAHs exhibit immuno-suppression, endocrine dysfunction, and reduced gonad size [1170]. Sediments contaminated with PAHs and heavy metals caused an increase in gill damage in the grouper *Epinephelus coioides*, compared to individuals exposed to uncontaminated sediment [2724]. In places with a history of industry that releases PAHs (such as Gladstone Harbour, Great Barrier Reef), continued dredging and development may be exposing coral reef fishes to PAHs [1298,1416].

Phenol is an important compound for several industrial and commercial commodities including plastic, and can be found in oil refinery effluents. It can irritate the gills and affect both the central nervous and endocrine systems of fishes [1213]. PCBs come from a variety of sources, including industrial outflows, atmospheric deposition from incineration, and leaching from dumpsites, and are therefore more common near industrial areas and large cities [2504]. Despite being banned in several places, they are still prevalent in the marine environment. The sinking rate of PCBs from the surface to deeper parts of the ocean is slower in the tropics, increasing the exposure of coral reef fishes to these contaminants [2460]. PCBs may cause significant endocrine disruption in invertebrates, fishes, birds, and mammals [591,1213]. The chronic exposure of coral reef fishes to these industrial contaminants could have major implications for population dynamics if the levels are high enough to trigger endocrine system disruption. Even at low concentrations, continuous exposure to these pollutants could leave fish vulnerable to additional stressors.

PHARMACEUTICAL AND PERSONAL CARE PRODUCTS

Pharmaceuticals and personal care products (PPCPs) have been receiving increased attention as their prevalence in the marine environment becomes more apparent [558,623]. PPCPs include synthetic estrogen, antibiotics, analgesics, antiseptics, anti-depressants, anti-inflammatory drugs, and many other everyday-use products and are, by their very nature, highly biologically active chemicals. They enter the marine environment via sewage outflows, wastewater treatment plants, and land run-off. As up to 80% of the sewage in Southeast Asia remains untreated, there is a direct pathway for PPCPs to be introduced into the marine environment [949]. Even in places where sewage is treated, wastewater treatment plants often do not remove PPCPs, due to both detection and removal difficulties [558,2641]. Aquaculture facilities and animal farms rely heavily on antibiotics [351,558] and are an important pathway for antibiotics to enter the marine environment [1128,2104].

Studies on the effects of PPCPs on fish have focused primarily on synthetic estrogen, anti-depressants, and antibiotics. As with most other marine pollutants, almost no studies exist on the effects of PPCPs on coral reef fishes, but some of their responses are likely to be similar to those observed in other aquatic systems. Synthetic estrogen can have strong endocrine disrupting effects on fish [397,2377]. Zha *et al*. [2765] demonstrated complete reproductive failure in the Chinese rare minnow *Gobiocypris rarus* when exposed to 0.2 ng l^{-1} of synthetic estrogen. This species was particularly sensitive to synthetic estrogen, however several other studies have reported reproductive abnormalities in fish living near wastewater treatment plants, including changes in steroid levels, increased hemaphrodism, and increased levels of the female egg yolk precursor, vitellogenin, in male fish [397,558]. Such profound effects on the reproductive abilities of fish will no doubt reduce the viability of populations exposed to PPCPs.

PPCPs can also work by shaping the environment around fish. For instance, the chronic, low-level addition of antibiotics into aquatic environments is a major concern due to the link to antibiotic-resistant bacteria [2398]. The effects of antibiotic contamination can occur even at levels that do not necessarily inhibit bacteria, due to their selective pressure on the bacterial communities [1128]. Additionally, raw sewage effluent can carry bacteria that are pathogenic to humans and terrestrial animals. The input of these bacteria to marine environments can create serious health concerns for fish, particularly if they are naïve to the bacteria [1128]. If fish are already experiencing pressure from the other pollutants, their immune systems could be compromised, thereby increasing their susceptibility to pathogens [1416].

One of the dangers of PPCPs is the potential for constant but subtle effects on fish population dynamics and communities, which can accumulate undetected [623]. For example, the commonly prescribed anti-depressant selective serotonin reuptake inhibitor (SSRIs), can accumulate in fish tissue [2641]. Exposure to SSRIs increased rates of nest-cleaning and aggression towards females in adult male fathead minnows, *Pimephales promelas* [2641]. Additionally their larvae had adversely affected C-start performance and slowed predator avoidance responses when exposed to SSRIs as embryos [1901]. One study on the coral reef inhabiting bluehead wrasse, *Thalassoma bifasciatum*, reported a reduced frequency of aggressive chases in treated individuals [1946]. The contrasting results of Perreault *et al*. [1946] and Weinberger and Klaper [2641] highlight the importance of studying species-specific responses of coral reef fishes, as changes in behavior due to exposure to PPCPs could have latent, but quite profound effects on populations.

