# POLLUTION OF COASTAL AREAS OF JAKARTA BAY: WATER QUALITY AND BIOLOGICAL RESPONSES

**Andreas Kunzmann[1]*, Zainal Arifin[2] and Gunilla Baum[1]**

[1]Leibniz Centre for Tropical Marine Research (ZMT). Bremen, Germany.
[2]Research Center for Oceanography. Indonesian Institute of Sciences. Jakarta, Indonesia.
*Correspondence author: <andreas.kunzmann@leibniz-zmt.de>

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**ABSTRACT**

Coastal development, growing urbanization and industrialization are the most important stressors of coral reefs worldwide. Jakarta is one of the largest megacities worldwide. The coral reefs of the Thousand Islands north of Jakarta have degraded dramatically over the last 30-40 years. While large-scale gradients (*i.e.*, regional drivers) have been extensively studied and shown shifts and declines in coral cover and composition, local drivers and their impact on spatial community composition have been neglected. The aim of our study is to investigate the spatial impact of anthropogenic stressors on local and regional scales on coral reefs north of Jakarta. Our results demonstrate that reefs in the north of the Thousand Islands are separated from the reefs in Jakarta Bay (JB), where a direct impact of Jakarta can be seen. Local anthropogenic effects rather than regional gradients have shaped a spatial patchwork of differentially degraded reefs along the nearshore islands. The main anthropogenic stressor is pollution and sedimentation rate, $NO_2$, $PO_4$ and chlorophyll-a explain over 80% of the variation. Surfactants and diesel-borne compounds from sewage and bilge water discharges are common pollutants. Responses to combinations of selected pollutant with elevated temperature (+3°C) were determined in the metabolic performance of the coral reef fish *Siganus guttatus*. During combined exposure, metabolic depression was observed. Effects of pollutants were not amplified by elevated temperature. In a study about two dominant soft coral genera, *Sarcophyton spp.* and *Nephthea spp.*, on dissolved inorganic nutrients (DIN), turbidity (NTU), and sedimentation combined with measurements of photosynthetic yield and respiratory electron system (ETS) activity water quality seems to control the relative abundance and physiology of dominant soft corals in JB. In order to reverse or prevent phase shifts from hard to soft corals, there is a need to manage the water quality better. It is concluded that the intense anthropogenic pressure from local as well as regional sources is responsible for the spatial structure and health of reefs. Therefore, improved spatial management with a focus on both local and regional stressors is needed for effective marine conservation.

**Keywords:** Benthic community composition, local stressors, spatial management, coral reefs, anthropogenic.

## Water Pollution in Jakarta Bay and the Thousand Islands

Jakarta Bay (JB) has become one of the most polluted marine water bodies in Asia (Bengen *et al.*, 2006). Various marine and coastal environmental impacts including decreased water quality, seafood contamination, depletion of fishery resources, coastal littering, land subsidence, loss of habitat as well as eutrophication and increased sedimentation rates are currently affecting the megacity of Jakarta. Directly to the north of Jakarta Bay (JB) is the island chain Kepulauan Seribu or "Thousand Islands" (Figure 1). This island chain extends up to 80 km off the coast and is directly in the expected main impact area of anthropogenic stressors originating from Jakarta. Different ecosystems including coral reefs and mangroves that are crucial for the survival of marine organisms and that form the basis for the livelihoods of local communities can be found along the islands (Arifin, 2004). However, large amounts of untreated sewage and industrial effluents with high pollutant levels are transported by several rivers directly into JB (Rees *et al.*, 1999). Many studies within the SPICE Programme have observed elevated concentrations of pollutants, especially within the bay. For instance, mercury contents in green mussels from aquaculture sites in JB had levels above the maximum allowable concentration (National Standard of Indonesia 1.0 mg/kg) and arsenic concentrations were both in green mussel as well as tuna samples above the national standard concentrations (1.0 mg/kg) (Koesmawati and Arifin, 2015). Similarly, Sindern *et al*. (2016) showed that river discharges into JB have led to an anthropogenic enrichment of heavy metals in the coastal sediments and Siregar *et al*. (2016) revealed that the concentrations of the heavy metals Hg, Cu and Cr exceed recommended values.

Thousands of people such as fishers in North Jakarta and along the Thousand Islands depend on the ecosystem goods and services provided by local coral reefs (Baum *et al*. 2016c, Figure 2). However, the extreme pollution with toxic chemicals, eutrophication and sediment load in the area, as well as overexploitation of marine resources are threatening coastal communities. According to quantitative data from the Indonesian Ministry of Marine Affairs and Fisheries, the decline of fish stocks in JB is linear to the increasing population growth in Jakarta (KKP, 2011). Coastal livelihoods, especially those that rely mainly on marine resources like in the JB/Thousand Islands complex, are vulnerable to long-term changes such as increasing pollution with toxic chemicals (Ferrol-Schulte *et al*., 2015).

This chapter summarizes our German-Indonesian joint research effort as part of the third phase of SPICE on the impacts of declining water quality on the physiology of reef organisms and communities.

