ORIGINAL ARTICLE

# Assessing Coral Reef Resilience to Climate Change in Thailand

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**Abstract** Major coral bleaching phenomena have resulted in widespread coral mortality in recent decades. The assessment of coral reef resilience to climate change is an important task but has been difficult to carry out because of a lack of empirical scientific data. Coral reef resilience at twenty study sites in Thai waters was quantitatively assessed, approximately two years following the 2010 severe bleaching event, based on the percentage of non-bleached coral colony, the percentage of surviving coral colonies and the density of juvenile corals. Coral reef resilience varied greatly among the study sites and major reef groups according to their community structure, largely due to the differing bleaching resistance and tolerance of the dominant coral species. Most study sites in the Gulf of Thailand had much lower coral recruitment rates compared to other reef sites in Thai waters. The study sites in the Inner Gulf of Thailand had the highest resilience while the study sites in the Andaman Sea had the lowest.

**Keywords** coral bleaching, recruitment, resilience, assessment, Thailand

## 1. Introduction

The concept of resilience was first introduced in an ecological context as a measure of the persistence of systems and their ability to absorb change and disturbance whilst still maintaining the same relationships between populations or state variables (Holling 1973). Resilience thinking has been increasingly debated in the context of social-ecological systems. Current resilience research overall is dominated by developed countries and it is in the urgent need for practically oriented solutions that would help inhibit further ecological degradation (Xu and Marinova 2013). Resilience concepts are being increasingly applied to coral reefs in the Caribbean, Indo-Pacific and other parts of the world (McClanahan et al. 2002; Bellwood 2004; Hughes et al. 2005; Obura 2005; Adjeroud et al. 2009; Maynard et al. 2010; Bachtiar et al. 2012; Halpern et al. 2012; McClanahan et al. 2012; Roff and Mumby 2012; Mumby et al. 2012). Many studies have conducted resilience assessment after natural and anthropogenic disturbances (Berumen and Pratchett 2006; Ledlie et al. 2007; Smith et al. 2008; Bachtiar et al. 2012; Ferrigno et al. 2016). Coral reefs across the world are under increasing pressure from natural disturbances and human impacts (Lesser 2004; Sarkar and Ghosh 2013). These include increased sediment and nutrient discharges (Dikou and van Woesik 2006; De'ath and Fabricius 2010; Erftemeijer et al. 2012), coral diseases (Richardson 1998; Green and Bruckner 2000; Lesser et al. 2007; Miller and Williams 2007; Vollmer and Kline 2008; Sutherland et al. 2010; Roger and Muller 2012), and coral bleaching (Glynn 1993; Brown 1997; McClanahan 2000; Baker et al. 2008, McClanahan et al. 2008; Montano et al. 2010; Depczynski et al. 2012; Hill et al. 2012; van Woesik et al. 2012). It is recognized that approximately 75% of the world's coral reefs are categorized as being threatened when local stresses are combined with thermal impacts arising from the recent threats of rising seawater temperature, linked to the widespread weakening and mortality of corals because of mass coral bleaching (Burke et al. 2011). Coral reef resilience to bleaching is a special case of ecological resilience, where coral recovery following mass bleaching mortality varies according to ecological processes and other factors. Some reefs appear to avoid, or be protected from, high temperatures and radiation, or to be resistant to bleaching or mortality (Obura 2005; Tkachenko et al. 2017). In the context of coral bleaching, resilience can be defined as the ability for the coral community to return to their initial state after significant mortality and to be controlled by local ecological factors, large scale connectivity and larval supply components. The assessment of ecosystem resilience can be also applied in coral reef management as an important tool (Roff and Mumby 2012; Buglass et al. 2016; Mora et al. 2016; Shlesinger and Loya 2016).

The coastal areas of Thailand, between latitudes of 6° and 13°N, offer suitable environmental conditions for the growth of coral reefs. There are approximately 153 $km^2$ of coral reefs, consisting of 78 $km^2$ in the Andaman Sea and 75 $km^2$ in the Gulf of Thailand, and over 300 relatively small islands along the nation's with approximately 3,000 km coastline. These reefs can be classified into four groups with different oceanographic conditions: the inner part of the Gulf of Thailand (Chonburi Province); the east coast of the Gulf of Thailand (Rayong, Chanthaburi and Trat Provinces); the west coast of the Gulf of Thailand (Prachuab Kirikhan, Chumporn, Suratthani, Nakhon Si Thammarat, Songkhla, Pattani and Narathiwat Provinces); and the coastline of the Andaman Sea (Ranong, Phuket, Pang-Nga, Krabi, Trang and Satun Provinces) (Yeemin et al. 2006). The 2010 mass coral bleaching event caused coral degradation to be more severe and extensive in the Andaman Sea than in the Gulf of Thailand, with the inner Gulf of Thailand exhibiting the lowest bleaching impact. Coral taxa in Thai waters are different in their susceptibility to coral bleaching which is a critical aspect of reef studies because it can remarkably result in coral community changes (Yeemin et al. 2012a; Sutthacheep et al. 2012). The present study quantitatively assessed coral reef resilience in the Gulf of Thailand and the Andaman Sea, based on empirical scientific evidence from the surveys about two years following the 2010 coral bleaching event.

## 2. Material and Methods

### *2.1. Study sites*

The study was conducted in the Gulf of Thailand and the Andaman Sea. Twenty study sites involving five locations; the inner Gulf of Thailand (seven sites), the eastern Gulf of Thailand (four sites), the western Gulf of Thailand (three sites), the north Andaman (three sites), and the south Andaman Sea (three sites), have been routinely surveyed for various scientific purposes since 2009 (Figure 1).

