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Diseases and compromised health states of massive *Porites* spp. in the Gulf of Thailand and the Andaman Sea

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Abstract

In this study, we assess coral health by detecting the severity of coral diseases and compromised health states on massive *Porites*. Field surveys are conducted at twenty-two sites covering the eastern, inner and western Gulf of Thailand as well as the Andaman Sea during 2010–2015. A total of nine coral diseases and signs of compromised health are observed in the waters of Thailand, consisting of pigmentation responses (pink lines, pink patches, pink spots and pink borers), white syndromes (white patches, white bands and ulcerative white spots), growth anomalies, and unusual bleaching patterns. The highest severity of all observed coral diseases and signs of compromised health are found at Ko Khang Khao in the inner Gulf of Thailand, while that observed in the Andaman Sea is relatively low. Composition of the diseases vary across the study sites. Four groups of study sites, in which there is an 80% similarity of diseases or signs of compromised health composition, are clustered and detected based on the Bray-Curtis similarity. The canonical analysis of principal coordinates reveal that most study sites in the Gulf of Thailand, especially the inner Gulf of Thailand, tend to show a high severity of the diseases. The association of disease severity and composition and the level of human impact are also detected. The study sites located near the shores and/or the areas with intensive tourism tend to have higher human impact, especially on poor water quality, which may be linked to the higher severity and composition of coral diseases and signs of compromised health in the Gulf of Thailand. Fish bites are also observed in many study sites. The severity of fish bites in the Gulf of Thailand is much lower compared to the Andaman Sea. Ko Rawi exhibits the highest severity, following by Ko Surin Nua and Ko Butang. The study sites within marine national park boundaries have a significantly higher severity of fish bites than those outside of the marine national park boundaries. This study suggests that higher coral diseases and signs of compromised health severity might be linked to anthropogenic disturbances on coral communities in the waters of Thailand.

Key words: coral diseases, fish bites, massive *Porites*, management, Gulf of Thailand, Andaman Sea

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1 Introduction

Competition, predation, parasitism and diseases have long been considered important elements in marine and coastal ecological processes for controlling coral populations (Jompa and McCook, 2003; Harvell et al., 2007; Myers and Raymundo, 2009). Although coral diseases are generally observed in healthy coral reef ecosystems, the outbreak of coral diseases could contribute to significant impacts on coral community structure and organization (Aronson and Precht, 2001; Sato et al., 2009; Couch et al., 2014; Ushijima et al., 2014). Coral diseases have been considered one of the major threats to global coral mortality, especially in the Caribbean region where the rapid emergence, high virulence, and widespread geographical distributions of coral diseases were reported (Weil, 2004). Many studies on coral diseases have been documented since the 2000s (Sutherland et al., 2004; Work and Meteyer, 2014). Several studies on coral diseases are also reported in the Indo-Pacific (Beeden et al., 2008; Yeemin et al., 2009; Kaczmarsky and Richardson, 2011; Weil et al., 2012). More than twenty diseases/syndromes affect corals in the Pacific, including growth anomalies, white syndrome, black band disease and pigmentation response (Voss and Richardson, 2006; Takabayashi et al., 2008; Lamb et al., 2014; Sato et al., 2016). It reports that coral diseases are increasing temporally and spatially and have reached remote reef sites (Aeby et al., 2011). Coral diseases and signs of compromised health have been linked to a combination of global and local stressors such as seasonal increases in sea surface temperature and light associated with climate change (Sato et al., 2009; Heron et al., 2010). Moreover, some studies show connections between the prevalence of coral diseases and local anthropogenic stressors, especially poor water quality such as excess nutrients, high sedimentation and low flow rates of oceanic current (Couch et al., 2014; Pollock et al., 2016; Shi et al., 2012; Shidqi et al., 2018).

The first study on coral disease in Thai waters is reported by Kenkel (2008), showing that four categories (pink line syndrome, white syndrome, black band disease, and aspergillosis) were found in eight coral genera. Preliminary studies in the inner and eastern Gulf of Thailand reveals that most massive *Porites* colonies shows coral partial mortality mainly due to the pink spot and white band syndromes. The partial mortality in coral colonies is

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also caused by the burrowing of several species of bivalves and polychaetes, and grazing of the sea urchin *Diadema setosum* (Sutthacheep et al., 2009; Yeemin et al., 2009; Donsomjit and Yeemin, 2010). Similarly, the highest disease infection of pink line syndrome is also reported in the western Gulf of Thailand (Angkhananukroh et al., 2016). In the Andaman Sea, five categories of coral diseases are observed including white syndrome, ulcerative white spot, focal bleaching, non-focal bleaching and pink spot. Also, the pink spot is found to be the most prevalent syndrome (Putchim et al., 2012). Few studies in Thailand attempted to link coral disease prevalence to anthropogenic disturbances. The disease prevalence is associated with the degree of pollution which is also varied spatially and seasonally (Kritsanapuntu and Angkhananukroh, 2014; Samsuvan et al., 2017a). Besides the pollution, recreational diving activities on coral reefs also cause a higher prevalence of coral disease due to physical injury, tissue necrosis from sediment, and non-normally pigmented coral tissues (Lamb et al., 2014). The studies in other aspects are also found, for example the study on bacterial assemblages of white plague in *Pavona duerdeni* and *Porites lutea* (Roder et al., 2014) and the histopathological investigation of white syndrome on massive *Porites* (Samsuvan et al., 2017b).