DISCUSSION

This chapter provides strong evidence that increased pollution levels from expanding agricultural, industrial, and domestic development in coastal zones can have significant negative effects on fish. Though there is still a paucity of information on how pollutants directly affect coral reef fishes, studies from other aquatic systems point to a strong likelihood that coral reef fishes are increasingly vulnerable to impacts due to exposure to reduced water quality. The types of responses elicited are varied. Effects range from changes to behavior, such as reduced habitat choice and foraging success with increased turbidity and sedimentation, impairment of important functions such as osmoregulation, slowing time for development as a result of exposure to suspended sediment, to serious neurological and endocrine disruption from exposure to pesticides, heavy metals, industrial contaminants and PPCPs, to increased mortality from exposure to toxic algal blooms (Table 15.2). The long-term effects of many of these factors remain unknown, but are of serious concern for the health and persistence of nearshore coral reef fish populations.

It is notable that for some of the naturally occurring contaminants, a small increase in their presence can actually be

Table 15.2 Direct ecological effects of pollutants on fishes from multiple aquatic ecosystems. References are provided between brackets.

Suspended sediment	
Changes to larval development; reduced settlement success; reduced foraging ability; change in predator–prey interactions; gill damage	[108,1265,2646,2647,2649, 2651]
Deposited sediment	
Suppressed herbivory	[203,943]
Nutrient enrichment	
Increased density of larval fish; increased ventilation from hypoxia; emigration from low oxygen environments; fish kills from anoxia and toxic algal blooms	[318,321,665,2481]
Pesticides	
Endocrine disruption; impairment of gonad and sperm development; olfactory impairment	[264,1405,2403]
Heavy metals	
Immuno-suppression; olfactory impairment; disruption of behavior; interference with production of acetylcholine; disruption of sex hormone metabolism; embryo malformation and reduced hatching success	[123,265,1030,1253,1358,1428, 1717,2295,2504,2763]
PAHs	
Immuno-suppression, endocrine dysfunction and reduced gonad size; gill damage; bioaccumulation	[1170,2504,2539,2724]
Phenol	
Gill irritation; effects on central nervous and endocrine system; bioaccumulation	[1213,2539]
PCBs	
Endocrine disruption; bioaccumulation	[591,2504,2539]
PPCPs	
Endocrine disruption and increased hermaphrodism in male fish due to synthetic estrogen; increase in antibiotic-resistant bacteria; change in aggression and slower predator avoidance response due to SSRIs	[397,558,1128,1901,1946,2377, 2398]

beneficial for coral reef fishes. For instance, there tends to be a non-linear response to nutrient enrichment, wherein fishes may benefit from the increase in plankton from initial nutrient loading [410,2481], but ultimately show a decline in abundance as nutrient enrichment increases [2096]. Wenger *et al*. [2649] also recorded a non-linear response in predator–prey interactions in suspended sediment, with the predator benefiting from a moderate increase in suspended sediment, but experiencing reduced prey capture when the suspended sediment concentration further increased. The non-linearity in responses suggests that for some of these factors there may be a threshold level at which detrimental effects begin to occur.

Setting appropriate guidelines for pollutants, in particular more toxic pollutants, is important, but is very difficult in practice. Many chemicals and compounds persist in the environment because of extremely long half-lives, and are often continuously added from both point and non-point sources. Nearly everything that is washed off the land, including both urban and agricultural run-off, along with sewage and other waste water, has the potential to enter coastal marine ecosystems. Although laboratory-based diagnostic tests exist for many contaminants, the diverse array of potential pollutants makes it time consuming and expensive to test for the presence of all possible contaminants [1091]. However, when undertaken, analysis of river discharges using modern analytical techniques reveals the presence of thousands of organic contaminants, including PPCPs, pesticides, food additives and industrial chemicals and many are present at concentrations high enough to allow assessment of ecological risk [472]. Laboratory tests used for toxicity testing in fish often cannot be related to field toxicity because of fluctuations in concentrations as well as the interaction with multiple other stressors [1091]. These factors along with the fact that most studies examine ecotoxicity at the species level have left the ecosystem-level impacts of pollution very poorly understood [586]. Where guidelines exist, such as guidelines in Australia and the United States for acceptable levels of toxic metal exposure for fish in other aquatic systems, it is not known if the same threshold may be applied to coral reef fishes.

