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Changes in hard coral abundance and composition on Koh Tao, Thailand, 2006-2014

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Abstract

The island of Koh Tao, Thailand, has experienced rapid development over the last two decades due to coral reef-based tourism, with as much as 0.5-1 million visitors per year. Today the island hosts over 67 dive centers, and is second in the world in terms of SCUBA certifications issued per year. In 2006, a study by Yeemin *et al.* recorded a 17% decline in coral coverage around the island over a five year period, and documented a lack of governance and policy initiatives to regulate the development and marine tourism. This study looks at the changes in coral coverage and community structure over the nine year period following the study by Yeemin et al. Although the reefs of Koh Tao are highly stressed and in some cases becoming more degraded, coral coverage has actually increased slightly since 2006. However, data also shows that the reefs of the island are experiencing major changes in community structure, and in some cases coral-algal phase shifts. The continued marginalization of the island's coastal areas has major implications for the local economy and communities, and more proactive policies and management on land based activities are required to preserve the resilience of the reefs in the face of climate change.

Keywords: coral reef monitoring, diving damage, Koh Tao, tourism

Introduction

Tourism is one of the major contributors to the economy of Thailand, with approximately 31.4 billion USD in 2013, or about 9.0% of the country's total GDP (World Travel and Tourism Council, 2014). Thailand is also one of the world's major fisheries regions, generating about 3.1 billion USD in 2008 (FAO 2009). Both the tourism and fishing industries in Thailand rely heavily upon the marine and coral reef resources, particularly in the southern part of the nation. The country has approximately 150km^2 of coral reefs, which contribute significantly to the country's economy through

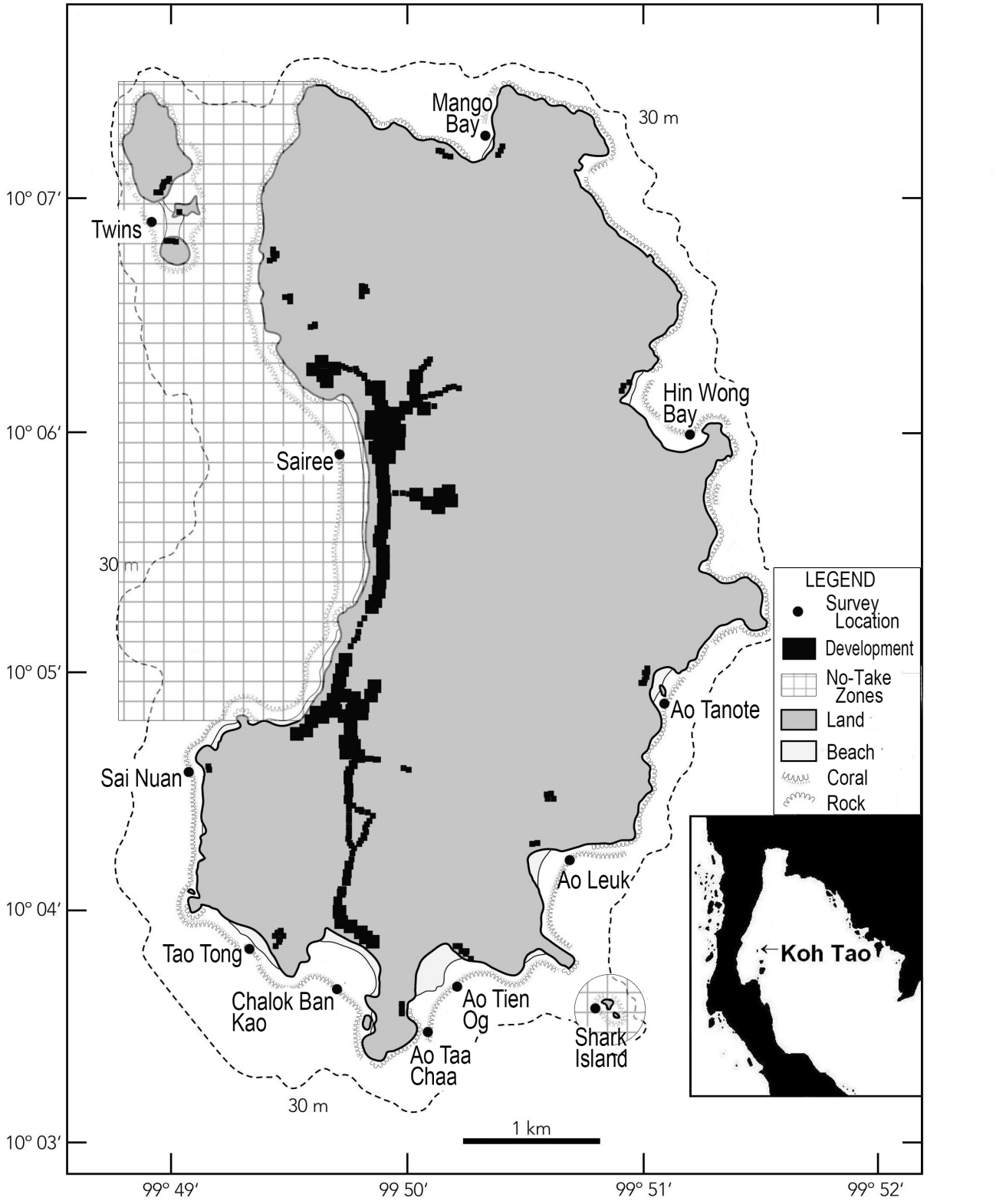

Fig. 1 Map of Koh Tao showing survey locations used in this study. (Modified from Hoeksema *et al.* 2012).

tourism, fishing, shoreline protection, and other direct and indirect services (Wilkinson 2008, Phongsuwan *et al*. 2013). However, in Thailand, coral reefs are highly threatened by human activities, with coral coverage greatly reduced in many areas across the Andaman and Gulf over the last two decades (Phongsuwan *et al*. 2013).