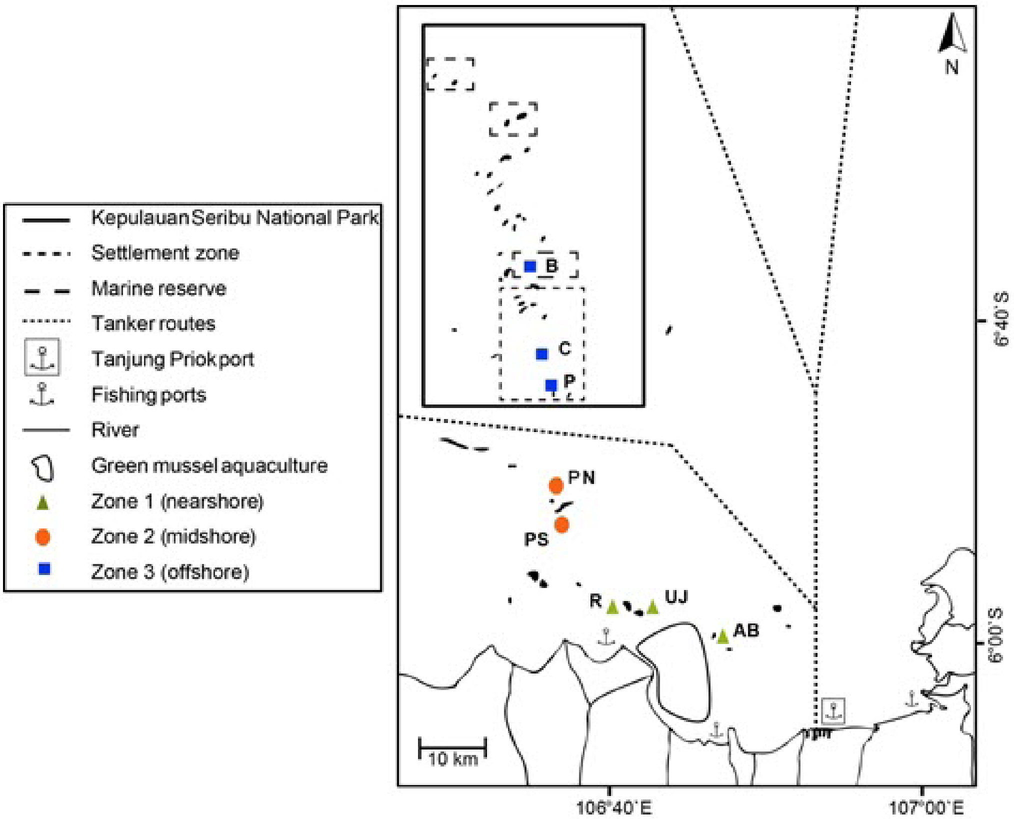


**Figure 1**. Jakarta Bay and the Thousand Islands (Indonesian: Kepulauan Seribu). Map includes study sites (Baum *et al*., 2015) from nearshore reefs (within Jakarta Bay), as well as from the outer Thousand Islands (mid- and offshore): AB = Ayer Besar, UJ = Untung Jawa, R = Rambut, PS = Pari South, PN = Pari North, P = Panggang, C = Congkak, B = Bira.

**Figure 2**. **(Left)** Fishing port in the bay of Jakarta in front of skyscrapers. **(Right)** A fisherman from the Thousand Islands.

**Biological Responses to Anthropogenic Stressors**

Local anthropogenic stressors such as pollution with toxic chemicals, eutrophication and increased sedimentation are some of the most pressing stressors on coral reefs (Fabricius, 2005; van Dam *et al*., 2011; Burke *et al*., 2012). Chemicals enter the marine environment most commonly via terrestrial runoff from rivers or through urban run-off carrying large amounts of domestic wastes and industrial effluents. These pollutants can then accumulate in marine organisms such as fish or invertebrates like corals (bioaccumulation), which can lead to various physiological impairments varying from sub-cellular changes such as direct effects on DNA to metabolic stress (see reviews by Logan, 2007; van Dam *et al*., 2011). Within the field of chemical stressors, the intensity and diversity of anthropogenic stressors have increased rapidly over the past decades. Organic contaminants such as hydrocarbons, surfactants, pesticides and herbicides as well as inorganic pollutants such as sodium cyanide mixtures used in cyanide fishing (Arifin and Hindarti, 2006), metals and organometallic compounds from industrial waste products are the most common groups (see review by van Dam *et al*., 2011).

Scientists use a wide array of different response indicators, from sub-cellular to metabolic indicators to determine stress responses in marine organisms (Logan, 2007). Stressed animals need additional energy to recover and maintain homeostasis (Calow and Forbes, 1998). The metabolism of an organism combines all processes controlling the performance of an organism in terms of behaviour, survival, growth and reproduction. By estimating the metabolic condition or fitness, *i.e*., the physiological status of changing environmental conditions, the stress level of an organism can be revealed (Fanslow *et al*., 2001; Lesser, 2013). Most commonly the oxygen consumption per unit mass as a measure of the metabolic rate is determined. A well-established and acknowledged method to estimate the metabolic rate and identify stress levels caused by *e.g.*, pollutants is respirometry (Lesser, 2013) (see Figure 3).

In general, organisms can tolerate stress to a certain extent; however, exposure to multiple stressors can pose additional threats to them and their ecosystems such as reefs. This in turn could lead to a higher sensitivity to other, additional stressors (Beyer *et al*., 2014). So far, effects of multiple stressors have mainly been assumed to be additive (Halpern *et al*., 2007). However, recent literature indicates that multiple stressors tend to interact with each other. This means that these stressors can act directly with each other, or the response of an organism to one factor can be altered by the occurrence of another (Crain *et al*., 2008). Such an interaction can be a synergism (*i.e*., amplification) such as higher UV radiation can increase negative effects of a toxin (reviewed by Pelletier *et al*., 1997). Alternatively, an antagonism (*i.e*., reduction), *e.g.*, nutrient enrichment can reduce negative effects of a second stressor, such as toxic chemicals or UV (Breitburg *et al*., 1998). Such combined effects can happen on both species levels, as well as on community or population levels (see Figure 3).