Yet, quantitative studies on coral diseases in the waters of Thailand are still limited and those previous studies were conducted only at a local scale. It is important to extend the research on a larger scale in order to obtain an overall picture of coral health through investigating coral diseases/the signs of compromised health and to enhance understanding on their spatial distribution patterns and composition as well as the association with anthropogenic disturbances. Massive *Porites* are selected in this study because they are dominant species and a major component in coral communities in both the Gulf of Thailand and the Andaman Sea. It is important to observe their health status for further establishing proper coral reef management strategies. Hence, the main purpose of this study is to assess the coral health by detecting the severity of coral diseases on massive *Porites* in the Gulf of Thailand and the Andaman Sea.

2 Materials and methods

2.1 *Study sites*

Twenty-two coral reef sites in the Gulf of Thailand and the Andaman Sea were selected covering the inner, eastern and western Gulf of Thailand and the Andaman Sea (Fig. 1, Table 1). Coral reefs in both the Gulf of Thailand and the Andaman Sea are dominant with massive *Porites* spp., especially *Porites lutea*.

The study sites in the inner Gulf of Thailand consisted of Ko Khang Khao, Ko Nok, Ko Sak, and Ko Phai. These are located near big cities and two main rivers (the Chao Phraya and the Bang Pakong River). The quality of seawater in these areas tends to have a higher concentration of sediment and nutrients. Eutrophication usually occurs during the rainy season. Ko Khang Khao is also located near main navigational routes and a large seaport. Based on our field observation, live coral covers in this region ranged from 18.34% to 37.64%.

The study sites in the eastern Gulf of Thailand consisted of Ko Samet, Ko Chan, Ko Kudi, Ko Bai Dang, Ko Thian, and Ko Kut. These are located in a boundary near the Khao Laem Ya–Mu Ko Samet National Park. Ko Samet and Ko Kudi are known to be popular tourist destinations where snorkeling is usually found. Ko Bai Dang and Ko Thian are membered in Mu Ko Chang National Park. No tourism was found in these islands. Ko Kut is located far away from the coast and has a low density of residence.

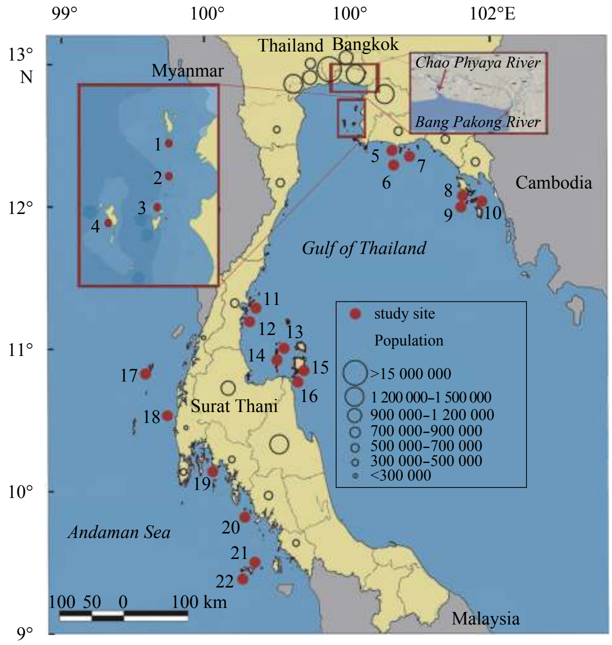

Fig. 1. Map of the study sites and population number of some areas in the Gulf of Thailand and the Andaman Sea.

Based on our field observation, live coral cover in this region ranged from 22.4% to 54.16%.

In the western Gulf of Thailand, several islands in Chumphon and Surat Thani Province were selected. Ko Mattra and Ko Rang Kachio are in Mu Ko Chumphon National Park while Ko Thai Phlao and Ko Sam Sao are in Mu Ko Ang Thong National Park. Most of the study sites have been utilized for tourism purposes. Ko Sam Sao and Ko Thai Phlao are influenced by high turbidity from the Tapi River. Ko Samui is a popular tourist destination. It is a large island with a high density of residence and lots of tourism activities. Approximately 3 km southward of Ko Samui, Ko Taen is also known as a tourism attraction. Based on our field observation, live coral cover in this region ranged from 20.68% to 74.63%.

The study sites in the Andaman Sea consist of both near and offshore sites. Had Thaimuang is located near the shore. Ko Surin Nua is in Mu Ko Surin National Park while Ko Mai Phai is in Noppharatthara Beach-Pee Pee Islands National Park. Ko Kadan is in Hat Chao Mai National Park while Ko Rawi and Ko Butang are in Tarutao National Park. These study sites are located offshore. These study sites are tourism hotspots except Had Thaimuang. Based on our field observation, live coral cover in this region ranged from 10.10% to 58.18%.

2.2 *Data collection*

Field surveys were conducted in 2011–2015. At each study site, coral diseases and signs of compromised health on massive *Porites* spp. were examined along three belt transects, 50 m×1 m each. All colonies were inspected for lesions causing any morphological tissue changes. Lesions were characterized through macroscopic observations based on the guidelines of Work and Aeby (2006) and Raymundo et al. (2008). Severities of coral diseases and signs of compromised health or fish bites were calculated and expressed as a percentage of colony area affected by diseases and signs of compromised health (Baker et al., 2007; Bruno et al., 2003).

