



## Sewage impacts coral reefs at multiple levels of ecological organization

Pasinee Reopanichkul<sup>a</sup>, Thomas A. Schlacher<sup>a,\*</sup>, R.W. Carter<sup>a</sup>, Suchai Worachananant<sup>b</sup>

<sup>a</sup> Faculty of Science, Health and Education, University of the Sunshine Coast, Maroochydore, Queensland Q-4558, Australia

<sup>b</sup> Department of Marine Science, Kasetsart University, Bangkok, Thailand

### ARTICLE INFO

#### Keywords:

Coral reefs  
Sewage pollution  
Nutrients  
Algae  
Reef fish

### ABSTRACT

Against a backdrop of rising sea temperatures and ocean acidification which pose global threats to coral reefs, excess nutrients and turbidity continue to be significant stressors at regional and local scales. Because interventions usually require local data on pollution impacts, we measured ecological responses to sewage discharges in Surin Marine Park, Thailand. Wastewater disposal significantly increased inorganic nutrients and turbidity levels, and this degradation in water quality resulted in substantial ecological shifts in the form of (i) increased macroalgal density and species richness, (ii) lower cover of hard corals, and (iii) significant declines in fish abundance. Thus, the effects of nutrient pollution and turbidity can cascade across several levels of ecological organization to change key properties of the benthos and fish on coral reefs. Maintenance or restoration of ecological reef health requires improved wastewater management and run-off control for reefs to deliver their valuable ecosystems services.

© 2009 Elsevier Ltd. All rights reserved.

### 1. Introduction

Coral reefs are under escalating pressure from a plethora of human stressors. Rising sea temperatures and ocean-acidification linked to climate change threaten coral reefs globally (Hoegh-Guldberg et al., 2007). At regional and local scales, other stressors such as sediment run-off, sewage pollution and fishing can cause significant impacts on reefs (Graham et al., 2008). Because coral reefs appear to be particularly susceptible to environmental change, many reefs are in poor condition or are declining in response to direct human impacts and anthropogenic changes to water quality and climatic factors (Fabricius and De'ath, 2004; Wilkinson, 2004; Fabricius, 2005; Rinkevich, 2005; Hoegh-Guldberg et al., 2007). Amongst the many stressors impacting reefs, discharge of sewage constitutes a significant pollution source in all coastal waters (Schlacher et al., 2005); it has multiple, detrimental effects on exposed organisms (Schlacher et al., 2007), and can alter key structural and functional attributes of ecosystems that are affected by wastewater loads, including corals reefs (Pastorok and Bilyard, 1985).

Anthropogenic changes to water quality on reefs are often manifested by elevated concentrations of inorganic nutrients (Fabricius, 2005). Excess nutrients can directly impair the health of corals and result in changes to whole reef communities; these changes, linked to nutrient pollution, can be multi-dimensional and often depend on the magnitude and timing of nutrient loads

and the sensitivity of the affected species (Ferrier-Pagès et al., 2000; Szmant, 2002; Fabricius and De'ath, 2004). Reported responses of reefs to nutrient stress span a wide ambit of biological effects, including: (i) local declines in coral biodiversity, (ii) low, or failure of, coral recruitment, (iii) high rates of mortality, (iv) increases in benthic macroalgae, cyanobacteria and algal blooms, (v) accelerated bioerosion, and (vi) loss of reef structure and habitat for reef-dependent organisms (Pastorok and Bilyard, 1985; Hallock et al., 1993; Szmant, 2002; Fabricius and McCorry, 2006).

Sediment loads delivered in terrestrial run-off are a main contributor to the decline of many coral reefs. High concentrations of suspended sediments mainly stress corals by smothering tissues and attenuating light (Anthony, 1999). Excess sediment damages reefs by: (i) reducing gross photosynthesis and calcification, (ii) slowing growth rate, (iii) reducing live coral cover and mean colony size, (iv) increasing the mortality of corals, and (v) inhibiting recruitment (Rogers, 1990; Riegl and Branch, 1995; Babcock and Smith, 2002; Fabricius, 2005, 2006). At the level of whole reefs, excess turbidity can result in local biodiversity loss and compressed depth zonation of corals (Dikou and van Woelk, 2006).

Coral reefs play a pivotal role in supporting communities in many coastal regions where tourism forms an important part of the economy, and they provide numerous other irreplaceable ecosystem services (Zakai and Chadwick-Furman, 2002). Conservation of reefs thus becomes paramount to protect not only their ecological values, but also to ensure that ecosystem services continue to be delivered (Graham et al., 2008); such conservation strategies need to identify threats and implement measures to mitigate them.

\* Corresponding author. Tel.: +61 7 5430 2847.

E-mail address: [tschlach@usc.edu.au](mailto:tschlach@usc.edu.au) (T.A. Schlacher).

Nutrients and suspended particles are key threats to coral reefs (Szmant, 2002; Dikou and van Woesik, 2006), and sewage and land run-off are the major sources of pollutant inputs in coastal waters (Schlacher et al., 2005). Because pollutant inputs are both localised (i.e., point source discharges) and regional (i.e., diffuse run-off), ecological responses of reefs to pollution may vary across spatial scales and change across gradients of water quality (Fabricius et al., 2005); accordingly, load abatement can operate at both local and regional scales. Given the vulnerability of corals reefs to nutrients and sediment loads and the need to mitigate these threats, it becomes critical to understand the types and magnitudes of ecological changes linked to sewage inputs and land-use changes. To this end, this paper examines how key ecological properties of coral reefs change across a water quality gradient caused primarily by localised inflows of wastewater.

## 2. Methods

### 2.1. Study site

Mu Koh Surin (Surin) was gazetted a National Park in 1981 and an Asian Heritage Site in 2003. The park is situated in the Andaman Sea, around 60 km from the coast and covers 135 km<sup>2</sup>, of which 102 km<sup>2</sup> (76%) is marine, including 8 km<sup>2</sup> of coral reef. Surin consists of five granitic islands and two exposed pinnacle rocks (Fig. 1). Tourist accommodation and facilities exist on North Surin at Chong Khad Bay and Mai Ngam Bay. In 2007, these two areas received 4196 day visitors and 17,930 tourists stayed overnight,

translating to ca. 53,790 bed nights; more tourists visit Chong Khad Bay which accounts for 60–70% of total visits.