The response of coral reef communities to multiple stressors depends on different factors such as the ecosystem type, species diversity and interactions, redundancy, trophic complexity as well as the ecological history (Vinebrooke *et al*., 2004). Both temporal and spatial changes in reef community composition can be determined to evaluate how stressors affect reef communities. Most commonly surveys are used to determine factors related to biodiversity as an indicator for the stability, function, and resilience of ecosystems (*e.g.*, English *et al*., 1994; Nyström *et al*., 2008). For example, species richness or the abundances of certain benthic groups such as macroalgae, turf, corals, other macroinvertebrates, as well as of fish communities are monitored. Furthermore, species can be divided into functional groups such as predators, grazers, primary producers and habitat builders in order to see how species diversity interacts with specific ecosystem processes (Bellwood *et al*., 2003). In addition, other indicators such as whole-system productivity (production, respiration, photosynthetic yield) can also be estimated (see Figure 3).

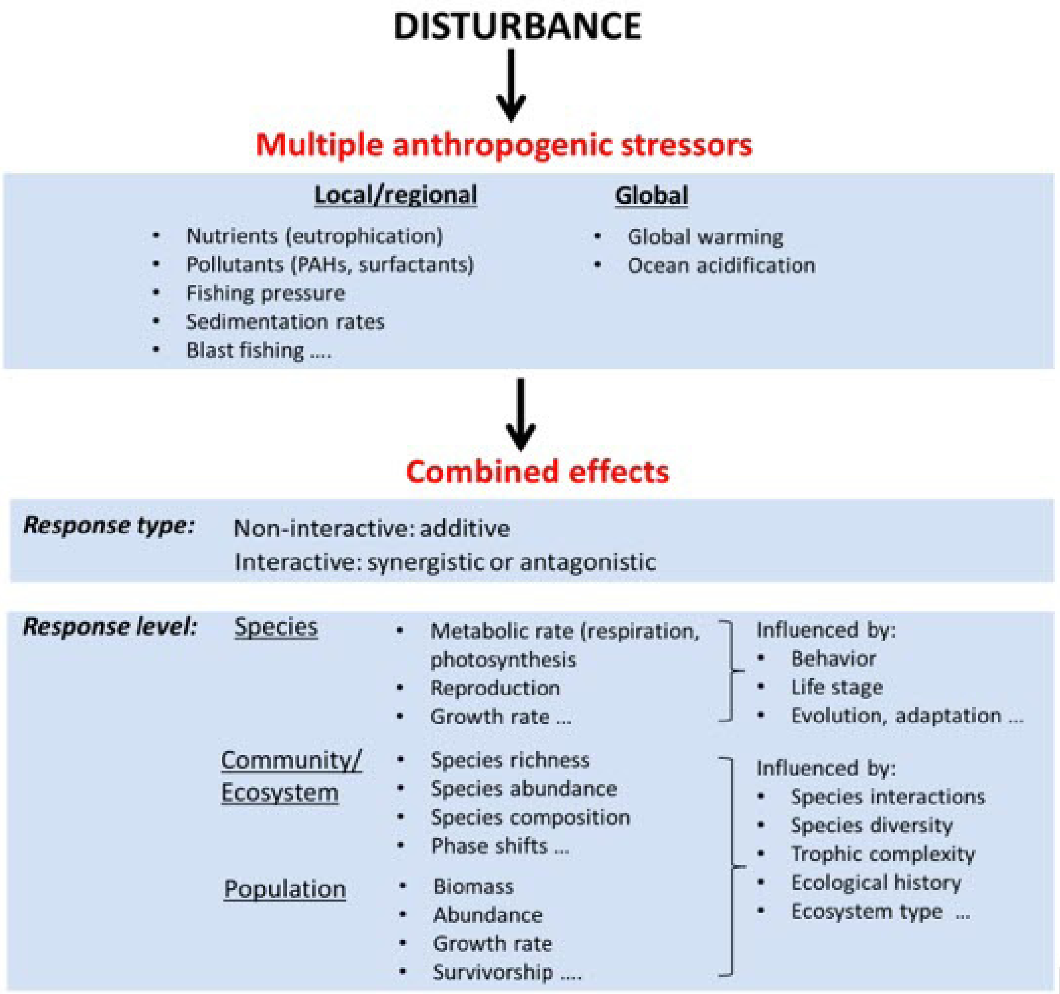


**Figure 3**. General overview of multiple anthropogenic stressors (local and global) and combined effects of these stressors including biological response types and levels.

**Local versus Regional Stressors in JB and the Thousand Islands**

In November 2012 during the transition time between northwest and southeast monsoon, a large coral reef survey was performed and eight coral reef sites across the Thousand Islands chain visited (see Figure 1). Results from this study confirm that the bay is facing extreme eutrophication coupled with increased primary production and turbidity (Baum *et al*., 2015). $PO_4$ levels in the upper layer of JB reached 4 µM/L and DIN (dissolved inorganic nutrients) levels up to 13 µM/L. Similarly, Ladwig *et al*. (2016) showed that inorganic and organic nutrient concentrations in the nearshore area of JB are highly increased. The river discharges from the urban area of Jakarta were identified as the most significant contributors to nutrient concentrations within the nearshore area of JB (Van der Wulp *et al*., 2016a). During the survey in 2012, at all sites in JB, Chl-a levels were between 5 and 15 µg/L, thus far above the Eutrophication Threshold Concentration for Chl-a of 0.2–0.3 µg/L (Bell *et al*., 2007), indicating high primary productivity. Phytoplankton bloom formations are fostered within JB and an oxygen deficiency area of 20 $km^2$ was found in the eastern part of JB (Ladwig *et al*., 2016). In addition, sites within JB had significantly higher sedimentation rates compared to offshore sites in the Thousand Islands, with up to 30 $g/m^2$ per day (Baum *et al*., 2015).