Some environmental parameters such as salinities, visibility

Table 1. Location of the study sites and the distance from the coastal community in the Gulf of Thailand and the Andaman Sea

Regions	Study sites (number of colonies surveyed)	Sampling time	North latitude	East longitude	*D*/km
Inner Gulf of Thailand	(1) Ko Khang Khao (*n*=147)	Feb. 2011	13°06′46.30″	100°48′31.10″	9.0
	(2) Ko Nok (*n*=96)	Feb. 2011	13°01′25.78″	100°49′16.25″	7.7
	(3) Ko Sak (*n*=89)	Feb. 2011	12°56′45.64″	100°47′25.77″	9.5
	(4) Ko Phai (*n*=143)	Feb. 2011	7°48′45.41″	98°47′47.50″	21.8
Eastern Gulf of Thailand	(5) Ko Samet (*n*=162)	Feb. 2015	12°33′41.12″	101°26′53.59″	6.9
	(6) Ko Chan (*n*=113)	Feb. 2015	12°30′52.09″	101°26′32.28″	12.1
	(7) Ko Kudi (*n*=92)	Feb. 2015	12°34′52.05″	101°30′35.92″	9.1
	(8) Ko Bai Dang (*n*=173)	Feb. 2015	11°54′54.40″	102°28′14.56″	34.4
	(9) Ko Thian (*n*=226)	Mar. 2015	11°49′04.43″	102°23′46.78″	37.9
	(10) Ko Kut (*n*=148)	Mar. 2015	11°45′00.71″	102°32′41.31″	65.4
Western Gulf of Thailand	(11) Ko Mattra (*n*=239)	Jul. 2014	10°23′54.33″	99°20′49.12″	14.5
	(12) Ko Rang Kachio (*n*=228)	Jul. 2014	10°19′03.31″	99°17′56.81″	11.0
	(13) Ko Thai Phlao (*n*=99)	Apr. 2015	9°42′22.42″	99°40′33.24″	62.9
	(14) Ko Sam Sao (*n*=128)	Apr. 2015	9°39′52.28″	99°40′46.66″	58.7
	(15) Ko Samui (*n*=108)	May 2012	9°25′06.75″	99°59′56.26″	53.3
	(16) Ko Taen (*n*=158)	May 2012	9°23′06.08″	99°56′18.90″	45.2
Andaman Sea	(17) Had Thaimuang (*n*=78)	Feb. 2013	8°26′19.77″	98°13′28.27″	3.2
	(18) Ko Surin Nua (*n*=72)	Feb. 2013	9°27′17.65″	97°53′50.53″	48.8
	(19) Ko Mai Phai (*n*=115)	May 2014	7°48′51.27″	98°47′36.74″	23.5
	(20) Ko Kadan (*n*=165)	Mar. 2011	7°18′24.74″	99°15′34.36″	19.8
	(21) Ko Rawi (*n*=135)	Mar. 2011	6°32′40.27″	99°13′42.44″	65.0
	(22) Ko Butang (*n*=105)	Mar. 2011	6°31′15.09″	99°09′57.54″	83.7

Remarks: *n* represents number of colonies surveyed, and *D* distance from the coastal community.

and suspended solids were measured at each study site as well as other relevant data, i.e., number of residents on the island and the number of tourists. The number of tourists was gained by interviewing staff at the national parks and talking to local tourism operators (Table 2).

Both qualitative and quantitative information relating to site characteristics, environmental parameters and human activities were also integrated to evaluate the levels of human impact on each study site. They were evaluated to describe the association of between the severity of coral diseases and the human impact.

2.3 *Statistical analyses*

The data were tested for normality and were transformed by square root to meet the assumptions of the parametric test prior to conducting the analyses. The one-way ANOVA was used to test the influence of locations on the severity of coral diseases and

Table 2. Threats and seawater quality at each study site

Study site number	National parks	Population on the islands	Number of tourists per day	Salinity	Visibility/m	Suspended solids /mg·L^{-1}	Depth/m
1	outside	0	0	28.83	1.1	27.69	2–4
2	outside	0	0	30.63	1.3	18.65	2–4
3	outside	0	0	29.32	1.3	17.54	2–5
4	outside	0	0	31.21	3.6	12.84	2–5
5	inside	2 500	150	33.23	2.4	13.56	2–4
6	inside	0	0	32.77	3.6	9.94	3–6
7	inside	0	150	32.84	2.0	7.96	2–4
8	inside	0	0	32.12	2.1	9.75	2–4
9	inside	0	0	32.28	6.7	5.38	3–6
10	outside	1 874	0	33.70	3.4	7.25	3–6
11	inside	0	50	34.30	3.4	12.56	2–4
12	inside	0	100	34.77	4.5	8.49	2–4
13	inside	0	50	33.86	1.3	12.54	2–4
14	inside	0	0	33.80	1.0	10.34	2–4
15	outside	65 847	0	32.11	1.5	14.34	2–4
16	outside	75	50	32.20	1.7	12.95	2–4
17	inside	0	0	32.85	2.3	9.86	3–5
18	inside	0	0	33.14	10.0	2.12	4–8
19	inside	0	0	34.01	6.4	5.78	2–5
20	inside	0	0	33.14	3.6	7.95	3–6
21	inside	0	0	35.23	6.8	4.97	3–8
22	inside	0	0	34.85	7.4	8.56	3–8

signs of compromised health, as well as fish bites. Where significant differences were established, the pairwise test of Tukey's HSD was employed to detect differences between the locations. Severity of fish bites was also analyzed using the independent *t*-test to compare the severity of fish bites between two groups of study sites: located inside and outside marine national park boundaries. For multivariate data analyses, the study sites were grouped based on the similarity of the composition of diseases and signs of compromised health. Dendrogram and two-dimensional MDS configuration of coral diseases and signs of compromised health severity were constructed through clustering and ordination methods based on the Bray-Curtis similarities (Bray and Curtis, 1957). Canonical analysis of principal coordinates (CAP) was performed to illustrate spatial severity patterns of coral diseases and signs of compromised health on two dimensional ordination based on the Bray-Curtis similarities. Spearman rank correlation was then calculated to produce vectors overlaid on the CAP plots to explain the overall severity of each disease and signs of compromised health. Each vector with a rho value of more than 0.4 was used to explain which diseases and signs of compromised health were most characteristic at different study site. The length of a vector illustrates the level of the relationship of each variable and the axes of CAP (Anderson et al., 2008). One-way PERMANOVA was also performed to explore the difference in the composition of coral diseases between groups of study sites that had different levels of human impact (Anderson et al., 2008). All multivariate techniques were done using PRIMER version 7.0 (Clarke and Gorley, 2015).