Disposal of wastewater is an environmentally harmful practice here and in other parts of Thailand. Yet, actual data on environmental impacts are lacking for this and most other localities where sewage has been identified as a putative threat. Consequently, to test for changes in coral reef assemblages that were hypothesized to be primarily linked to sewage pollution, four bays were sampled that included two sites with expected high wastewater pollution loads, and two sites with expected low pollution loads. At Mai Ngam Bay, sewage is secondary discharged, untreated, directly to the sea. At Chong Khad Bay, sewage is secondary treated and discharged around 500 m offshore beneath a floating pier. There are no known direct point sources of wastewater inputs at the two other bays, Mae Yai and Suthep.

Surin is influenced by the south-west Monsoon (wet season) from May to October, alternating with a drier period from December to April, which is also the peak tourist season. We predicted that during the dry season spatial differences in water quality would be more pronounced when tourist numbers were high (along with sewage discharge) and diffuse land run-off was low. Conversely, differences in water quality between bays were predicted to be lower during the rainy season when diffuse land run-off is a more important nutrient and sediment source across all of the islands, irrespective of sewage inputs linked to tourist concentrations. Thus, data were collected in both the wet and dry season (peak and low tourist season) in January, May and December 2007.

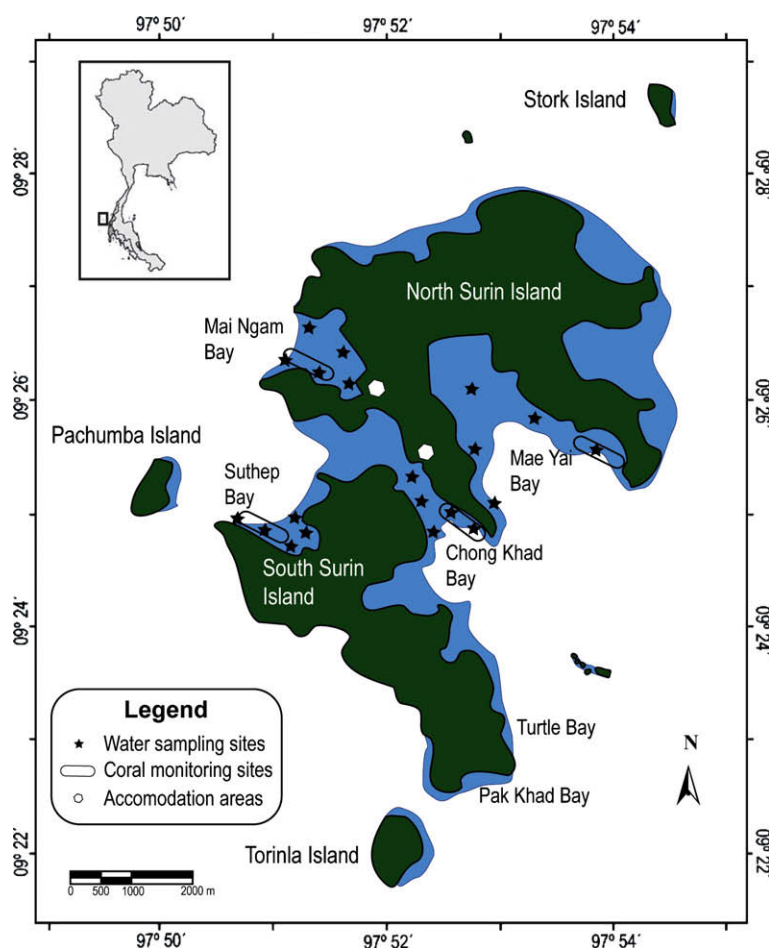


Fig. 1. Map of the study area showing sampling locations for water quality, benthic biota and fish on coral reefs in four bays of Surin National Park, Thailand.

## 2.2. Field collections

Water quality was measured at five sites within each bay at three depths (5, 10 and 15 m). During each of the three surveys (January, May and December), water quality samples in the four bays were collected over two days, covering two bays per day; a complete set of measurements and sample collections for all five sites in a bay took approximately 1.5 h. Water samples were collected with Nansen bottles and stored on ice until analysis at the Phuket Marine Biological Centre.

Benthic assemblages were surveyed with replicate line intercept transects (English et al., 1997). Categories used in the classification of the seabed were: (a) coral growth form (branching, tabulate, encrusting, massive, submassive, foliaceous), (b) algae taxa (lowest practical taxonomic level), (c) type of bare substrate (sand, rock, dead coral, coral rubble), and (d) others (e.g., soft corals, sea anemone, etc.). Corals were classified according to their susceptibility to human impacts as 'tolerant' (massive, sub-massive and encrusting), 'fragile' (branching, tabulate and foliose), and 'dead' (Worachananant, 2007).

Fish abundance and diversity were quantified using 5 m wide belt transects (English et al., 1997). Fish were identified to the lowest possible taxon, mostly the species level. Species were subsequently divided into four groups according to their feeding ecology: carnivores, herbivores, omnivores and planktivores (Randall et al., 1990). The abundance of schooling fish and those occurring in very high numbers were estimated using Log<sub>4</sub> abundance categories (English et al., 1997). To complete the survey of a fish transect required approximately 15 min, and all three depths (5, 10 and 15 m) per site were surveyed within an hour.

All transects were 50 m long, with three parallel replicate lines, spaced 3 m apart, per sampling station. Because coral reef habitats change with depth and position on the reef, line transects were replicated at 5, 10 and 15 m depth within each site; these are the standard depth zones used in coral monitoring in Thailand (Phongsuwan et al., 1993).