This decline in water quality, especially in JB, went hand in hand with severe changes in reef communities (Figure 4). The reef condition along the Thousand Islands has dramatically declined since the first scientists conducted investigations in the area at the beginning of the 20th century and described reef systems with high species diversity (Umgrove, 1939). In 2012, the hard coral cover was around 2% at sites within JB. But also along the outer Thousand Islands, the overall reef condition is poor since total coral cover at most sites was < 25%. Furthermore, shifts to soft coral dominance were found in the bay. Even though shifts to soft coral dominance are far less common than those to macroalgae dominance, such shifts have been reported for other degraded reefs in the Indo Pacific (Chou and Yamazato 1990; Fox *et al*., 2003). Severe changes were also found for fish communities in the area, with currently 80 % lower fish abundance in the bay compared to sites from the outer Thousand Islands (Baum *et al*., 2015).

The results from Baum *et al*. (2015) also showed a clear difference in benthic and fish communities between sites in JB and the outer Thousand Islands (see Figures 5 and 6). No clear nearshore to offshore gradients in water quality was found, suggesting that even though Jakarta is a megacity with large-scale urbanization, industry and shipping, the direct impact on shallow coral reefs may be restricted to within the bay itself. Localized effects of anthropogenic stressors rather than regional gradients appear to shape the spatial structure of reefs in the outer Thousand Islands. Furthermore, results showed that over 80% of the variation in benthic community composition was linked to factors related to terrestrial run-off and eutrophication, especially $NO_3$, sedimentation, turbidity, $PO_4$ and Chl a. This supports findings from a recent ocean-wide study that local anthropogenic stressors can

**Figure 4. (Left)** A highly degraded reef in Jakarta Bay at the island Rambut. **(Right)** A still relatively intact reef further offshore at Pari Island.

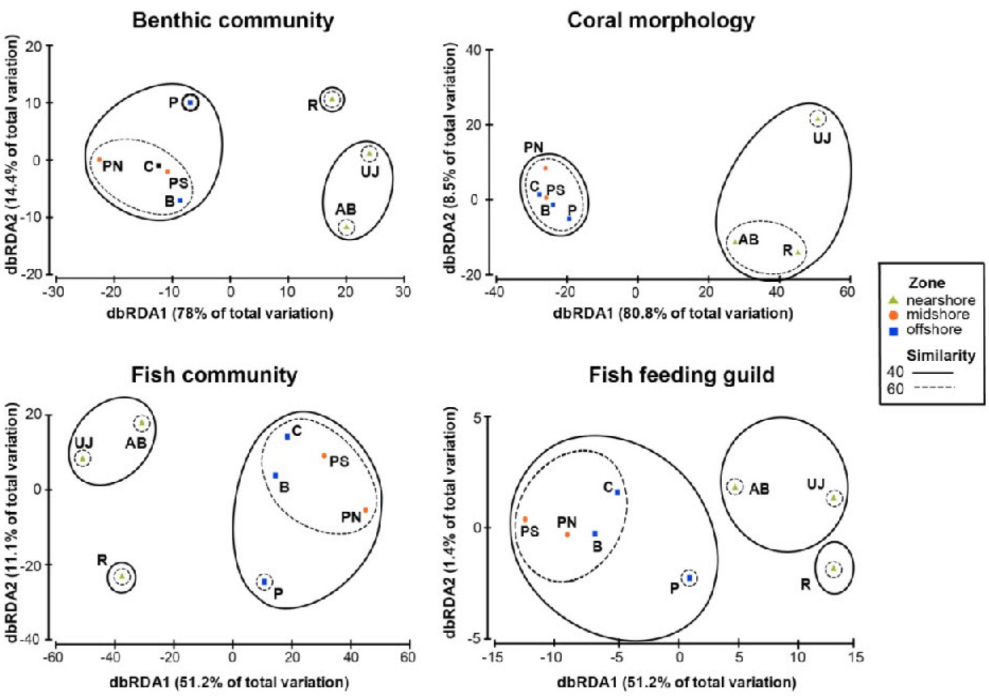


**Figure 5.** Visualization of fish and benthic community composition based on distance-based redundancy analysis (dbRDA). Benthic community composition, coral morphology composition, fish community taxonomic composition and fish feeding guild composition are shown. Study sites: AB = Ayer Besar, UJ = Untung Jawa, R = Rambut, PS = Pari South, PN = Pari North, P = Panggang, C = Congkak, B = Bira (Baum *et al*., 2015).