3 Results

3.1 *Severity of coral diseases and signs of compromised health*

A total of nine coral diseases and signs of compromised health were observed in the waters of Thailand consisting of pigmentation responses (pink lines, pink patches, pink spots and pink borers), white syndromes (white patches, white bands and ulcerative white spots), growth anomalies, and unusual bleaching patterns (Fig. 2). Besides these, signs of fish bites were also observed during this study. The most severe coral diseases/signs

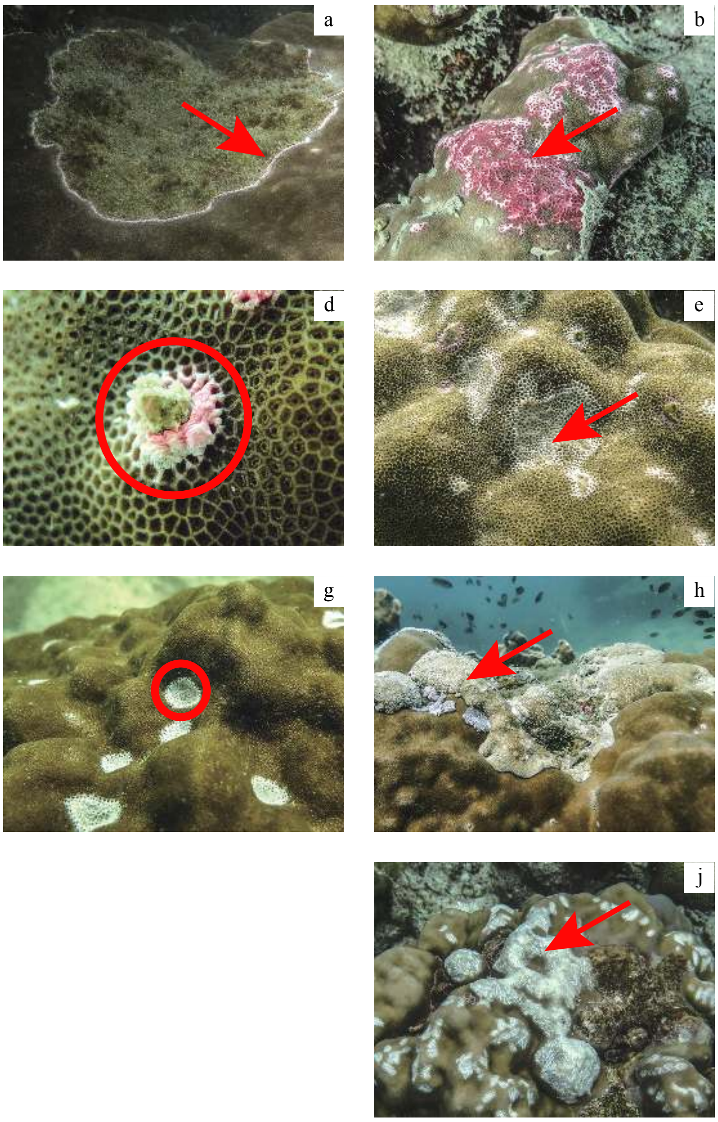

Fig. 2. Characteristics of coral diseases, signs of compromised health, and fish bites: pink lines (a), pink patches (b); pink spots (c), pink borers (d), white patches (e), white bands (f), ulcerative white spots (g), growth anomalies (h), unusual bleaching patterns (i), and fish bites (j).

of compromised health were found at Ko Khang Khao (35.1%±1.9%), Ko Nok (20.2%±4.6%) and Ko Sak (17.3%±4.6%) in the inner Gulf of Thailand; at Ko Samet (19.6%±5.2%), Ko Kudi (15.6%±4.9%) in the eastern Gulf of Thailand; at Ko Thai Phlao (14.4%±4.9%), and Ko Sam Sao (11.5%±3.1%) in the western Gulf of Thailand. In the Andaman Sea, the total severity was relatively low including Had Thaimuang (6.6%±2.1%), Ko Butang (3.1%±0.8%), Ko Kadan (1.5%±0.6%), Ko Mai Phai (1.4%±0.7%), Ko Surin Nua (1.3%±1.1%), and Ko Rawi (0.3%±0.2%) (Fig. 3).

Pink lines were highly severe at Had Thaimuang (0.7%±0.5%). Pink patches were recorded at Ko Nok (2.4%±0.7%), Ko Sak (2.1%±0.6%), Ko Phai (2.5%± 0.4%), Ko Bai Dang (1.9%±0.9%), and Ko Samui (1.5%±0.9%). Pink spots were observed with a high severity at Ko Khang Khao (4.8%±1.4%), Ko Nok (8.5%±1.9%), Ko Sak (6.0%±2.1%), and Ko Samet (7.4%±1.9%). Pink borers were found in all studied sites ranging from 0.3% to 9.8%. Seven study sites were recorded with a high severity of pink borers including at Ko Khang Khao, Ko Nok, Ko Sak, Ko Samet, Ko Kudi, Ko Thai Phlao, and Ko Sam Sao. In case of white syndromes, the highest severity of white patches and white bands were observed at Ko Thai Phlao (6.8%±2.8%) and Ko Surin Nua (1.3%±1.1%), respectively. Ulcerative white spots were found in all study sites except at Ko Surin Nua and Ko Rawai. The highest severity of ulcerative white spots was found at Ko Khang Khao (6.5%±0.9%), followed by Ko Samet (4.6%±2.0%). Growth anomalies were only found in five study sites and the higher severity was observed at Ko Rang Kachio (0.5%±0.2%), Ko Thai Phlao (0.4%±0.2%), and Ko Khang Khao (0.2%±0.06%). Unusual bleaching patterns were recorded in all study sites in the western Gulf of Thailand while the highest severity was observed at Ko Kadan in the Andaman Sea (1.8%±0.5%) (Fig. 4).