## 2.3. Data analysis

To obtain a composite measure of water quality across individual parameters we used the water quality index (WQI) of Fabricius et al. (2005). Individual variables (i.e., dissolved nutrient concentrations, DO, pH, turbidity) were normalized (z-score) and summed to form the compound WQI per site, depth and time (Fabricius et al., 2005). Because high values of dissolved oxygen usually indicate good water quality and vice versa, the inverse of the z-score of this variable was used in the WQI calculations. Conversely, high numeric values of dissolved nutrients and turbidity readings usually denote poorer water quality. Overall, higher values of WQI indicate turbid, nutrient-rich waters of lower DO, whereas samples of low WQI are characterised by clearer water, low in nutrients and high in oxygen (Fabricius et al., 2005).

Spatial and temporal patterns in water quality were analysed in the multivariate domain using principal component analysis (PCA) on untransformed, normalized water quality variables (Clarke and Gorley, 2006), complemented by analysis of variance (ANOVA) for univariate measures (Underwood, 1981). The ANOVA models were factorial comprising three terms: (a) bay, (b) date and (c) depth. Following significant main or interaction effects, post-hoc comparisons were performed with Student Newman Keuls (SNK) tests. Relationships between water quality, as measured by the composite WQI (Fabricius et al., 2005), and compound measures of reef assemblage structure (e.g., abundance and species richness of biota) were tested using Pearson correlations and ordinary least squares (OLS) regression models (Zar, 1996).

## 3. Results

### 3.1. Water quality impacts

Location and season strongly influenced water quality over the reefs at Surin (Table 1, Figs. 2 and 3). Sites within bays which had significant tourism development and sewage disposal to nearshore waters were characterised by a water column markedly enriched in dissolved nutrients and suspended solids, but low in dissolved oxygen (Fig. 2). By contrast, sites without known wastewater discharges or insignificant land development generally had lower nutrient concentrations, the water was clearer, and it was better oxygenated (Fig. 2). These spatial patterns in water quality support the *a priori* predictive hypothesis of deteriorated water quality as a result of land-use changes and wastewater disposal practices.

Suspended solids were particularly elevated in the developed bays during times of increased land run-off in the wet season (May '07), but remained high at these locations also during the dry season in January and December (Fig. 3e); such elevated turbidity was usually accompanied by lower dissolved oxygen levels (Fig. 3f). Dissolved reactive phosphorus had the strongest seasonal signal of the measured nutrients, increasingly strongly in the two bays receiving run-off from more developed land (Fig. 3a). Species of dissolved inorganic nitrogen showed a more variable temporal pattern, but were significantly elevated in one bay with known sewage discharges (Fig. 3).

### 3.2. Biotic responses

Variations in water quality over the reefs were accompanied by marked changes in key ecological attributes of the benthos and reef fishes (Figs. 4 and 5). Fragile forms of scleractinian corals decreased significantly in bottom cover in more nutrient-rich and turbid waters (Fig. 4a). Death of corals was observed across all sites, but it was significantly more prevalent at locations characterised by poor water quality, reaching 88% at one site (Fig. 4c); the cover of stress-tolerant scleractinia was, by contrast, not significantly correlated with water quality (Fig. 4b;  $r = -0.16$ ,  $P = 0.34$ ), nor were observed decreases in soft coral cover significant across the measured water quality gradient ( $r = -0.30$ ,  $P = 0.07$ ).

In contrast to lower coral cover in eutrophic and turbid waters, macroalgae were thriving in these conditions (Fig. 4d–f). The cover of green, brown and red macroalgae increased as water quality became poorer (Fig. 4). Not only was more of the seafloor covered with algae in eutrophic and turbid waters, but the algal assemblages also become more speciose: species richness of algae increased significantly along the water quality gradient (Chlorophyta:  $r = 0.36$ ,  $P = 0.03$ ; Phaeophyta:  $r = 0.61$ ,  $P < 0.001$ ; Rhodophyta:  $r = 0.76$ ,  $P \leq 0.001$ ).

Structural ecological changes across the water quality gradient were not only evident for the benthos (i.e., cover and composition

**Table 1**

Summary of ANOVA contrasting concentrations of dissolved inorganic nutrients (PO<sub>4</sub>, NO<sub>2</sub>, NO<sub>3</sub>, NH<sub>4</sub>) and total suspended solids (TSS) among bays, dates and depth (<sup>ns</sup> $P > 0.05$ , \* $P < 0.05$ , \*\* $P < 0.01$ , \*\*\* $P < 0.001$ ).

| Source of variation | df   | F-ratio            |                    |                    |                    |          |
|---------------------|------|--------------------|--------------------|--------------------|--------------------|----------|
|                     |      | PO <sub>4</sub>    | NO <sub>2</sub>    | NO <sub>3</sub>    | NH <sub>4</sub>    | TSS      |
| Bay                 | 2105 | 2.65 <sup>ns</sup> | 6.71***            | 11.69***           | 2.78*              | 73.74*** |
| Date                | 2105 | 7.94**             | 21.22***           | 6.04**             | 4.92**             | 90.11*** |
| Depth               | 2105 | 2.21 <sup>ns</sup> | 0.30 <sup>ns</sup> | 0.29 <sup>ns</sup> | 2.21 <sup>ns</sup> | 15.90*** |
| Bay × date          | 4105 | 1.19 <sup>ns</sup> | 3.17**             | 3.99**             | 3.47**             | 3.75**   |
| Bay × depth         | 4105 | 1.98 <sup>ns</sup> | 2.50*              | 2.33*              | 1.76 <sup>ns</sup> | 5.20***  |
| Date × depth        | 4105 | 1.54 <sup>ns</sup> | 0.46 <sup>ns</sup> | 3.42*              | 0.57 <sup>ns</sup> | 7.97***  |
| Bay × date × depth  | 8105 | 1.64 <sup>ns</sup> | 2.98**             | 2.04*              | 0.83 <sup>ns</sup> | 5.93***  |