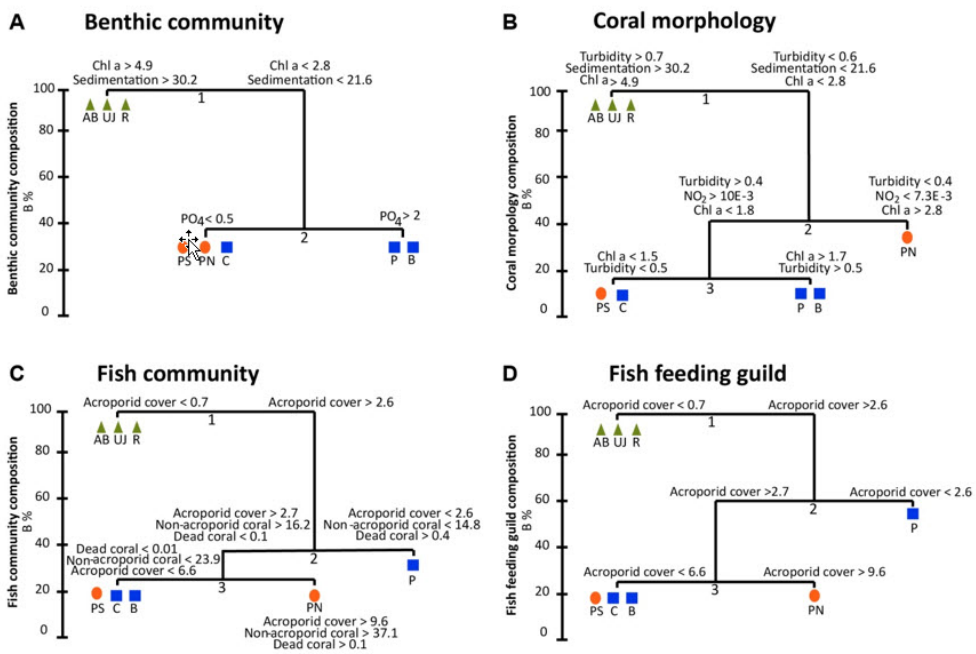


**Figure 6.** Linkage tree and associated thresholds of proximate drivers that relate to the separation of benthic community, coral morphology, fish community taxonomic and fish feeding guild composition. Thresholds at the end of each branch indicate that a left or right path respectively should be followed through the tree. Study sites: AB = Ayer Besar, UJ = Untung Jawa, R = Rambut, PS = Pari South, PN = Pari North, P = Panggang, C = Congkak, B = Bira. Zones are indicated by symbols: circle (nearshore), triangle (midshore), square (offshore) (taken from Baum *et al*., 2015).

become the dominant factors shaping benthic reef communities (Williams *et al*., 2015).

Overall, the spatial structure of reefs in the JB/ Thousand Islands reef complex is directly related to both local as well as regional anthropogenic sources. The results from all studies mentioned above show that high spatial variability in reef condition on a smaller regional scale can be found. This emphasizes the potential role of especially local stressors in shaping the structure of benthic communities in coral reefs.

**Impacts on the Physiology of Key Coral Reef Organisms**

Organic toxic pollutants are of growing concern to marine ecosystems (Logan 2007; van Dam *et al*. 2011; Arifin and Falahudin, 2017). Polycyclic aromatic hydrocarbons (PAHs) are the most widespread class of organic pollutants and some PAHs are considered to have mutagenic, carcinogenic, and endocrine-disrupting characteristics (Logan, 2007). Common sources for PAHs are combustion of organic matter at low temperatures, such as in biomass burning, forest fires, internal combustion engines and garbage incineration, as well as crude oil and petroleum products (Rinawati *et al*., 2012). In general, different hydrocarbons are released as a mixture into the marine environment (Capone and Bauer, 1992). For instance, through the release of bilge and ballast water from boats, both from large tankers and small fishing boats alike, organic contaminants such as PAHs from diesel used to fuel these boats can enter marine waters as part of the water accumulated fraction (WAF). This is of concern since many coral reefs are in proximity to shipping lanes, where contaminated bilge water is disposed off (Halpern *et al*., 2007). Besides PAHs, another ubiquitous pollutant class is surfactants, which are contained in detergents and soaps and applied by households and industries in large amounts. Notably in untreated effluents, some surfactants can be present at concentrations that may be toxic to aquatic organisms (Ankley and Burkhard 1992). The amount of linear alkylbenzenes (LABs) can be used as indicators for environments affected by sewage (Rinawati *et al*., 2012).

Other research groups within SPICE III found that especially contaminants originating from municipal wastewater discharges are present in high concentrations in JB and that higher concentrations of PAHs, as well as LABs can be found within JB (Dsikowitzky *et al*., 2016; Dwiyitno *et al*., 2016). For instance, high concentrations of PAHs and LABs were detected in green mussel and fish samples from JB (Dwiyitno *et al*., 2016). The authors also observed compound-specific accumulation, which could point to towards highly specific metabolism processes.