Coral reefs in general are poorly protected, highly degraded, and exposed to many ongoing threats. It is estimated that between 40-60% of the world's reefs will decline over the next 50 years, and that 80% of the reefs in South East Asia are at risk (Bruno & Selig 2007, Rinkevich 2008, Wilkinson 2010). The most important and salient threats to global reef health today is mortality due to bleaching and diseases brought on by climate change and localized declines in water quality (Wilkinson 2008). Increased sea surface temperatures tends to cause highest mortality rates amongst fast growing and structurally diverse corals such as acroporids (Brown 1997, Hoegh-Guldberg 1999). Multiple bleaching events, in increasing frequency and severity, over the last two decades has led to major changes in the community (Walther *et al.* 2002, Chavanich *et al.* 2012).

Koh Tao is a small but economically important island located in the Western Gulf of Thailand (Fig 1). The island is surrounded by dense fringing reefs and submerged granite pinnacles (Fig. 2), with some of the highest coral coverage and biodiversity in the Gulf (Yeemin *et al*. 2006, Pongsuwan *et al*. 2013). In recent years, the island has become one of Asia's most popular island destinations, and is second in the world for the number of SCUBA divers certified each year (Wongthong & Harvey 2014). By 2015, the 19 km^2 island had 67 dive schools, and is also the main point of interest for snorkelers and divers visiting from neighbouring islands or the mainland on day trips. The burgeoning diving industry has led to rapid development of support infrastructure such as restaurants, bars, and resorts; with the island now receiving as much as 500,000 visitors per year (Wongthong & Harvey 2014).

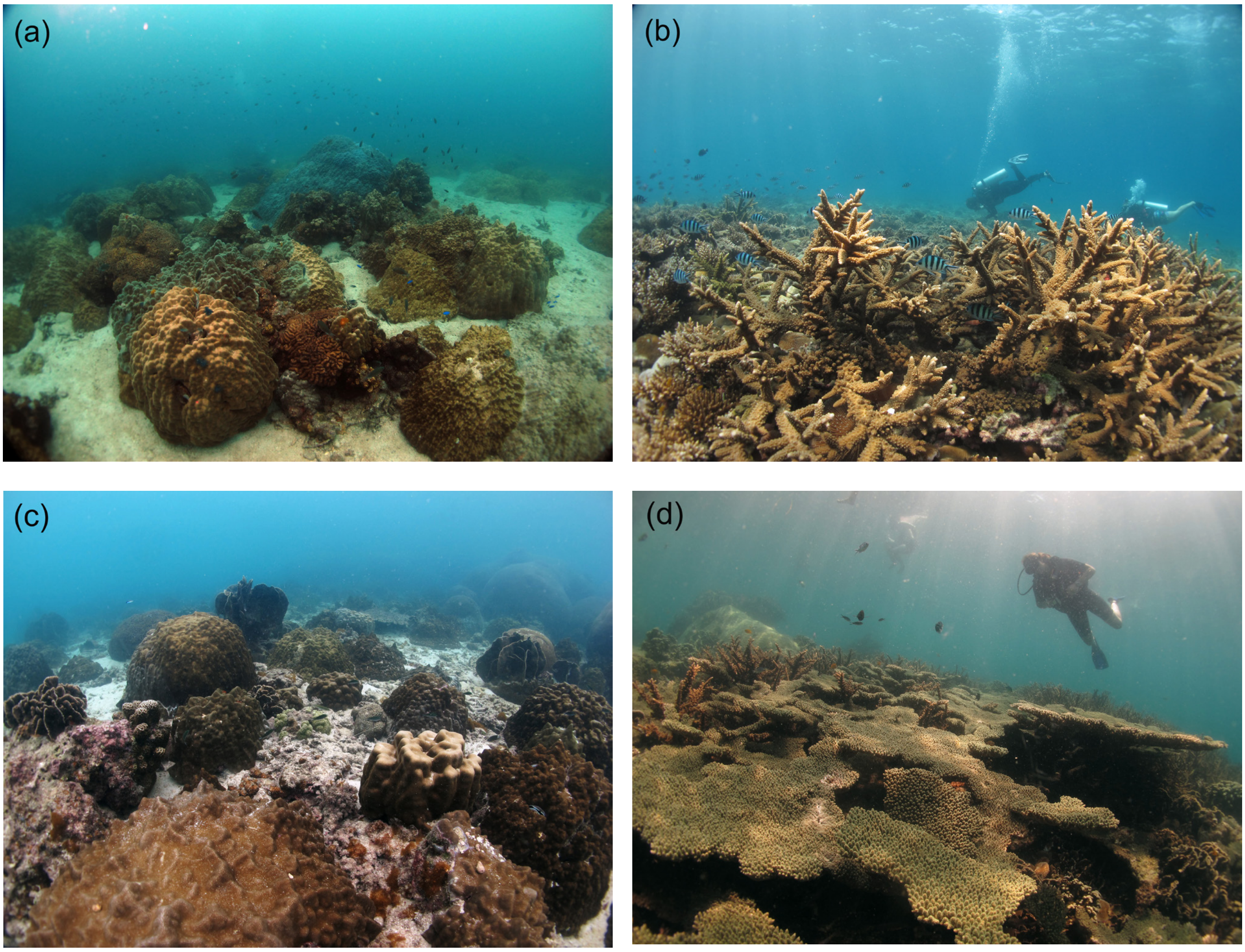

Fig. 2 (a) Ao Leuk (10°4'18.37"N, 99°50'28.44"E) - Shallow bay with small fringing reef and then coral heads scattered in sand, (b) Chalok Ban Kao (10°3'44.73"N, 99°49'30.02"E) - Shallow bay with dense fringing reef, (c) Had Sai Nuan (10°4'41.45"N, 99°48'55.90"E) - Shallow bay with small fringing reef and then coral heads scattered in sand, (d) Hin Wong Bay (10°6'5.52"N, 99°51'2.89"E) - Large, deep bay with dense fringing reef, [continued to next page]