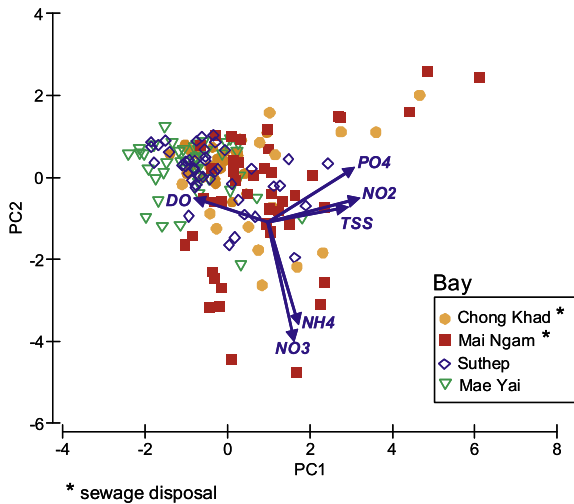


**Fig. 2.** Ordination (principal component analysis – PCA) of spatial patterns in water quality across four bays of Surin Marine Park (cf. Fig. 1); two sites (Chong Khad and Mai Ngam – marked with \*) have known direct discharges of wastewater, contrasted by two sites without known point-source inputs (Suthep, Mae Yai); all variables were normalized prior to PCA.

of corals and algae) but were also manifest for reef fishes (Fig. 4g–i). Significantly fewer individuals were recorded at sites of poorer water quality ( $r = -0.54$ ,  $P < 0.001$ ). These changes in fish

abundance in relation to water quality were evident for fishes with substantial associations with the benthos, observed in carnivores (Fig. 4g;  $r = -0.32$ ,  $P = 0.06$ ), herbivores (Fig. 4h;  $r = -0.43$ ,  $P < 0.01$ ) and omnivores (Fig. 4i;  $r = -0.42$ ,  $P = 0.01$ ). Conversely, the density of planktivorous species was not related to water quality ( $r = -0.05$ ,  $P = 0.78$ ). While the number of individuals of reef fishes declined significantly in poor-quality water, species richness of assemblages was not altered ( $r = -0.02$ ,  $P = 0.88$ ).

#### 4. Discussion

Wastewater disposal and changed land-use related to tourism activities were linked to marked spatial contrasts in water quality, and these changes in environmental conditions propagated upwards to cause significant shifts in the density and diversity of algae, cover of corals and abundance of fishes (Fig. 5). Thus, pollution produces a cascade of environmental impacts on coral reefs that impacts more than one level of ecological organization, propagating from deteriorating water quality to changes in key structural and functional components of the benthos and fish (Fig. 5).

Corals responded strongly to changes in water quality (Figs. 4 and 5). At polluted sites, tolerant coral types, which have more resistance to physical and chemical impacts (Stimson, 1985), dominated, while fragile types dominated at unpolluted sites. We also recorded a lower cover of corals at Suthep Bay which might be attributable to a massive landslide in late 2001 that increased turbidity, followed by direct physical disturbance to the reefs in the form of drifting logs and tree branches that smashed into the reef

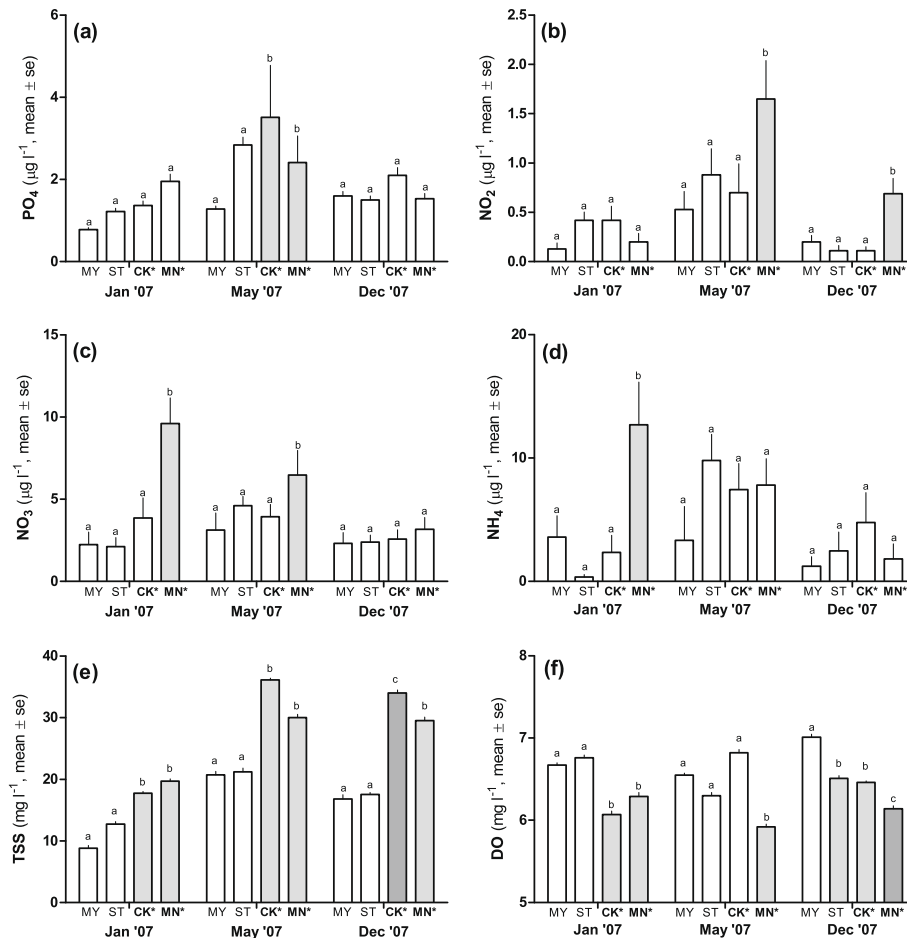
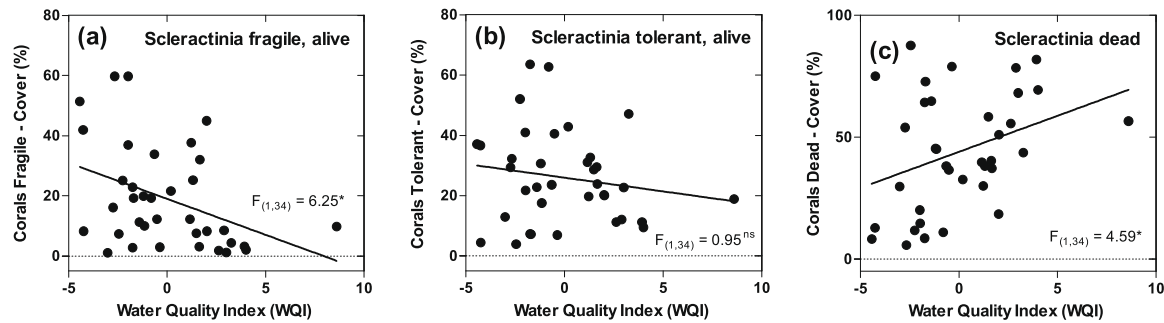
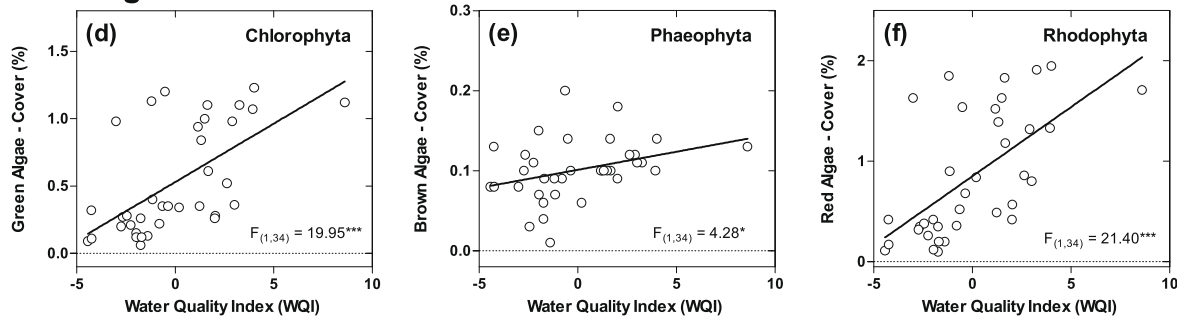