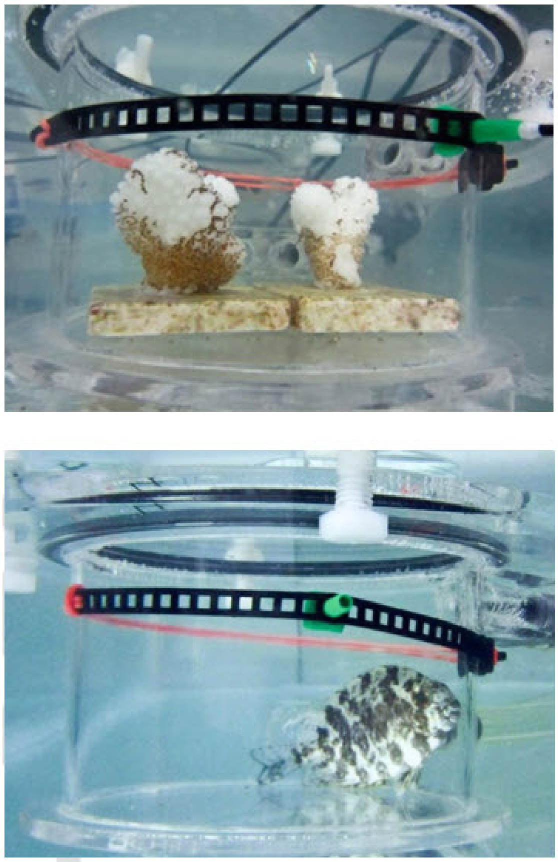

**Figure 7.** Study organisms in the experimental respiration chambers to measure their metabolic rates in response to organic pollutants. **(A)** The hard coral *Pocilopoora verrucasa*. **(B)** The herbivore coral reef fish *Siganus guttatus* (see Baum *et al*., 2016a, Kegler *et al*., 2015).

Here, results from two different physiological studies (Baum *et al*., 2016b; Kegler *et al*., 2015) are presented in which the effects of PAHs and the surfactant LAS (linear alkyl benzene sulfonate) were analyzed on key coral reef organisms (Figure 7). Results from Baum *et al*. (2016b) show that both the surfactant LAS from sewage run-off and diesel borne compounds such as PAHs from bilge water discharges are two very common local pollutants, not only within JB but also along the outer Thousand Islands due to lack of sewage treatment and high boat traffic. Short-term exposure of sublethal concentrations of WAF-D (water accumulated fraction from Diesel) and LAS caused metabolic stress to various degrees in the commercially important herbivore coral reef fish *Siganus guttatus* (Baum *et al.,* 2016a) and the hard coral *Pocillopora verrucosa* (Kegler *et al*., 2015). Exposure to WAF-D led to lower metabolic rates in *S. guttatus*, while no visible effect on the hard coral metabolism of *P.* verrucosa could be found. In contrast, LAS exposure led to a significant increase in standard metabolic rates in *S. guttatus,* indicating an increased energy demand as a result of the higher stress (Sloman *et al*., 2000). The coral *P. verrucosa* reacted to LAS with a severe tissue loss and a decreased photosynthetic efficiency. Furthermore, the experiments could show that both pollutants interacted with each other. This highlights the need to account for stressor interactions in future management and conservation plans. Under combined exposure to both WAF-D and LAS, metabolic depression was observed in *S. guttatus*. LAS led to a significantly higher PAH concentration in the water, therefore suggesting that the effect of WAF-D (decrease in respiration) may have counteracted and neutralized the effect of LAS (increase in respiration).

The local chemical stressors investigated in these two studies presented here are very likely to occur in combination with global warming (see Tables 1 and 2). Therefore, the experiments were extended and the impacts of both pollutants on the two species also investigated in combination with higher temperature. Results showed that a 3-4°C increase in temperature, reflecting predicted global warming effects for the end of this century (IPCC, 2013), caused more severe metabolic stress with regard to LAS and WAF-D toxicity for *S. guttatus* and *P. verrucosa*. However, in *S. guttatus* a synergistic, i.e., amplified reduced (WAF-D) or increased (LAS) change in metabolic rates, was not observed. Nonetheless, effects were additive during combined exposure to high temperature and LAS, which further decreased the metabolic condition of *S. guttatus*. In the coral *P. verrucosa*, the combination of WAF-D and high temperature led to an increase in dark respiration, and the combination of LAS and high temperature to severe tissue loss and subsequent high mortality.

So far, effects of both diesel or other oil products and surfactants on both corals and fish seem to be ambiguous (Maki 1979; Zaccone *et al*., 1985; DeLeo *et al*., 2015). The underlying physiochemical processes causing the toxicity of these pollutants are still barely understood. Even though the exact physiological mechanisms could not be discovered using only metabolic rates as indicators, the two studies presented here still indicate the severity of the toxicity. This could potentially have implications for fish and coral populations and communities (Johns and Miller, 1982).

Similar to this study, another study by Huhn *et al*. (2016) on the green mussel *Perna viridis*,

**Table 1.** Summary of PAH and LAS concentrations.

PAH [ΣEPA, μg/L; n = 1 or 2] and LAS [mg/L; n = 3] concentrations during the experiments, as well as under natural and short-term exposure conditions. Start and end measurements are given separately for each experimental treatment, as well as for control and elevated temperature experiments. PAH concentrations reflecting PAH background at "natural" exposure conditions were measured at different sites in Jakarta Bay (JB) and LAS concentrations in the harbor area at Pari Island. PAH concentrations reflecting short-term exposure conditions were measured after bilge water was dumped into the water and for LAS after the washing of a fishing boat. Data are means ± SD in case of n > 2 and blank corrected, except for natural exposure conditions. Detection limit for PAH samples were between 0.4 and 2 pg (see Methods section for details) and for LAS < 0.05 mg/L.