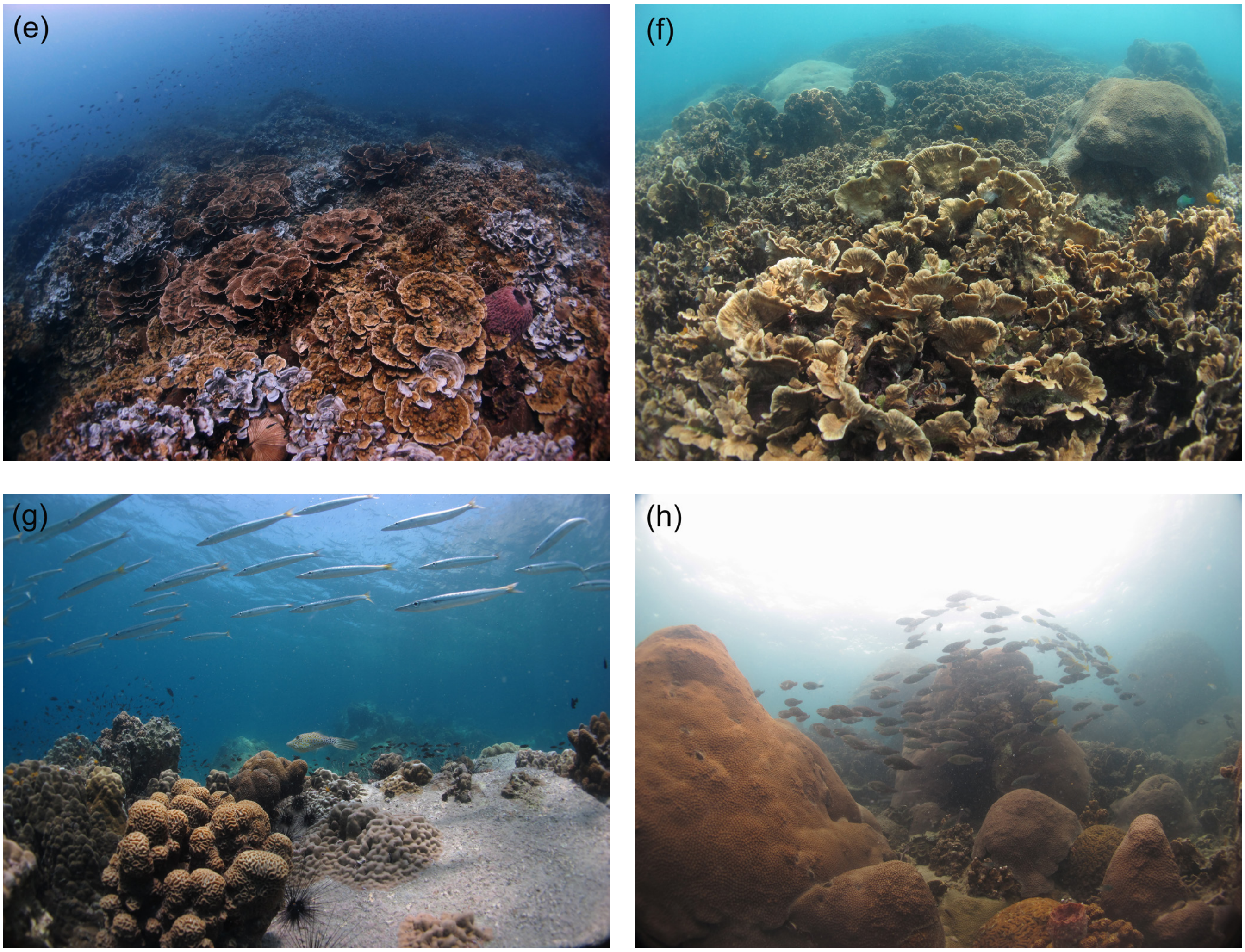

Fig. 2 continued. (e) Mango Bay (10°7'21.54"N, 99°50'9.31"E) - Large, deep bay with dense fringing reef, (f) Sairee (10°6'8.15"N, 99°49'29.86"E) - Long, narrow barrier reef with dense coral cover, (g) Shark Island West (10°3'42.21"N, 99°50'38.46"E) - Submerged granite pinnacle/island with scattered coral cover, (h) Tanote Bay (10°4'59.49"N, 99°50'53.81"E) - Sandy bay with corals growing on rocky shore and granite pinnacle, [continued to next page]

Remote sensing studies show that in 1975, only about 3.2% of the island had been altered by human activities (settlements and coconut farming), which had increased to 42.8% by 2005 (Weterings 2011). Development on the island has been unregulated, with little to no adherence to planning guidelines such as those by the Thailand Institute for Scientific and Technical Research published in the early 1990's (Szuster and Dietrich 2014). Most of the primary forest on the island has been altered (Weterings 2011, Szuster and Dietrich 2014), and road construction or development projects have in some cases had a recorded or directly observable negative effect to coral reef areas (Larpnun, Scott, & Surasawadi 2011).

Public infrastructure is inadequate and unable to keep pace with development, with shortages of fresh water and electricity being commonplace. Interviews conducted in 2015 found that although the island produces over 8 tons of solid waste per day, the capacity at the island's incinerator is only 5 tons per day (Save Koh Tao, unpublished data). There is no centralized waste water treatment for the island, and each resort or home is left to manage their own waste water, with no oversight or permitting system in place. In the most densely populated area of the island, Sairee Beach, bioassay results from macro-algae samples indicate that untreated human sewage is flowing directly into the reef area (Romeo 2015). Such land based threat factors are inevitably having direct and indirect negative effects on the surrounding reefs.

Only sparse data, usually collected using manta tow techniques, exists on the health of the island's coral reefs prior to the initiation of the Ecological Monitoring Program in 2006 (Scott 2012). Flummerfelt (1999) identified multiple

stress factors and the growing concern for the health of the island's reefs, highlighting anchor dropping as one of the most salient, with only 3 mooring lines installed around the island. Yeemin *et al.* (2006) found that there had been a 17% decline in hard coral abundance over a 5 year study period, assumedly after the 1998 global mass bleaching event. Another long term study, also using manta tow data, by Phongsuwan *et al.* (2013) identified the 1998 mass bleaching event as highly damaging to the island's reefs, but recorded high levels of recovery by 2006, with coral coverage levels about equal to those in 1996, at roughly 35%.