**Fig. 3.** Comparison of inorganic nutrient concentrations (a–d), total suspended solids (e) and dissolved oxygen levels (f) between bays. Sites marked with \* are those with known discharges of wastewater, derived mainly from tourism facilities (CK – Chong Khad, MN – Mai Ngam). Superscripts (a, b, c) and shading denote homogenous groups defined by SNK (Student Newman Keuls) post-hoc tests.

## Hard Coral Cover



## Macroalgae Cover



## Fish Abundance

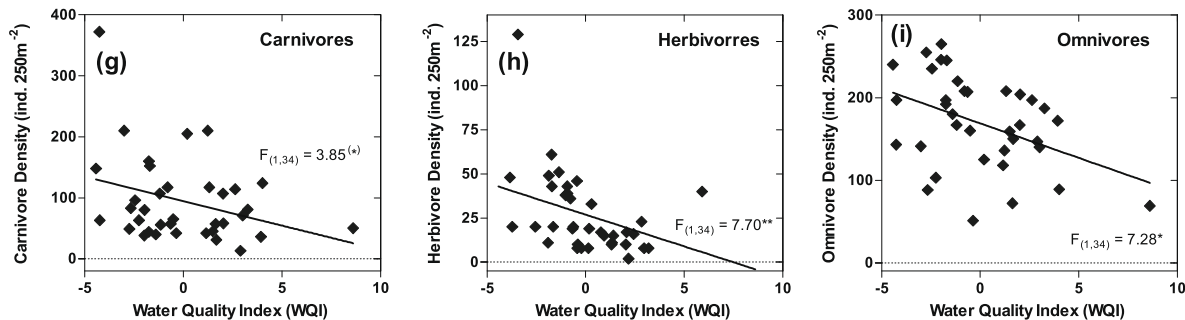


**Fig. 4.** Variation in the cover of live (a, b) and dead hard corals (c), the cover of the three main groups of macroalgae (d–f) and the abundance of fish (g–i) across a water quality gradient. Measure of water quality is the composite water quality index – WQI (Fabricius et al., 2005), where high values of WQI denote turbid and nutrient-rich waters, whereas low numeric values of WQI signify clear water and nutrient-poor conditions.

during the 2004 Tsunami (Worachananant, 2007). At Mai Ngam Bay, the cover of living coral declined from 64% in 2005 (Worachananant, 2007) to 40% in 2007, and parallels the unabated discharges of untreated sewage at this locality. While historical data are unavailable, anecdotal information suggests that Chong Khad Bay is experiencing a similar temporal trend in response to the semi-treated wastewater regularly released from the poorly maintained treatment system there. Our results of strongly decreasing cover for sensitive corals under nutrient stress concur with those from other locations where nutrient pollution was shown to result in lower cover of living coral, especially branching or fragile coral types (Brown and Holley, 1982; Worachananant, 2007); they do, however, contrast with those of Fabricius (2005) who found no change along a water quality gradient in the most sensitive genera and families.

Healthy corals are central to the structural and functional integrity of coral reefs, but are also highly susceptible to changes in the physico-chemical environment and reef community (Hoegh-Guldberg et al., 2007). Susceptibility of corals to deteriorating water quality has contributed substantially to the globally observed

declines of many reefs (Hughes et al., 2003). Such degradation of reefs has in many cases resulted in substantial changes to fish assemblages associated with reefs (Wilson et al., 2006). The response of coral-reef fishes to coral depletion can be variable, but net declines in abundance of many species are common; effects of coral loss are most severe for habitat specialists and obligate corallivores (Wilson et al., 2006).