| Group | PAH [ΣEPA, μg/L] | | | LAS [mg/L] | | |
|---|---|---|---|---|---|---|
| Experiments | Control temp | Start | 490 ± 96 | Control temp | Start | 2.0 ± 0.1 |
| | | End | 434 ± 176 | | End | 1.6 ± 0.1 |
| | Elev. temp | Start | 1078 | Elev. temp | Start | 2.1 ± 0.1 |
| | | End | 604 | | End | 1.6 ± 0.1 |
| | WAF-D | Start | 394 | LAS | Start | 2.1 ± 0.1 |
| | | End | 57.7 | | End | 1.7 ± 0.1 |
| | WAF-D + LAS | Start | 585 | WAF-D + LAS | Start | 2.0 ± 0.1 |
| | | End | 811 | | End | 1.5 ± 0.1 |
| | WAF-D + temp | Start | 1078 | WAF-D + temp | Start | 2.1 ± 0.1 |
| | | End | 604 | | End | 1.6 ± 0.1 |
| Natural exposure conditions | Jakarta Bay (JB) sites | Pari Island | 10.2 | Pari island: distance to harbor | 1 m | 0.8 ± 0.1 |
| | | 1 | 99.2 | | 10 m | 0.8 ± 0.1 |
| | | 2 | 385 | | 50 m | 0.6 ± 0.1 |
| | | 3 | 227 | | 150 m (reef area) | 0 |
| | | 4 | 69.7 | | | |
| Short-term exposure conditions | Time after bilge water discharge | 30 s | 13.4 | Time after washing of boat | 30 s | 5.7 ± 0.4 |
| | | 5 min | 631 | | 5 min | 1.3 ± 0.1 |
| | | 10 min | 193 | | 10 min | 0.5 ± 0.3 |

**Table 2**. Summary of *Pocillopora verrucosa* responses.

| | Dark respiration [$mgO_2\ h^{-1}\ cm^{-2}$] | Net photosynthesis [$mgO_2\ h^{-1}\ cm^{-2}$] | Gross photosynthesis [$mgO_2\ h^{-1}\ cm^{-2}$] | Maximum quantum yield 48 h [$F_v/F_m$] | Maximum quantum yield 84 h [$F_v/F_m$] | Tissue loss after 84 h [% loss] |
|---|---|---|---|---|---|---|
| Control | 0.019 ± 0.005 | 0.008 ± 0.003 | 0.011 ± 0.003 | 0.71 ± 0.02 | 0.71 ± 0.02 | - |
| High temperature | 0.012 ± 0.003 | 0.003 ± 0.001 | 0.009 ± 0.003 | 0.74 ± 0.01 | 0.72 ± 0.01 | - |
| Diesel | 0.015 ± 0.001 | 0.006 ± 0.003 | 0.001 ± 0.003 | 0.71 ± 0.02 | 0.71 ± 0.02 | - |
| LAS | - | - | - | 0.73 ± 0.01 | | 52.5 ± 30.15 |
| Diesel + high temperature | 0.023 ± 0.003 | 0.008 ± 0.002 | 0.014 ± 0.005 | 0.74 ± 0.01 | 0.71 ± 0.01 | - |
| LAS + high temperature | - | - | - | 0.63 ± 0.13 | | 92.25 ± 7.26 |

Physiological responses of the coral holobiont for all treatments. Given are holobiont dark respiration, net and gross photosynthesis and maximum quantum yield measured after 48 h and 84 h. Maximum quantum yield after 84h and respiration in treatments containing LAS were not measured due to the separation of coral host and symbiotic algae by tissue loss. (see LAS results and discussion section). Tissue loss as seen in treatments containing LAS is given as determined at the end of the experiment.

could also show that the stress tolerance of these mussels was reduced in areas in Jakarta Bay compared to areas with less pollution (West Java). Using various indicators such as respiration, body condition index and relative shell weight, they could show that individuals from the impacted JB performed better under hypoxia than their conspecifics from the natural sites. Physiological studies such as these are highly needed to be able to assess impacts of pollution on marine organisms. While studies in the past focused primarily on pollutants such as heavy metals (*e.g.*, Guzmán and Jiménez, 1992), single PAHs (*e.g.*, Oliviera *et al*., 2008) and pesticides (*e.g.*, Richmond, 1993), lesser studied pollutants such as surfactants and WAF-D should also be in the focus of future studies. Especially, considering the frequency and amount of bilge water discharge and untreated sewage run-off in the JB/Thousand Islands complex and all over Indonesia, these two pollutants may be a regional problem rather than a local problem for marine organisms. Moreover, the two studies also highlight that to avoid long-term effects on fish and coral health the import of these pollutants in coastal areas has to be reduced.

### Impacts on Reef Composition

Both local and regional factors interact and have caused severe reef degradation in the JB/Thousand Islands reef complex, including shifts to soft coral dominance in the bay. However, the processes involved in shifts to soft coral dominance are still poorly understood, especially to what extent soft coral abundance and physiology are influenced by declining water quality (Dinesen, 1983; Norström *et al*., 2009). Here, results from the study by Baum *et al*. (2016b) are presented in which the physiological response of soft corals in the JB/Thousand Islands reef complex was set in relation to the water pollution. The findings suggest that water quality may control abundance and physiology of dominant soft corals (*Sarcophyton sp.* and *Nephthea sp.*) in Jakarta Bay. This could in turn facilitate phase shifts from hard to soft coral dominance. The results indicate that water quality, mostly inorganic nutrient concentrations and sedimentation rates, affect photosynthetic yield and ETS activity of the two soft corals species. The abundances of both species were moreover directly linked to declining water quality. Thus the findings from this study indicate that metabolic condition in both species is affected by reduced water quality. This highlights the need to improve management of water quality in order to prevent or reverse phase shifts.