Both Flummerfelt (1999) and Yeemin *et al.* (2006) identified a complete lack of governance, effective polices, or management measures in place to protect the marine resources of Koh Tao. However, since the formation of the Marine Branch of the Save Koh Tao Community Group in 2008, the management of the island's coastal areas has been improving (Scott and Phillips 2012). By 2015, the island has five alterative dive sites, hundreds of artificial reefs, eight coral nursery sites, over 150 mooring lines, and several dive centers with dedicated marine conservation departments. The local community and dive businesses have effectively cooperated to manage their own resources with monthly meetings, clean-ups, educational workshops, and other activities. Over the period of 2008-2012 a series

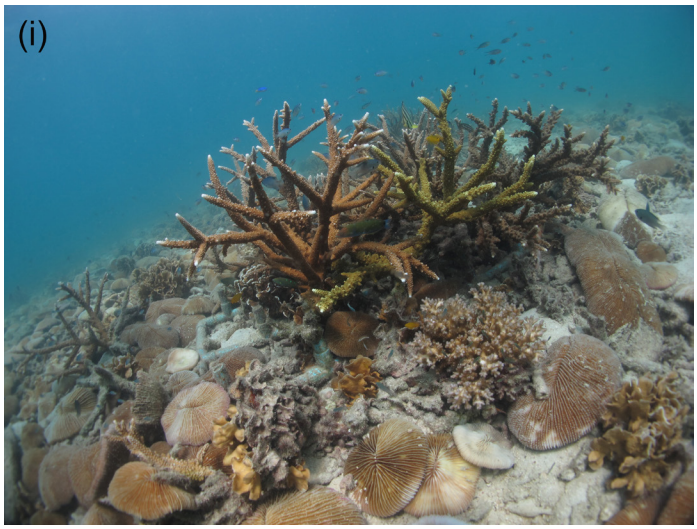

Fig. 2 continued. (i) Tao Tong (10°4'0.29"N, 99°49'7.03"E) - Narrow, dense fringing reef, (j) Tien Og (10°3'47.99"N, 99°50'1.36"E) - Shallow bay with dense fringing reef/fields of mushroom coral, (k) Twins (10°7'1.46"N, 99°48'46.72"E) - Dense fringing reef and coral on submerged granite pinnacles.

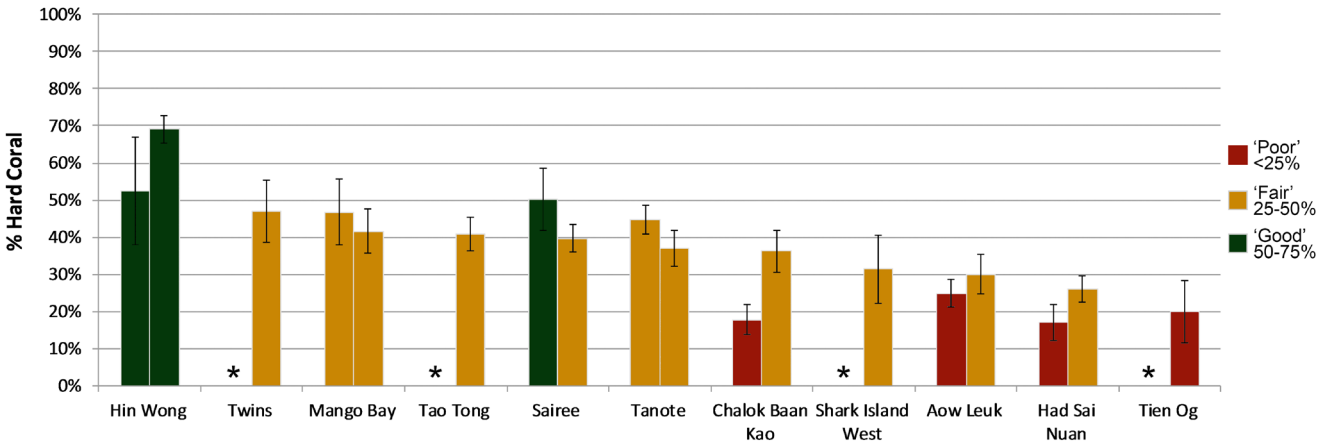

Fig. 3 Coverage of hard corals (%, mean±1SE) at different sites on Koh Tao in 2006 (left bars) and 2014 (right bars). No sites were in 'very good' condition (>75%), however, most 'Poor' sites had improved to 'Fair between the time period. Asterisks represent data not available for that year.

of stakeholder meetings resulted in an initial draft of coastal regulations and zoning, culminating in 2012 with the "Strategic Plan: Integrated Coastal Management for Koh Tao" (Platong *et al.*). In 2015, the majority of marine tourism related business signed onto a Memorandum of Understanding to adhere to an additional 47 rules and regulations concerning the use of coastal areas and coral reef resources.

Despite increased awareness, community participation, and effective marine protection policies being implemented since 2008, land and marine based threats are still having an obvious effect on coral reef health and resilience. Indeed, little has been done to effectively manage development and land use on the island, and there is no enforcement of terrestrial rules and regulations in place. Several recent studies have identified and thoroughly documented the five most salient reef threats on Koh Tao as mass coral bleaching events of 1998, 2010, and 2014 (Yeemin *et al*. 2006, Chavanich *et al*. 2012, Hoeksema *et al*. 2013, Phongsuwan *et al*. 2013); coral disease (Lamb *et al*. 2014, Hein *et al*. 2014); development, run-off, erosion/sedimentation, water pollution, and other land based threats (Larpnun *et al*. 2011, Weterings 2011, Szuster and Dietrich 2014, Romeo 2014); coral predation (Hoeksema, Scott & True 2013, Scott, Mehrotra & Urgell 2014, Moerland *et al*. 2016, Scott *et al*. 2017): and over-use by SCUBA diving, snorkeling and other marine based tourism (Weterings 2011, Nichols 2013, Wongthong & Harvey 2013, Hein *et al*. 2014).

Materials and Methods

Data for this study were collected through the Ecological Monitoring Program (EMP) (Scott 2012) originally initiated by the Coastal Preservation and Development Foundation in 2006. Data were collected by trained and certified volunteers, primarily the staff at the New Heaven Reef Conservation Program. Permanent transect lines, with each study site having a shallow (3-5 meters) and deep (6-9 meters) line. Each line was 100 meters long, and divided into four 20 meter sections, with a 5 meter gap between each section. Data for the four sections was averaged for each line.