In this study, fish abundance declined significantly with decreasing water quality (Figs. 4 and 5); it decreased from 691 individuals per 250 m<sup>2</sup> at unpolluted sites to 167 individuals per 250 m<sup>2</sup> at polluted sites. In addition, fish abundance was positively correlated with coral cover ( $r = 0.37$ ,  $P < 0.05$ ). This suggests that fish assemblages on reefs are influenced by habitat complexity and water quality (McClanahan et al., 2000; Zekeria and Videler, 2000; McClanahan et al., 2001; Able et al., 2002; Bozec et al., 2005; Fabricius et al., 2005; Nero and Sealey, 2006).

Over half (55%) of the fish species were omnivorous, 31% carnivorous, while herbivores (9%) and planktivores (5%) were less common. Most omnivores were from the family Pomacentridae which is one of the most abundant and diverse groups of tropical reef

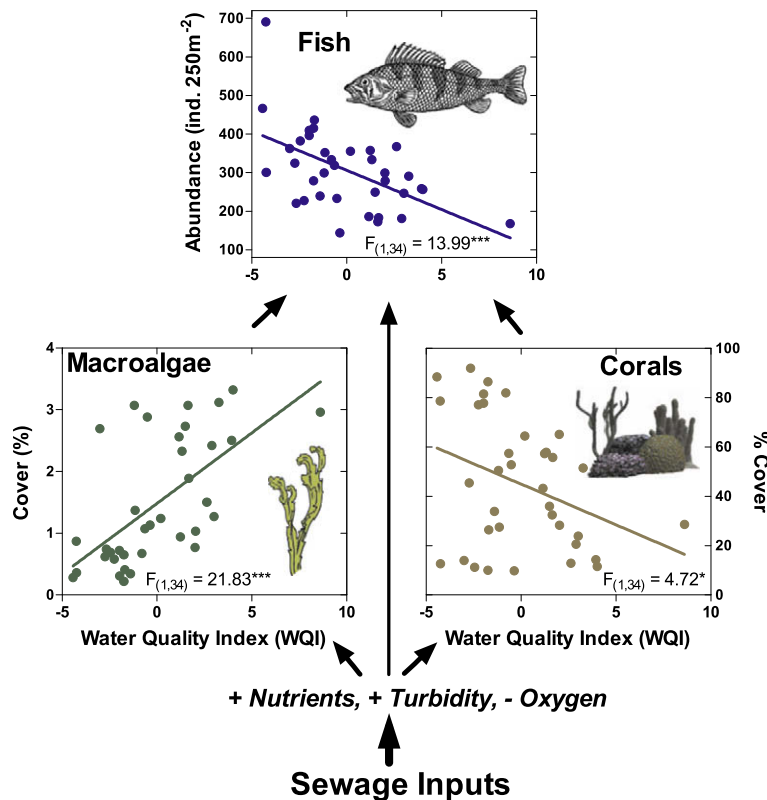


**Fig. 5.** Summary model of multiple sewage effects on coral reefs, propagating from deteriorating water quality to changes in key ecological properties of the benthos (macroalgae and coral cover) and fish abundance. Measure of water quality is the composite water quality index – WQI (Fabricius et al., 2005), where high values of WQI denote turbid and nutrient-rich waters, whereas low numeric values of WQI signify clear water and nutrient-poor conditions. Regressions are OLS (ordinary least square regressions) between the WQI and biological variables for each bay  $\times$  time  $\times$  depth combination ( $n = 36$ ), and  $F$ -statistics for tests of slopes  $\neq$  zero; \*\*\* $P < 0.001$ , \* $P < 0.05$ .

fishes (Randall et al., 1990). Carnivorous fish comprised Labridae, Serranidae, Chaetodontidae and Lutjanidae. Most herbivores were Scaridae and Acanthuridae. Abundance of all trophic groups above, which have close associations with the benthos, decreased significantly with deteriorating water quality and where the cover of corals was reduced (Figs. 4 and 5). The abundance of herbivorous fish has been shown to increase with coral cover, especially massive and branching corals (Jones and Syms, 1998; Floeter et al., 2007), and our data support this pattern (Fig. 4). Conversely, fewer herbivores were recorded at higher bottom covers of macroalgae ( $r = -0.43$ ,  $P < 0.01$ ); this may suggest that bulk food availability *per se* did not limit herbivore fish in our study. Conversely, foraging preferences may be more important because parrotfish feed preferentially on calcareous algae and sparse turfs of endolithic algae rather than larger, erect macroalgae (Bruggemann et al., 1994).

Reef disturbance that causes declines in corals often results in more algal cover, increasing the availability of trophic resources for herbivorous fishes; algal feeders are therefore expected to become more abundant on degraded reefs (Sheppard et al., 2002). However, not all herbivorous fish species show consistent increase in abundance following reef disturbance (Wilson et al., 2006). Similarly, total herbivore abundance may also respond inconsistently to changes in coral cover, ranging from significant increases (Sheppard et al., 2002) to no detectable change (Sano, 2004). Coral health and cover can also profoundly shape replenishment processes of coral reef fish communities. Reductions in coral cover have been shown to have persistent negative effects on the recruitment of coral-associated fishes, and postlarvae generally avoid dead, algal-covered colonies (Feary et al., 2007). Such recruitment-modulated effects may also partly explain why herbivorous

fishes may not respond immediately to increased supplies of dietary resources or habitat availability, because such density responses are ultimately reliant on sufficient recruitment.

Herbivores can be instrumental in controlling excess algal growth on reefs (Lewis, 1986), allowing coral recruitment on cleared patches (Hughes et al., 1992). However, if grazers are not present in sufficient numbers, algal communities will move towards more stable communities, preventing the recovery of a degraded reef to its usual coral-dominated state (McManus and Polsenberg, 2004). In fact, nutrient enrichment will affect the competitive balance between corals and algae only when herbivore pressure is significantly reduced (Jompa and McCook, 2002). We found that the cover of macroalgae increased significantly under conditions of nutrient enrichment, but this was also accompanied by lower densities of herbivorous fish (Figs. 4 and 5). Thus, the increased algal growth fuelled by elevated nutrients may have exceeded algal consumption by the fewer herbivores present.