Significant variations in the overall severity of coral diseases and signs of compromised health among study sites were detected (one-way ANOVA, $F_{21,44}$=40.42, p<0.01) (Fig. 3). Post-hoc tests showed that the overall severity of coral diseases at Ko Khang Khao was significantly different compared to other sites (p<0.01). Similarly, the overall severity of coral diseases and signs of compromised health at study sites in the inner Gulf of Thailand were also significantly different from other study sites (p<0.05) except those of Ko Thai Phlao and Ko Sam Sao in the western Gulf of Thailand (Fig. 3).

3.2 *Similarity of coral disease composition*

Clustering and ordination methods were carried out using the severity data on coral diseases and signs of compromised health. The study sites with a similar composition of coral diseases/signs of compromised health were found to be clustered based on the Bray-Curtis similarity. These results revealed that at the similarity of 80%, four different groups of the study sites that had similar composition of coral diseases were clustered. The first group consisted of Ko Khang Khao, Ko Samet, Ko Nok, and Ko Sak. These islands are located near estuaries, coasts and large cities, while Ko Samet is highly influenced by tourism. Ko Thai Phlao, Ko Kudi, and Kosam Sao, located near coasts and cities, were in the second group. The third group included Ko Surin Nua, Ko Rawi, Ko Butang, Ko Rang Kachio, Ko Mattra, Ko Mai Phai, Ko Kut, and Ko Kadan. Most study sites in this group are located in the Andaman Sea with less human impact. The final group consisted of Ko Samui, Ko Taen, Ko Phai, Ko Bai Dang, Ko Chan, Ko Thian, and Had Thaimuang. Most of the study sites in this group are located in the Gulf of Thailand with less human impact (Figs 5 and 6).

The CAP analysis revealed that the diseases and signs of compromised health which were strongly correlated to the CAP axes (rho>0.4) included white patches, pink spots, pink borers, and pink patches. Based on the CAP analysis, most study sites in the Gulf of Thailand tended to show a high severity of various diseases. In terms of the severity of pink spots and pink borers, the higher severity was found at some study sites in the inner and eastern Gulfs of Thailand such as Ko Kang Khao, Ko Nok, Ko Sak, Ko Kudi, and Ko Samet, while a lower severity was found at the study sites in the western Gulf of Thailand and the Andaman Sea such as at Ko Rawi, Ko Mai Phai, Ko Rangkachiew, and Ko Surin Nua. Pink patches and white patches were only distributed in the Gulf of Thailand, especially at Ko Khang Khao (the inner Gulf of Thailand) and Ko Thai Phlao (the western Gulf of Thailand), respectively (Fig. 7).

3.3 *Association of human impacts and the severity of the coral diseases/signs of compromised health*

The severity of the coral diseases/signs of compromised health has been documented and found to be associated with the levels of human impact. In this section, the study sites were clustered into three groups based on the levels of human impact

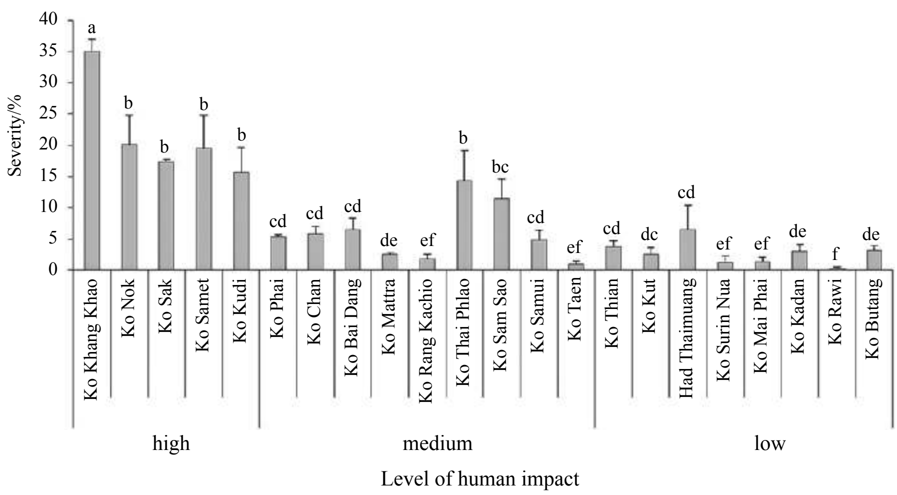

Fig. 3. Percentage of coral diseases and signs of compromised health severity (means±SD) (all coral diseases combined). Means sharing the same letters are not significantly different from each other (Tukey's HSD, p<0.05).