## CONCLUSION

The coral reef degradation in JB and the Thousand Islands is caused by a combination of multiple anthropogenic stressors acting simultaneously. Especially within JB, pollution has become disastrous leading to extremely degraded coral reefs. Further offshore along the Thousand Islands, reefs are in a slightly improved condition. However, the increasing threat due to overfishing, global warming, eutrophication due to highly densely populated islands and a lack of sewage treatment, as well as chemicals released from increasing shipping traffic and urban run-off from islands, will pose severe threats for those reefs in the future. Since a high spatial variability in reef condition on a regional scale was observed for the reefs of the Thousand Islands due to more localized rather than regional stressors, this has to be considered in future conservation and management plans. We conclude that the spatial structure and health of reefs is directly related to intense anthropogenic pressure from local as well as regional sources. This emphasizes the potential role of especially local stressors in shaping the structure of benthic communities in coral reefs.

**Future Implications**

Marine spatial planning that is adjusted to local conditions and takes into consideration the different spatial scales on which stressors and resource use to interact with reef communities (*Sale et al*., 2014) is an alternative to current management strategies (i.e. marine protected- and no-take areas (MPA's and NTA's; see Douvere, 2008, Wilson *et al.,* 2010). Furthermore, monitoring key biological and environmental parameters continuously over several years and across seasons is crucial for the establishment of successful management and conservation plans. Besides these reef management strategies, the involvement of local communities in reef protection is needed (Ferse *et al*., 2010). Marine awareness and local education campaigns could aid the enforcement of protection areas (Breckwoldt *et al*., 2016) and, for instance, help to change the washing habits of local fishermen and reduce WAF-D and LAS pollution in the region. Any conservation and management plan, however, will only be successful if pollution in Jakarta is reduced, e.g., by implementing sewage treatment and waste disposal plans (*Clara et al*., 2007). In Indonesia, as in most adjacent countries in South-East Asia, treatment of sewage is still largely missing (Burke et al. 2012). Reducing environmental exposure by anthropogenic stressors, *i.e.*, the initial cause of vulnerability of coastal communities will improve livelihoods of people (Ferrol-Schulte *et al*., 2015). Nevertheless, without a better understanding of impacts of combined stressors on marine organisms and underlying mechanisms (Knowlton and Jackson, 2008), these mitigation efforts and management strategies such as marine planning and conservation are however void in the end. Furthermore, current proposed projects by the Indonesian government, such as the raising of a Giant Sea Wall to reduce the annual flooding in Jakarta (Van der Wulp *et al*., 2016b) should consider the negative consequences on marine ecosystems in the area, as the seawall is likely to lead to an accumulation of pollutants and nutrients within JB. As Van der Wulp *et al*. (2016b) show based on models, municipal wastes and nutrients will lead to extremely high levels causing increased eutrophication.

As seen in the studies as mentioned earlier, chemical pollutants such as WAF-D and LAS can influence each other's toxicity for corals and fish. However, given the diversity of anthropogenic stressors present in marine environments such as the coral reefs in the JB/ Thousand Islands reef complex, it remains difficult to establish simple causal relationships between stressors and biological responses (Adams, 2005). Consequently, there is a need for more in controlled factorial experiments in the future investigating physiological and ecological stress responses of marine organisms to different pollutants simultaneously to detect possible interactions. Our studies focused on this gap in knowledge and answered the response to combinations of chemical pollutants and higher temperature. This can aid management strategies such as ocean zoning (Crowder *et al*., 2006) and change expected outcomes of conservation and management efforts. For instance, in the case of additive effects between stressors, reducing the magnitude of any stressor should lead to a reduction of the overall stress. Antagonistic stressors may create more management challenges, since all or most stressors would need to be eliminated to improve the condition of species or communities, except in cases where the antagonism is driven by a dominant stressor (*e.g.*, Folt *et al*., 1999). In contrast, synergisms may respond positively to the removal of a single stressor as long as the system has not passed a threshold into an alternative state (see review by Crain *et al*., 2008).

Increased stress such as metabolic impairment on the organism level, as seen in the short-term exposure experiments by Baum *et al*. (2016a) and Kegler *et al*. (2015), may shift responses to populations and ecosystem levels and reduce reef resilience and the potential for recovery (Hoegh-Guldberg *et al*., 2007). Trade-offs in terms of reduced survival, fitness and growth of individuals are very likely (Calow and Forbes 1998; Van Straalen and Hoffmann, 2000). Lower reproductive output is one of the severe consequences of chronic stress (Logan, 2007; Dixson *et al*., 2014). Overall though, not only the amount of stressors a system is exposed to simultaneously but also the magnitude (*i.e*., concentrations of stressors) and frequency of exposure (*e.g*., number of times of bilge water release or sewage run-off) of each stressor will determine the stress condition of the system and lower its resilience. In the long run, the threshold for tipping points to alternate states that are often far less economically and ecologically valuable, are lowered and recovery is hampered (Hoegh-Guldberg *et al*., 2007).

Indonesia´s continuing growth in population, especially along the coast, poses severe problems for ecosystems such as coral reefs. Reef degradation due to global and local stressors will eventually cause a loss of ecosystem services that sustain millions of people (Hoegh-Guldberg *et al*., 2007; Burke *et al*., 2012). Any relief from stressors would help coral reefs and give them the chance to recover and provide livelihoods also for future generations. However, ocean management can no longer focus on individual stressors (Halpern *et al*., 2007) but must incorporate combined stressor effects. Combined effects of multiple stressors are still barely understood (Ban *et al*., 2014) and studies such as this one are needed to determine responses of organisms and ecosystems to these stressors. While these are considerable challenges, complacency is not an option. Tackling these massive problems will require all stakeholders to work together, a pro-active government, and a reduction in corruption (Dutton, 2005; Bengen *et al*., 2006). More effective coral reef management is urgently needed, particularly when considering the importance of coral reefs for the livelihoods of millions of people in developing countries.

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