Marine-based tourism is an important economic sector of Thailand. Surin is reputed to rank among the most diverse shallow-water reef sites in the country, and reefs are the main attraction for tourists visiting the islands. Declines in reef quality are therefore likely to have negative socio-economic consequences. Yet, here we show that wastewater discharges from tourist facilities are linked to detrimental impacts on coral reefs in the receiving waters of Surin. This situation clearly argues for improved wastewater management (e.g., tertiary treatment) and run-off control to prevent further declines in reef health which is critical for the continued provision of the multiple ecosystem services, including economic ones, delivered by coral reefs.

## Acknowledgements

We gratefully acknowledge the H.R.H. Princess Maha Chakri Sirindhorn Charity fund for providing a scholarship for this study and the assistance of Surin Marine National Park superintendents and park staff who assisted in data collection. We are also indebted to Phuket Marine Biological staff for carrying out the water quality analyses. Thanks also go to Sombat Poovachiranon and Dr Thon Thamrongnawasawat for supporting field collections and Nittakan Haemin, Suttirat Daengsakul, Parinya Limviriyakul, and the Sea Papa Team for their assistance in the field.

## References

- Able, K.W., Fahay, M.P., Heck, K.L., Roman, C.T., Lazzari, M.A., Kaiser, S.C., 2002. Seasonal distribution and abundance of fishes and decapod crustaceans in a Cape Cod estuary. *Northeastern Naturalist* 9, 285–302.
- Anthony, K.R.N., 1999. A tank system for studying benthic aquatic organisms at predictable levels of turbidity and sedimentation: case study examining coral growth. *Limnology and Oceanography* 44, 1415–1422.
- Babcock, R., Smith, L., 2002. Effects of sedimentation on coral settlement and survivorship. In: Moosa, M.K. et al. (Eds.), *Proceedings of the 9th International Coral Reef Symposium*, Bali, October 23–27, 2000, vol. 1. Ministry of Environment, Indonesian Institute of Sciences, International Society for Reef Studies, Jakarta, Indonesia, pp. 245–248.
- Bozec, Y.M., Kulbicki, M., Chassot, E., Gascuel, D., 2005. Trophic signature of coral reef fish assemblages: towards a potential indicator of ecosystem disturbance. *Aquatic Living Resources* 18, 103–109.
- Brown, B.E., Holley, M.C., 1982. Metal levels associated with tin dredging and smelting and their effect upon intertidal reef flats at Ko Phuket, Thailand. *Coral Reefs* 1, 131–137.
- Bruggemann, J.H., Van Oppen, M.J.H., Breeman, A.M., 1994. Foraging by the spotlight parrotfish *Sparisoma viride*. I. Food selection in different, socially determined habitats. *Marine Ecology Progress Series* 106, 41–55.
- Clarke, K.R., Gorley, R.N., 2006. *PRIMER v6: User Manual/Tutorial*. PRIMER-E, Plymouth, UK, p. 190.
- Dikou, A., van Woesik, R., 2006. Survival under chronic stress from sediment load: spatial patterns of hard coral communities in the southern islands of Singapore. *Marine Pollution Bulletin* 52, 1340–1354.
- English, S., Wilkinson, C., Baker, V. (Eds.), 1997. *Survey Manual for Tropical Marine Resources*. Australian Institute of Marine Science (AIMS), Townsville, Australia, p. 390.
- Fabrizius, K.E., 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Marine Pollution Bulletin* 50, 125–146.
- Fabrizius, K.E., 2006. Effects of irradiance, flow, and colony pigmentation on the temperature microenvironment around corals: implications for coral bleaching? *Limnology and Oceanography* 51, 30–37.
- Fabrizius, K.E., De'ath, G., 2004. Identifying ecological change and its causes: a case study on coral reefs. *Ecological Applications* 14, 1448–1465.
- Fabrizius, K.E., McCorry, D., 2006. Changes in octocoral communities and benthic cover along a water quality gradient in the reefs of Hong Kong. *Marine Pollution Bulletin* 52, 22–33.
- Fabrizius, K., De'ath, G., McCook, L., Turak, E., Williams, D.M., 2005. Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. *Marine Pollution Bulletin* 51, 384–398.
- Feary, D.A., Almany, G.R., McCormick, M.I., Jones, G.P., 2007. Habitat choice, recruitment and the response of coral reef fishes to coral degradation. *Oecologia* 153, 727–737.
- Ferrier-Pagès, C., Gattuso, J.P., Dallot, S., Jaubert, J., 2000. Effect of nutrient enrichment on growth and photosynthesis of the zooxanthellate coral *Stylophora pistillata*. *Coral Reefs* 19, 103–113.
- Floeter, S.R., Krohling, W., Gasparini, J.L., Ferreira, C.E.L., Zalmon, I.R., 2007. Reef fish community structure on coastal islands of the southeastern Brazil: the influence of exposure and benthic cover. *Environmental Biology of Fishes* 78, 147–160.
- Graham, N.A.J., McClanahan, T.R., MacNeil, M.A., Wilson, S.K., Polunin, N.V.C., Jennings, S., Chabanet, P., Clark, S., Spalding, M.D., Letourneur, Y., Bigot, L., Galzin, R., Ohman, M.C., Garpe, K.C., Edwards, A.J., Sheppard, C.R.C., 2008. Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. *Plos ONE* 3, 1–9.
- Hallock, P., Muller-Karger, F.E., Halas, J.C., 1993. Coral-reef decline. *National Geographic Research and Exploration* 9, 358–378.