Substrate and coral health data were collected using the point intercept method, with data recorded every 50 centimetres within the four 20 meter sections, yielding 160 data points per line, or 320 per site. Substrate types were recorded with five non-living categories (silt/clay, sand, rubble, rock, trash) and 5 living categories (macro-algae, sponge, soft corals, hard corals, and other). Hard corals (HC) were further classified by growth forms (10 categories), genera (Since 2010), and health (healthy, partially bleached, fully bleached, recently killed, and dead). Coral colonies were also noted for coral diseases and other forms of compromised health (predation, overgrowth, growth/pigment anomalies, etc.) Data were also collected for fish and invertebrate abundance and biodiversity (5m by 20m belt transects), but have not been included in this study.

A total of 430 transect data were available for the period

of 2006-2014 and used in this study. There is a high degree of heterogeneity in the amount of data collected per site per year, depending on the number of trained volunteers conducting the surveys, weather, and other factors, as shown in Table 1. Furthermore, new sites have been added since the original implementation of the monitoring program in 2006, increasing from 7 sites in 2006 to a total of 17 by 2014 (Fig. 1). However, due to a lack of consistent and regular data at six of the sites, only 11 are included in this study for the total coverage in 2014, and only 6 sites were used to estimate the change in coral coverage over the period 2006-2014. Erroneous, duplicate, or incomplete entries into the database (i.e. those showing null values for all substrate types) were not included in the analysis.

Results

Analysis of the 2006 data from all seven available sites shows that overall the reefs were in 'Fair' condition, (according to the metrics of Wilkinson 2008), with an average hard coral coverage of 36.2% ± 5.9. Three of the seven sites, however, were in 'poor' condition (Ao Leuk, Chalok Baan Kao, and Sai Nuan) with coral coverage of 24.8% ± 3.7, 17.8% ± 4.1, and 17.1% ± 4.9, respectively. Only one of the sites assessed, Hin Wong Bay, had 'Good' coral coverage (52.5% ± 14.4), and none of the reefs had 'Very Good' levels of hard coral cover (> 75%) (Fig. 3). Note that coral genera were not recorded in 2006.

Between 2006 and 2014, coral coverage fluctuated slightly, with the lowest coverage levels in 2011-2012 (27.1% ±3.1 and 27.1% ± 3.6, respectively), following the mass bleaching event of 2010 (Fig. 4). By 2014 the reefs reached their highest coverage level at 39.1% ± 4.3 based

Table 1. Overview of available surveys in the Koh Tao Ecological Monitoring Program database, 2006-2014.

	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
Number of surveys	41	4	30	41	90	26	45	56	97	430
Sites included	7	3	6	10	10	5	9	13	14	17

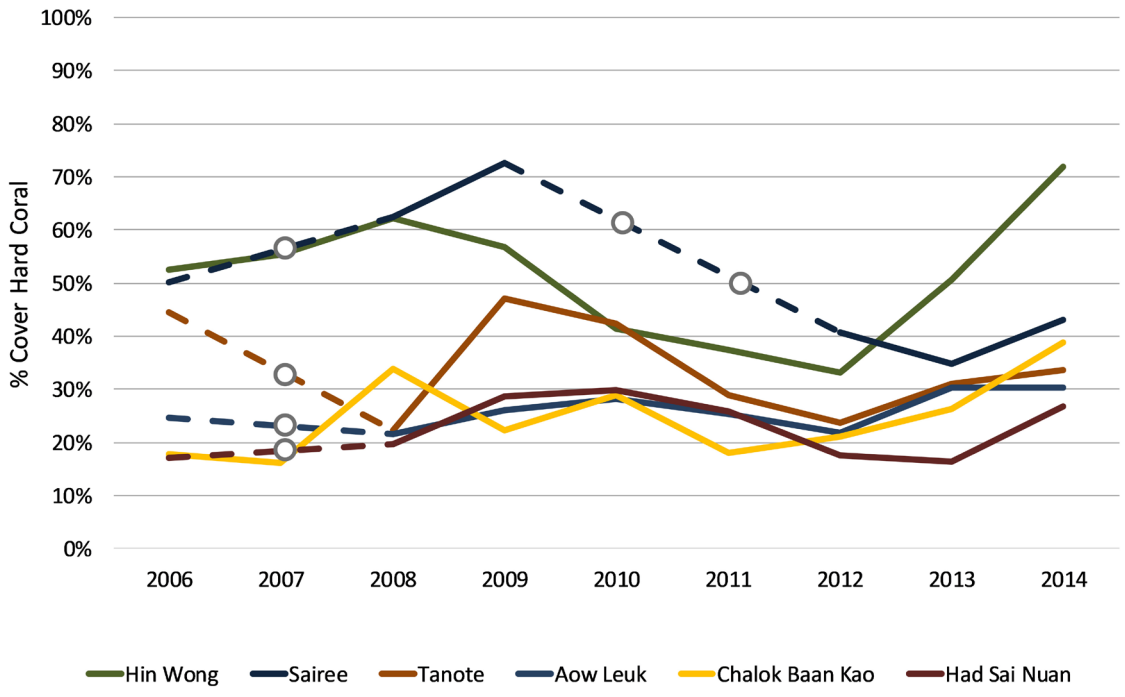

Fig. 4 Change in percentage coral cover on Koh Tao reefs based on data from only the 6 sites with most regular surveys between 2006-2014. Open circles denote no data for that site/year, broken lines have been extrapolated over missing years.