There are currently too few studies on the responses of coral reef fishes to most contaminants to allow for the determination of environmentally acceptable levels. Studies on suspended sediment, however, predict some thresholds. Specifically, Wenger *et al*. [2651] found that time to development in *A. percula* was altered at and above 15 mg l^{-1} suspended solids (~2.5 NTU). Wenger *et al*. [2649] and Wenger and McCormick [2648] observed decreased home range movement in *P. moluccensis* and increased predation upon *Chromis atripectoralis* at 30 mg l^{-1} suspended solids (~5 NTU). This sediment concentration corresponds well with the observed reduction in foraging that Johansen and Jones [1265] recorded at 4 NTU. Finally, Wenger *et al*. [2647,2649] saw reductions both in planktivorous foraging in *A. polyacanthus* and piscivorous foraging in *Pseudochromis fuscus* at 45 mg l^{-1} (~7.5 NTU), which is approximately the same turbidity level at which *N. bankieri* experienced impaired foraging ability [1265].

Coral reef fish species are incredibly diverse in their food preferences, foraging techniques, sensory abilities, and habitat associations, meaning that they will likely exhibit varied responses to both the type and concentration of pollutants. The majority of the species studied to date have been planktivorous species meaning that the ability to extrapolate to other functional groups may be limited. Differential responses observed for predator and prey species to suspended sediment [2649] or of different taxa to PPCPs [1946,2641] underscore the importance of assessing pollutant responses of fishes across trophic groups and size classes.

The ability to determine when a pollutant might begin to affect coral reef fishes is critical to our understanding of how to best minimize the impact of coastal development. For some of the diffuse source pollutants, such as suspended sediment, nutrients and pesticides coming from agriculture, reductions can be achieved through implementing improved agricultural management practices such as more efficient use of fertilizer [346]. In the Great Barrier Reef catchments, large-scale programs such as Reef Plan [346] have been implemented to improve land-use practices and these are now showing significant success [411]. Industrial contaminants are predominantly point source in nature and amenable to management through regulation. Because of the difficulty of detecting and removing PPCPs from waste water, management strategies for reducing PPCP input may be complex. It is clear that determining the concentrations at which some of the more toxic pollutants, such as those with endocrine disrupting properties, begin altering physiological processes in fishes is necessary to evaluate the current risks to both coral reef fish populations and the species that are consuming them.

Although the effects of sedimentation, eutrophication, and different pollutants have been considered separately here, there are likely to be additive or synergistic interactions among different pollutants that could magnify the intensity of a response to a pollutant or lower the threshold of response. For instance, sediments contaminated with PAHs and heavy metals caused an increase in gill damage in the grouper *Epinephelus coioides* compared to individuals exposed to uncontaminated sediment [2724]. Olfactory impairment from heavy metal exposure could further exacerbate a reduction of sensory perception caused by sediment [1030,2646] or immuno-suppression caused by heavy metal exposure could leave fish more vulnerable to bacteria delivered into the marine environment by sewage outflows [123,1128]. The impact of toxic chemicals is also likely to increase in response to ocean warming, as the toxicity of many toxins is positively related to temperature. For example, the LC_{50} (the concentration lethal to half the population over a certain time) for copper decreases with temperature – meaning that toxicity increases [1532]. PCBs will stay in shallow waters for longer in warmer water, meaning coral reef fishes will be exposed to them for longer [2460]. As mentioned previously, hypoxia is more prevalent in warmer water due to elevated rates of organic decomposition [321,435]. Additionally, studies on corals are starting to highlight the risk of corals to reduced water quality coupled with increased temperatures [1839,2734,2735].

In conclusion, our understanding of the effects of sedimentation, eutrophication, and chemical pollution on coral reef fishes has lagged behind, as studies on other anthropogenic disturbances have taken precedence. However, the early indications are that marine pollution has already had major impacts, both indirectly via the loss or degradation of critical habitat, and directly on short-term physiological and ecological processes. Further work is needed to understand how behavioral and physiological changes translate into longer-term impacts on population densities, reef fish biodiversity, ecosystem function, and health hazards. While studies in other aquatic systems can be instructive in predicting the likely effects on coral reef fishes, it is essential that more research focuses on coral reef fishes in their changing environment. Recent genetic work has highlighted the potential for run-off to create barriers to connectivity between populations, which could further worsen the effects of reduced water quality by impairing new recruitment into suffering populations [1829,2045]. Continued efforts to understand the complex relationship between declining water quality and reef fishes are essential to guide management actions that give maximum benefit to coastal reef fish populations, and sustain coastal reef fisheries into the future.

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