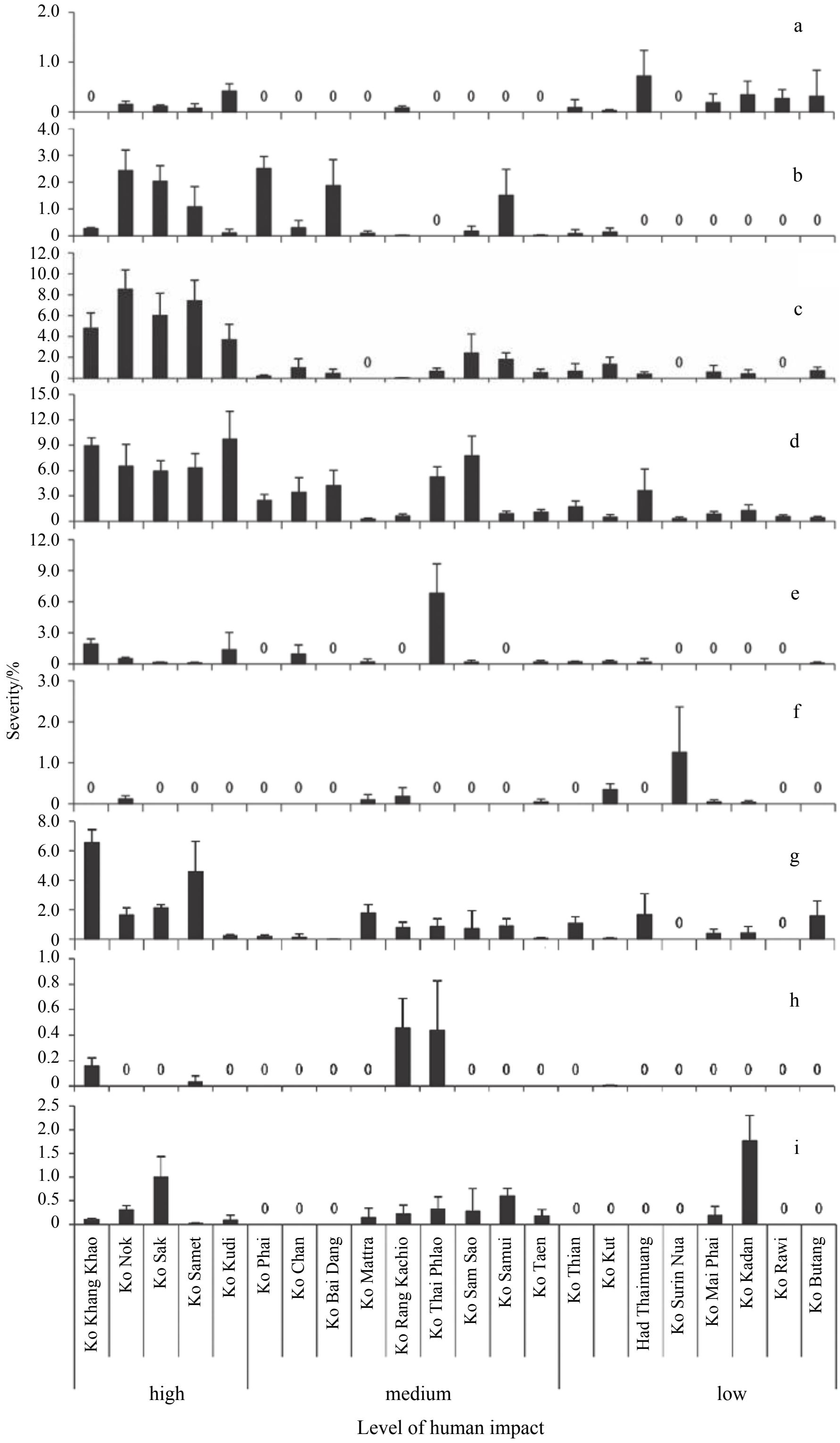

Fig. 4. Percentage of coral diseases and signs of compromised health per study sites in Thailand waters (mean±SD): pink lines (a), pink patches (b), pink spots (c), pink borers (d), white patches (e), white bands (f), ulcerative white spots (g), growth anomalies (h), and unusual bleaching patterns (i).

as following:

Group1: High human impacts consisted of Ko Khang Khao, Ko Nok, Ko Sak, Ko Samet, and Ko Kudi. Ko Khang Khao, Ko Nok, and Ko Sak are located close to the mainland where big cities with high population numbers are located. Various human activities, industrial estates, coastal developments, and aquacultures are generally found in the areas. Besides, these islands are also influenced by the main rivers such as the Choapraya and Bangpakong. During the rainy season, a large amount of fresh water is discharged into the sea causing changes in sea water quality such

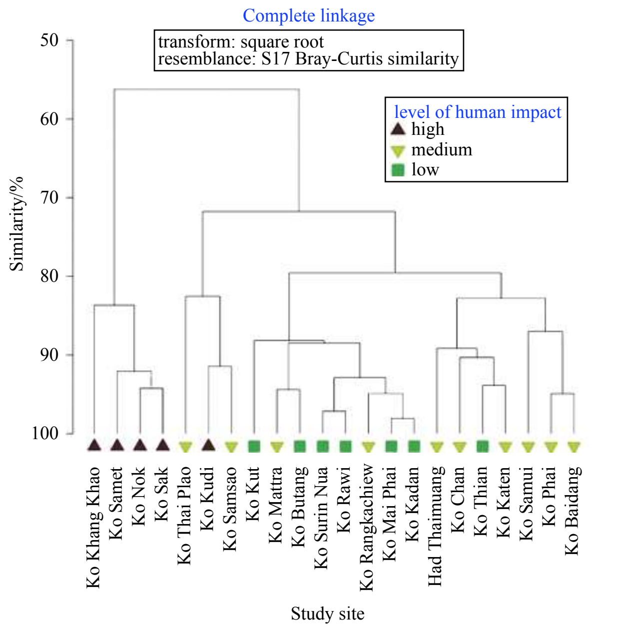

Fig. 5. Dendrogram for hierarchical clustering of 22 study sites using complete linkage of Bray-Curtis similarities of coral diseases and signs of compromised health.

as higher nutrients, lower salinity, lower visibility and a higher concentration of suspended solids. Eutrophication was also occurred. Ko Khang Khao is also located close to main navigational routes and maritime activities. Water quality in this area was quite poor with low visibility and high concentration of suspended solids due to anchoring, discharge of ballast water, and oil pollution etc. Ko Samet is a tourism island with local residents inhabiting the island. Resorts and tourism activities are generally found along beaches at Ko Samet. Ko Kudi is located close to the mainland with dense snorkeling activities.