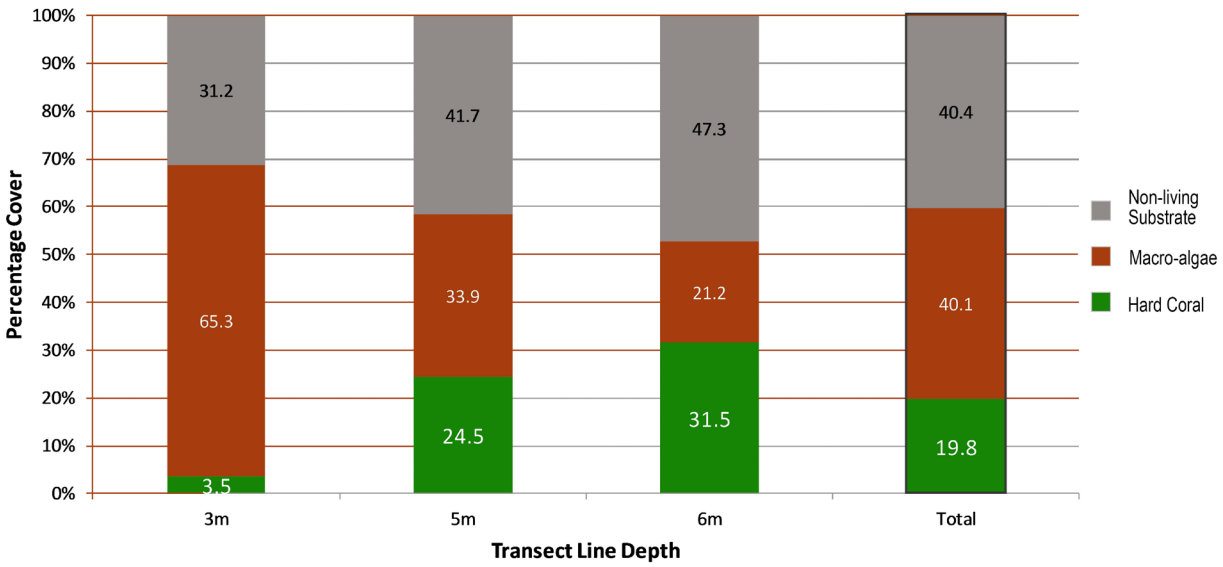

Fig. 5 Substrate composition in Tien Og Bay, Koh Tao in March 2014. Macro-algal abundance at the site was around ten-fold higher than the island average.

on the 6 sites as in 2006. As of 2014, 10 of the 11 reefs for which adequate data were available were in 'fair' condition, with one reef being in 'good' condition (Hin Wong, 69.1% ± 3.7). One reef (Tien Og, 19.8% ± 8.4%) was found to be in 'poor' condition, and no reefs were in 'very good' condition. Tien Og also recorded the highest rates of macro-algae for any site studied, with 40.1% of the substrate dominated by macro-algae (Fig. 5). In the shallow reef (<5m) of Chalok Ban Kao, coral coverage decreased from 60.3% ± 4.0 in 2010, to just 26.5% ± 4.5 by 2013, primarily due to predation by *Drupella* snails (Fig. 6). Combining the averages for all 11 of sites, the average coral coverage was 39.7% ± 3.5 in

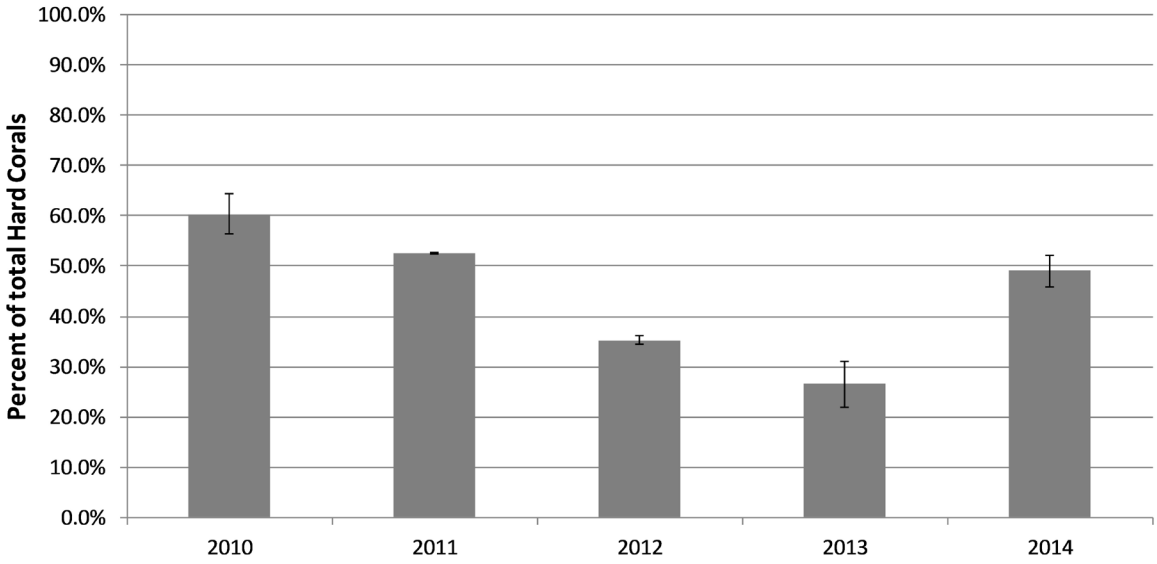

Fig. 6 Changes in the proportion of acroporans (mean±1SE of all surveys) in Chalok Ban Kao from 2010 to 2014. Decline was due largely to chronic predation by an outbreak/overpopulation of *Drupella* snails following the mass bleaching event of 2010.

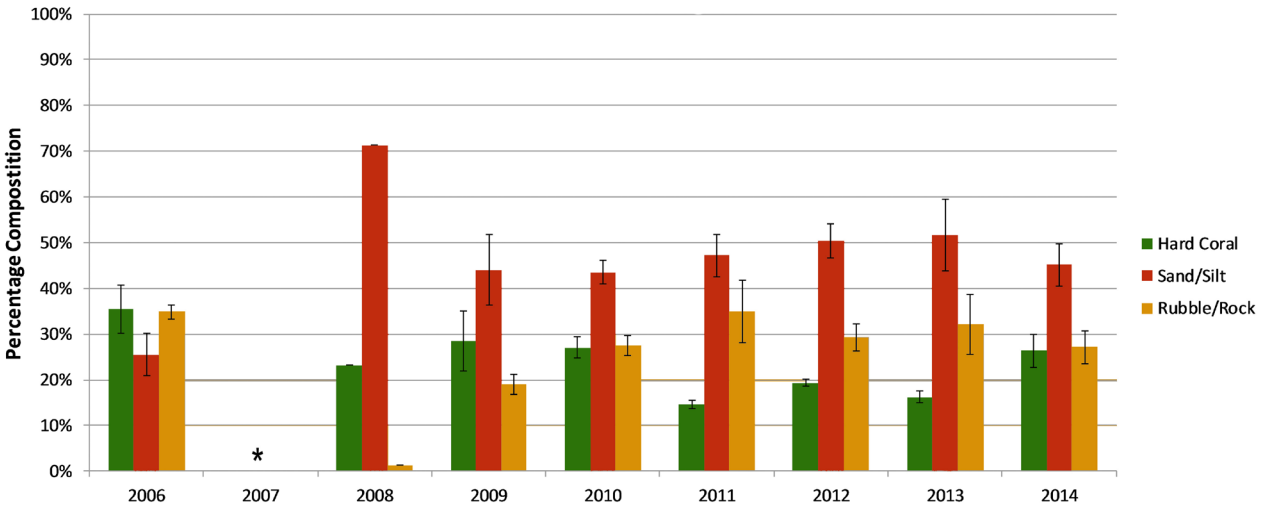

Fig. 7 Substrate composition (%, mean±1SE of all surveys) in Tanote Bay, Koh Tao, from 2006 to 2014. No data were collected in 2007.