- Hoegh-Guldberg, O., Mumby, P.J., Hooten, A.J., Steneck, R.S., Greenfield, P., Gomez, E., Harvell, C.D., Sale, P.F., Edwards, A.J., Caldeira, K., Knowlton, N., Eakin, C.M., Iglesias-Prieto, R., Muthiga, N., Bradbury, R.H., Dubi, A., Hatzioiols, M.E., 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 318, 1737–1742.
- Hughes, T.P., Ayre, D., Connell, J.H., 1992. The evolutionary ecology of corals. *Trends in Ecology and Evolution* 7, 292–295.
- Hughes, T., Baird, A., Bellwood, D., Card, M., Connolly, S., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J., Kleypas, J., Lough, J., Marshall, P., Nystroem, M., Palumbi, S., Pandolfi, J., Rosen, B., Roughgarden, J., 2003. Climate change, human impacts, and the resilience of coral reefs. *Science* 301, 929–933.
- Jompa, J., McCook, L.J., 2002. The effects of nutrients and herbivory on competition between a hard coral (*Porites cylindrica*) and a brown alga (*Lobophora variegata*). *Limnology and Oceanography* 47, 527–534.
- Jones, G.P., Syms, C., 1998. Disturbance, habitat structure and the ecology of fishes on coral reefs. *Australian Journal of Ecology* 23, 287–297.
- Lewis, S.M., 1986. The role of herbivorous fishes in the organization of a Caribbean reef community. *Ecological Monographs* 56, 183–200.
- McClanahan, T.R., Bergman, K., Huitric, M., McField, M., Elfving, T., Nystrom, M., Nordemar, I., 2000. Response of fishes to algae reduction on Glovers Reef, Belize. *Marine Ecology Progress Series* 206, 273–282.
- McClanahan, T.R., McField, M., Huitric, M., Bergman, K., Sala, E., Nyström, M., Nordemar, I., Elfving, T., Muthiga, N.A., 2001. Responses of algae, corals and fish to the reduction of macroalgae in fished and unfished patch reefs of Glovers Reef Atoll, Belize. *Coral Reefs* 19, 367–379.
- McManus, J.W., Polsenberg, J.F., 2004. Coral-algal phase shifts on coral reefs: ecological and environmental aspects. *Progress in Oceanography* 60, 263–279.
- Nero, V.L., Sealey, K.S., 2006. Fish-environment associations in the coastal waters of Andros Island, The Bahamas. *Environmental Biology of Fishes* 75, 223–236.
- Pastorok, R.A., Bilyard, G.R., 1985. Effects of sewage pollution on coral-reef communities. *Marine Ecology Progress Series* 21, 175–189.
- Phongsuwan, N., Chansang, H., Satapoomin, U., 1993. A Study and Analysis of Conditions of Coral Reefs in Marine National Parks, Andaman Sea (in Thai). Phuket Marine Biological Center, Department of Fisheries, Phuket, Thailand.
- Randall, J.E., Allen, G.R., Steen, R.C., 1990. *Fishes of the Great Barrier Reef and Coral Sea*. University of Hawaii Press, Honolulu, p. 541.
- Riegl, B., Branch, G.M., 1995. Effects of sediment on the energy budgets of four scleractinian (Bourne 1900) and five alcyonacean (Lamouroux 1816) corals. *Journal of Experimental Marine Biology and Ecology* 186, 259–275.
- Rinkevich, B., 2005. What do we know about Eilat (Red Sea) reef degradation? A critical examination of the published literature. *Journal of Experimental Marine Biology and Ecology* 327, 183–200.
- Rogers, C.S., 1990. Responses of coral reefs and reef organisms to sedimentation. *Marine Ecology Progress Series* 62, 185–202.
- Sano, M., 2004. Short-term effects of a mass coral bleaching event on a reef fish assemblage at Iriomote Island, Japan. *Fisheries Science* 70, 41–46.
- Schlacher, T.A., Liddell, B., Gaston, T.F., Schlacher-Hoenlinger, M., 2005. Fish track wastewater pollution to estuaries. *Oecologia* 144, 570–584.
- Schlacher, T.A., Mondon, J.A., Connolly, R.M., 2007. Estuarine fish health assessment: evidence of wastewater impacts based on nitrogen isotopes and histopathology. *Marine Pollution Bulletin* 54, 1762–1776.
- Sheppard, C.R.C., Spalding, M., Bradshaw, C., Wilson, S., 2002. Erosion vs. recovery of coral reefs after 1998 El Niño: Chagos Reefs, Indian Ocean. *Ambio* 31, 40–48.
- Stimson, J., 1985. The effect of shading by the table coral *Acropora hyacinthus* on understory corals. *Ecology* 66, 40–53.
- Szmant, A.M., 2002. Nutrient enrichment on coral reefs: is it a major cause of coral reef decline? *Estuaries* 25, 743–766.
- Underwood, A.J., 1981. Techniques of analysis of variance in experimental marine biology and ecology. *Oceanography and Marine Biology. An Annual Review* 19, 513–605.
- Wilkinson, C. (Ed.), 2004. *Status of Coral Reefs of the World: 2004*. Australian Institute of Marine Science, Townsville, Australia, p. 301.
- Wilson, S.K., Graham, N.A.J., Pratchett, M.S., Jones, G.P., Polunin, N.V.C., 2006. Multiple disturbances and the global degradation of coral reefs: are reef fishes at risk or resilient? *Global Change Biology* 12, 2220–2234.
- Worachananant, S., 2007. *Management Approaches in Marine Protected Areas: A Case Study of Surin Marine National Park, Thailand*. Ph.D. thesis. University of Queensland, Brisbane, Australia, p. 256.
- Zakai, D., Chadwick-Furman, N.E., 2002. Impacts of intensive recreational diving on reef corals at Eilat, northern Red Sea. *Biological Conservation* 105, 179–187.
- Zar, J.H., 1996. *Biostatistical Analysis*. Prentice Hall, Upper Saddle River, p. 662.
- Zakeria, Z.A., Videler, J.J., 2000. Correlation between the abundance of butterflyfishes and coral communities in the Southern Red Sea. In: Moosa, M.K. et al. (Eds.), *Proceedings of the 9th International Coral Reef Symposium*, Bali, October 23–27, 2000. State Ministry for the Environment, Indonesian Institute of Science, Bali, Indonesia, pp. 487–492.