Group 2: Medium human impacts consisted of Ko Bai Dang, Ko Phai, Ko Mattra, Ko Rang Kachio, Ko Thai Phlao, Ko Sam Sao, Ko Samui, Ko Taen, Ko Chan, and Had Thaimuang. Ko Phai, Ko Chan, Ko Mattra, Ko Rang Kachio, and Had Thaimuang are located near the mainland but they had less pollution and human activities compared with the first group. Tourism can be found in Ko Mattra and Ko Rang Kachio while Ko Phai, Ko Chan, and Had Thaimuang had less tourism. The concentration of suspended solids tended to be lower with higher visibility. Tourism can be found at Ko Thai Phlao and Ko Sam Sao. High concentrations of suspended solids observed in these areas may have been influenced by the Tapi River in Surat Thani. Although Ko Samui and Ko Taen are known as popular tourism hotspots, only local pollution sources were found because these islands are located far from the mainland. The high concentration of suspended solids observed at Ko Bai Dang was also influenced by human and tourism activities in Ko Chang, one of the popular tourism hotspots in Thailand.

Group 3: Low human impacts consisted of Ko Thian, Ko Kut, Ko Surin Nua, Ko Mai Phai, Ko Kadan, Ko Rawi, and Ko Butang. These islands are located far away from the mainland and have less tourism activities, and land-based pollution compared to other groups. Based on the level of human impact, the severities (mean±SD) of coral diseases/signs of compromised health for groups 1, 2, and 3 were 21.5%±7.9%, 6.3%±4.2%, 1.8%±1.4%, respectively. The one-way ANOVA with Tukey's HSD reveals that the total severity of each group is significantly different ($F_{2,\,63}$=75.89, p<0.01). In terms of the composition of coral diseases and signs of compromised health, the PERMANOVA shows significant differences in disease composition across groups that have different levels of human impact (*pseudo*-$F_{2,\,19}$=13.27, p<0.001).

3.4 *Severity of fish bites*

Fish bites were also found in most study sites in both the Gulf of Thailand and the Andaman Sea. The fish bites were observed at all study sites in the Andaman Sea where Ko Rawi exhibited the highest severity (15.2%±4.8%) followed by Ko Surin Nua (13.6%±6.6%), Ko Butang (17.4%±5.8%), and Had Thaimuang (6.4%±2.6%). The severity of fish bites in the Gulf of Thailand was much lower with a range of 0–3.3% compared to the Andaman Sea. The highest severity of fish bites observed in the Gulf of Thailand was found at Ko Thian, in the eastern Gulf of Thailand,

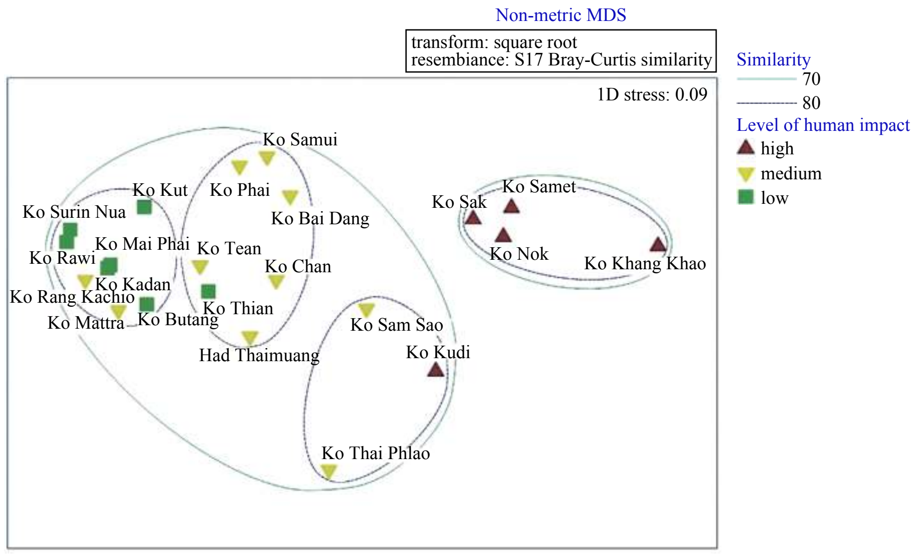

Fig. 6. Two-dimensional MDS configuration of coral diseases and signs of compromised health from 22 study sites from both the Gulf of Thailand and the Andaman Sea.

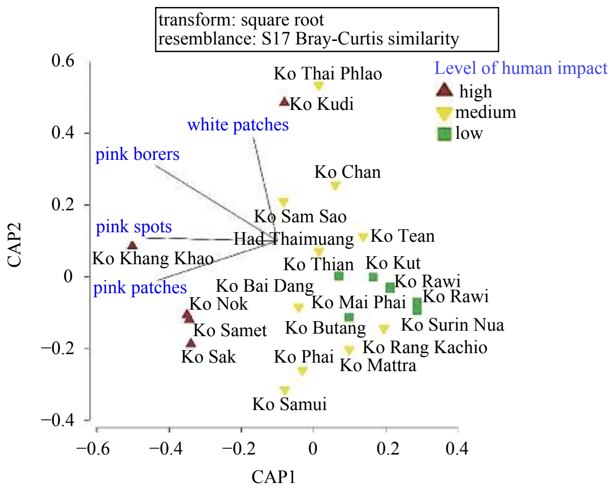

Fig. 7. The CAP plots illustrating the difference in coral disease severity among study sites. Vectors (rho>0.4) indicate the coral diseases that were characteristic at different study sites.