2014. In Tanote Bay, 1.5-2 meters of sediment buried the nearly all the corals in the center of the bay. The permanent transect lines, located on the rocky side of the bay, fared better, but still incurred a loss of hard corals from 35.4% ±5.3 to 23.13% ±6.5, and a change in the abundance of sand and silt from 25% ±4.6 to 71.3% ±2.5 between 2006-2008 (Fig. 7).

A total of 24 coral genera were identified from 97 transects in 2014, with *Pavona*, *Porites*, *Acropora*, and *Fungia* making up over 65% of corals (20.6% ± 2.1, 16.6% ± 1.9, 14.7% ± 1.8, and 13.7% ± 2.4, respectively) (Table 2). *Pavona* and *Porites* are recognized as corals which are resistant to thermal and sedimentation related stresses (Brown 1997, Marshall and Baird 2000, Guest *et al.* 2012), and together with Pocillopora and Fungia (due to their reproductive strategies) can be considered more resilient genera which dominate communities in marginalized or degraded coral reefs. In contrast, corals of *Acropora*, *Monitpora*, *Diploastrea*, *Turbinaria*, and *Astreopora* tend to be more susceptible to thermal and other stresses, and can be considered as 'vulnerable' corals that would only dominate in reefs with high water quality and low levels of stress. Comparing the abundance of the resilient and vulnerable genera (Fig. 8) shows that in 2010, vulnerable genera were about 16% more abundant than resilient genera (40.4% ± 2.8 and 33.9% ± 2.2, respectively.) By 2014 the trend had reversed, with more resistant coral genera dominating the communities around the island (53.6% ± 2.8 and 27.7% ± 2.3, resistant and vulnerable, respectively).

Table 2. Cover of different coral genera in Koh Tao, based on 97 surveys in 2014

genus	Proportional (%) cover (mean with 1SE)
Pavona	20.6 (2.2)
Porites	16.6 (1.9)
Acropora	14.7 (1.8)
Fungia	13.7 (2.4)
Diploastrea	6.4 (1.5)
Montipora	6.3 (0.9)
Pocillopora	3.9 (0.7)
Goniopora	1.8 (0.6)
Goniastrea	1.7 (0.5)
Lobophyllia	1.1 (0.2)
Platygyra	1.0 (0.3)
Favia	0.6 (0.2)
Favites	0.4 (0.1)
Astreopora	0.3 (0.1)
Symphyllia	0.3 (0.1)
Echinopora	0.3 (0.1)
Merulina	0.2 (0.1)
Hydnophora	0.1 (0.1)
Montastrea	0.1 (0.1)
Euphyllia	0.04 (0.03)
Pachyseris	0.03 (0.02)
Gardineroseris	0.01 (0.01)
Galaxea	0.01 (0.01)

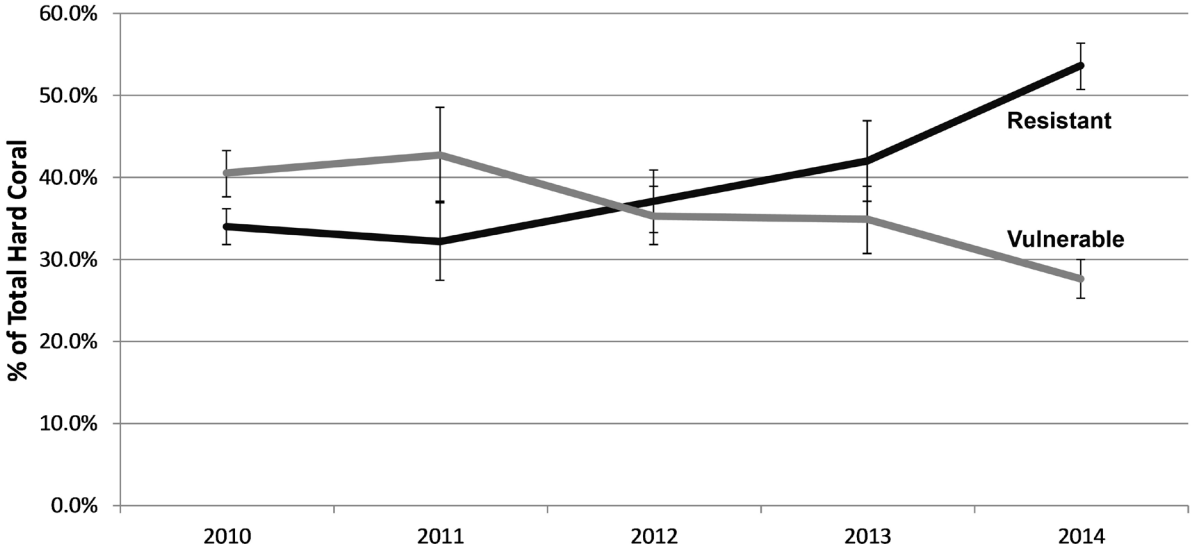

Fig. 8 Variation in the proportional abundance (mean±1SE of all surveys) of resistant and vulnerable coral genera on Koh Tao, 2010-2014.

Discussion

Following the 1998 global mass coral bleaching event and other local threats, reefs on Koh Tao had lost about 17% of their coral coverage over just five years (Yeemin *et al.* 2006). However, coral recovery was high compared with other sites in Thailand (Phongsuwan *et al*. 2013). As of 2006, the reefs of Koh Tao were in 'Fair' condition, with an average of about 36% live coral cover. However, some sites were more degraded, with three sites (Ao Leuk, Chalok Baan Kao, and Had Sai Nuan) having 'Poor' coral cover ranging from about 17.1% - 24.8%. It is unclear whether those reefs suffered greater levels of mortality during the bleaching event, or if subsequent disturbances or chronic stresses impeded the recovery of those reefs relative to areas such as the more remote Hin Wong Bay. However subsequent disturbances as well as direct and indirect long-term effects of thermal stresses can continue to reduce coral coverage for several years after a bleaching event (reviewed in Baker *et al.* 2008).

Competition and overgrowth by macro-algae can lead to mortality of living coral colonies and also inhibit the settlement of coral larvae needed for reef recovery (Birrell *et al.* 2008). An example of this would be the site of Ao Tien Og, at the south of Koh Tao. In 1988, it was found to have nearly 100% coverage of Acropora corals, which by 1992 had reduced to 55% after Typhoon 'Gay' in 1989, and further dropped to just 5% after the 1998 mass bleaching event (T. Yeemin, pers. comm.) By 2014 the bay had still not recovered, with a two-fold higher ratio of macro-algae to hard coral (Fig. 5), the highest abundance recorded for any site on the island. A coral-algal phase shift at the site is probably related to increased nutrient loading from development and deforestation in the overlying water shed, as well as a loss of the structural diversity which provided habitat for grazing fish species (Romeo 2014).

The average coral coverage for the island was similar in 2006 when compared with 2014, from 36.2% ± 5.9 to 39.7% ± 3.5 (Fig. 3). However, this trend was not homogenous across all sites, with some reefs gaining and some reefs losing in terms of total coverage. Although coral bleaching is one of the most obvious and salient causes for coral mortality in the area (as detailed in Yeemin *et al*. 2006, Yeemin et al. 2012, Chavanich *et al*. 2012, Hoeksema, Scott & True 2013 and Phongsuwan *et al.* 2014) a consortium of local and global direct and indirect stresses continues to impact the island's reefs.

Coral disease is an emerging threat around Koh Tao, with disease prevalence increasing throughout the study period. Coral disease outbreaks tend to follow bleaching events (Knowlton 2001, Bruno *et al*. 2007) and tend to be higher in areas with a high amount of land or marine based human activity. A recent study by Lamb *et al*. (2014) compared coral disease prevalence at 'high' and 'low' use sites around

Koh Tao and found a nine-fold decrease in the number of healthy corals at high use sites than low use sites (78.8% ± 2.5 and 45.2% ± 6.2 healthy coral at low and high use sites, respectively). The study implies that coral disease and other factors of compromised health (i.e. predation, sedimentation damage, physical damage, etc.) are strongly influenced by use levels. A recent study by Hein *et al.* (2014) found that using low estimates of diver numbers based on boat traffic, the average dive site on Koh Tao experiences 150 divers per day, much higher than the recommended carrying capacity of around 6,000 dives per year (Hawkins and Roberts 2007, Zakai and Chadwick-Furman 2002). As of summer 2015, two sites on the island, Hin Wong Bay and Mango Bay, had experienced outbreaks of Brown Band and Skeletal Eroding Band Diseases amongst branching and tabulate acroporids, with less than 25% of the corals coded as healthy in recent EMP surveys (unpublished data). As reef based tourism from the island and surrounding areas continues to increase each year, coral disease is expected to become a larger problem for the reefs in the future.

Coral predation rates often increase following bleaching events (Baird 1999, Hoeksema, Scott & True 2013) and also in marginalized reefs (Antonious & Riegl 1998). Coral predation by both *Drupella* snails and the crown of thorns starfish (*Acanthaster planci*) is a growing concern on the island as outbreaks and over populations are being documented (Hoeksema, Scott & True 2013, Moerland *et al.* 2016, Scott *et al*. 2017). Specific to *Drupella* snails, there has been a doubling of the abundance of the snails across all reefs surveyed in 2009-2014 (Scott *et al*. 2017). Similar to disease outbreaks, increased *Drupella* snail populations around the island have been linked to the effects of coral bleaching (Hoeksema, Scott & True 2013), over-use of reefs by tourism activities (Lamb *et al.* 2014, Hein et al. 2014) and sedimentation (Hein *et al*. 2014). This has been observed most notably in Chalok Ban Kao, but the presence of the snail is ubiquitous across all sites. The *Acropora* dense shallow reefs of Chalok had partially recovered in 2014, yet still in 2015 the abundance of *Drupella* snails in the bay was at outbreak levels, despite over 40,000 individual *Drupella* snails being removed from the area by volunteers.

Sedimentation affects corals through decreased light availability, increased microbial density, impaired feeding ability, physical abrasion, smothering, or burial (Fabricius 2005). Local sources of sedimentation on Koh Tao derive mainly from land based activities such as deforestation and development which has been occurring at an increasing rate over recent years such that today over half of the island's surface is developed or highly altered (Weterings 2011, Szuster and Dietrich 2014). The inundation of sediment in Tanote Bay was caused by the construction of a large reservoir (Fig. 7) which buried the reef flat in 1.5-2 meters of silt and decreased local water quality in the bay and in adjacent areas for several years (Larpnun *et al.* 2011).

Recent progress with respect to stakeholder involvement, governance, and regulations/zoning concerning the marine resources of Koh Tao is promising. The island community has largely solved previous issues identified in the late 1990's (Flummerfelt 1999) of anchor dropping and marine debris. By 2015, the island has over 150 mooring lines, monthly land and underwater clean-ups, improved solid waste management, and a ban on foam boxes. The efforts of the local dive industry to manage resources through alternative dive sites, artificial reefs, coral nurseries, and monitoring programs shows marked improvement over previous decades and grants some optimism for the future.

Although the observed increase in coral cover is fairly consistent throughout the 2006-2014 survey, the present study highlights a marked change in community structure of the coral reefs (Fig. 8). Reefs around the island are becoming dominated by resilient/resistant coral genera as more vulnerable species decline (cf. Hein *et al*. 2014). This is congruent with other studies showing that coral communities shift towards brooding species and reduced diversity in terms of recruitment and recovery, in stressed and degraded reefs (Hughes 1994, Baker *et al*. 2008). The shift towards structurally and functionally less diverse *Pavona*, *Fungia*, and *Porites* corals has larger implications for the composition and biodiversity of fish and invertebrate assemblages on the reefs.

Acknowledgments

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