(3.3%±0.9%), followed by Ko Mattra, in the western Gulf of Thailand (1.4%±1.7%). Spatial variation of the severity of fish bites was also detected (one-way ANOVA, $F_{21,\,44}$=21.58, p<0.01) (Fig. 8). Post-hoc tests show that the severity of fish bites at Ko Rawai was significantly different compared to other sites (p<0.01) except Ko Surin Nua. No sign of fish bites was found at Ko Khang Khao, Ko Kok, Ko Sak, Ko Phai, Ko, Ko Samui, Ko Chan, and Ko Bai Duang. This study also found that the severity of fish bites observed in the study sites within marine national park boundaries (3.34%±0.81%) was significantly higher than that observed outside the marine national park boundaries (0.091%±0.47%) (t-statistic=2.71, df=64, p<0.01).

4 Discussion and conclusions

This study reveals that the highest severity of all observed coral diseases and signs of compromised health were found at the study sites which were intensively used for tourist activities such as Ko Samet, Ko Kudi, and Ko Thai Phlao. A previous study at Ko Tao, in the western Gulf of Thailand, shows a significant increase in coral disease severity, sponge overgrowth, physical injury, tissue necrosis from sediment, and non-normally pigmented coral tissues at high use dive sites (Lamb et al., 2014). These findings should be carefully considered by coral reef managers to identify and mitigate potential impacts from coastal development associated with tourism. The highest severity of coral diseases was observed at Ko Khang Khao, in the inner Gulf of Thailand. Although this island is not an intensive tourism site, it is located relatively near the Chao Phraya (52 km) and Bang Pakong (40 km) river mouths. It might be affected by freshwater run-off during the rainy season in May-October with high sediment loads, nutrients and land-based pollutants (Sangmanee et al., 2012) which is linked to several coral diseases (Bruno et al., 2003; Kaczmarsky and Richardson, 2011).

Pigmentation responses have been recognized as a general immune response to physical stress or biological agents (Ravindran and Raghukumar, 2006; Palmer et al., 2008; Donsomjit and Yeemin, 2010). Non-normal pigmentation has high concentrations of melanin which is a significant component of innate immunity in invertebrates and functions in defense reactions against foreign bodies such as pathogens (Palmer et al., 2008). The high prevalence of pink syndromes observed at several study sites may indicate the signs of an immune response to multiple stressors caused by coral associated borers (Yeemin et al., 2009). Additionally, sediment burial (Erftemeijer et al., 2012; Sheridan et al., 2014) also has an effect on the coral immunity leading to increased susceptibility to diseases.

According to the results, the highest severity of fish bites observed in the study sites within marine national park boundaries is significantly higher than that observed outside marine park boundaries. It could be directly inferred that fishing pressure within marine national park boundaries is less than that outside because fishing in marine national parks is generally prohibited. An abundance of several fish in marine protected areas (MPAs) is generally higher in marine protected areas than having open access areas. Various researches illustrates that MPAs had greater species richness, density, and biomass of fishes, especially grazing herbivores and piscivores, than non-MPAs (Patankar et al., 2016; Bonaldo et al., 2017).

Coral diseases in Thailand have become a major concern for reef managers, therefore coral disease surveys are becoming more important. However, some of the obstacles facing marine and coastal ecosystem managers are based on how to identify the resilience level of coral reefs and how to effectively mitigate local stressors. Our results suggest that spatial planning and manage-

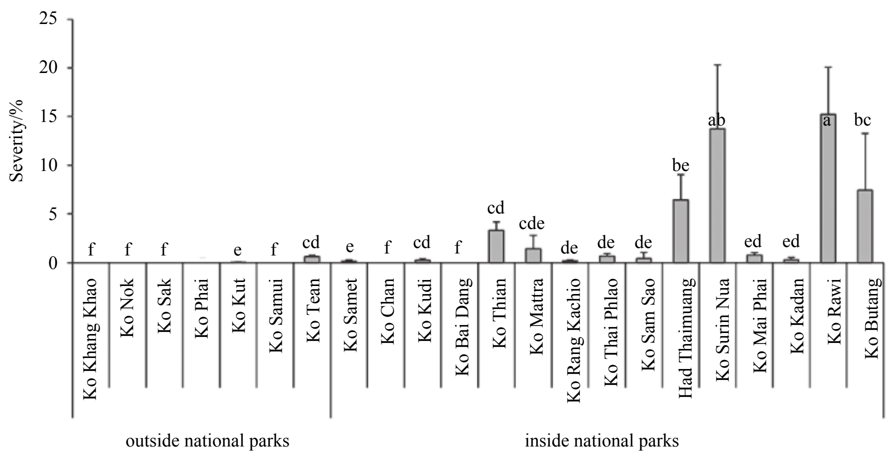

Fig. 8. Percentage of fish bites per study site in Thailand waters (mean±SD). Means sharing the same letters are not significantly different from each other (Tukey's HSD, p<0.05).

ment strategies to prevent or mitigate the impact on coral reef health in Thailand waters are urgently needed to ensure the maintenance of ecosystem services, particularly from the fisheries and tourism sectors. Several management strategies under the coral reef restoration plan of Thailand with focus on reducing the threat from tourism, water pollution, sedimentation and fisheries could be applied and effectively implemented (Suraswadi and Yeemin, 2013). After the 2010 bleaching event, a group of marine scientists and relevant agencies gathered and proposed coral reef management actions relating to the coral bleaching crisis in which three concepts, i.e., protecting coral resistance, building coral tolerance and promoting coral recovery (Yeemin et al., 2012). The management actions are also beneficial to the reduction of coral diseases caused by anthropogenic disturbances and strengthening coral resilience. This study presents quantitative evidence of the disease severity and the association of anthropogenic disturbances to higher coral diseases and signs of compromised health severity on several coral communities in the Thailand waters, highlights the importance of science-based management of coral reef ecosystems in Thailand.

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