The study sites in the Inner Gulf of Thailand were shallow coral communities developed on rock and/or sandy bottoms. Hin Ta Sin and Ko Khang Khao are affected from freshwater runoff as they are located close to major rivers and are comparatively turbid most of the year. The study sites in the eastern Gulf of Thailand were offshore fringing reefs, approximately 30 km from the mainland. The coral reefs were generally shallow, around 2-8 m in depth. The study sites in the western Gulf of Thailand were shallow fringing reefs in Ko Samui area, recognized as an important tourism site in Thailand with severe impact from tourism development. The study sites in the north Andaman Sea were offshore fringing reefs which had greater water clarity, resulting in well-developed coral reefs. The coral reefs extend from 1 to 18 m depth. Ko Surin is one of the top diving sites in the Andaman Sea. The study sites in the south Andaman Sea were located at a near-shore sheltered area, approximately 13 km from the mainland. The coral reefs were in clear shallow water of about 1-9 m depth. All six reef sites in the Andaman Sea are in the jurisdiction of the Department of National Parks, Wildlife and Plant Conservation, Thailand. The location, environmental conditions, and anthropogenic disturbances in each study site are summarized in Table 1.

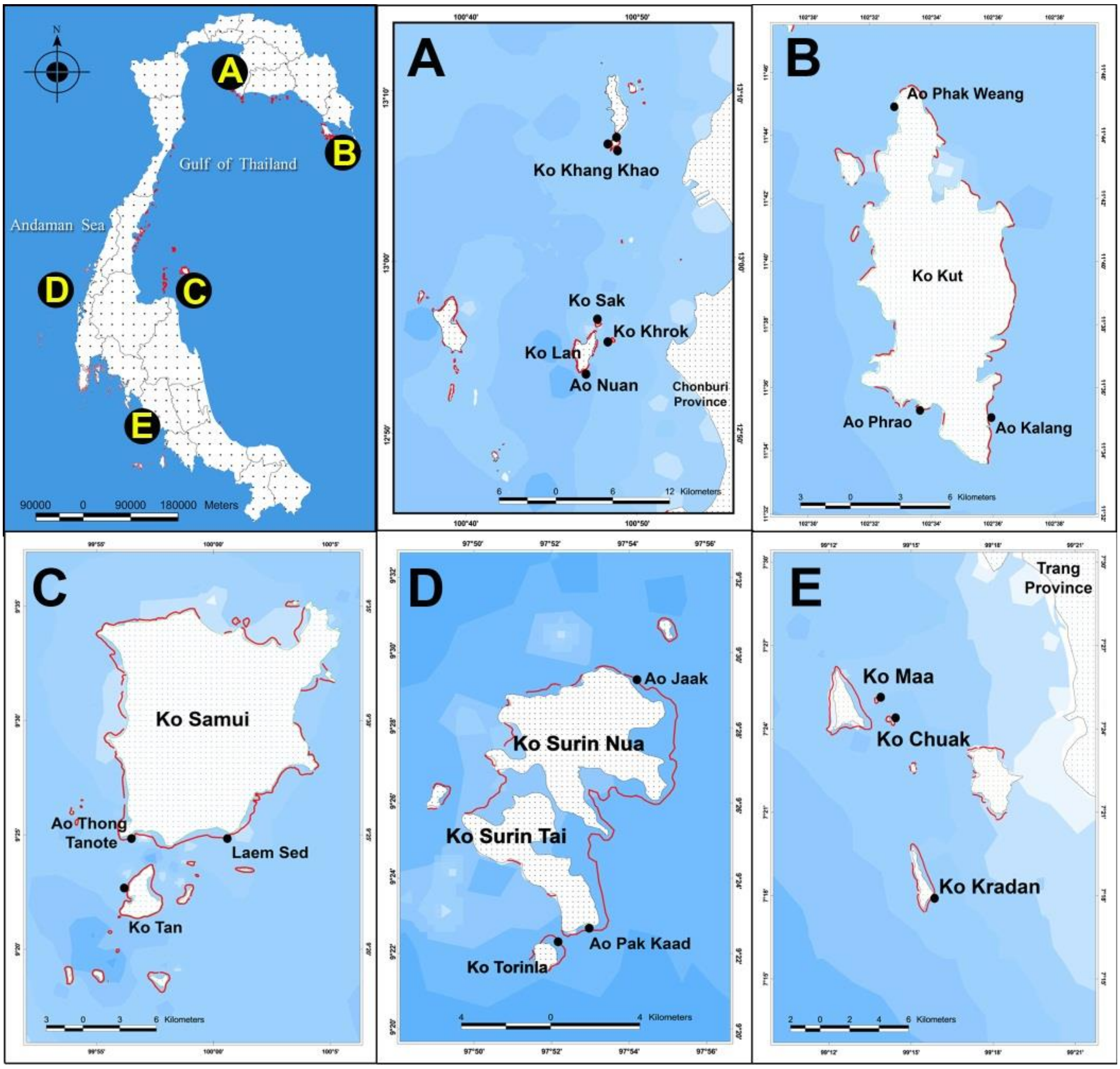


**Figure 1.** Map of study sites. (A) the Inner Gulf of Thailand, (B) the Eastern Gulf of Thailand, (C) the Western Gulf of Thailand, (D) North Andaman Sea, (E) South Andaman Sea.

**Table 1.** Location and information of study sites in the Gulf of Thailand and the Andaman Sea, Thailand

| Study Sites | Latitude (N), Longitude (E) | Exposure condition | Water transparency | Depth (m) | Anthropogenic disturbance |
|---|---|---|---|---|---|
| **A) Inner Gulf of Thailand** | | | | | |
| Hin Ta Sin | N 13° 07' 55.60" E 100° 49' 05.10" | Exposure | Turbid | 1-3 | Fishery |
| Ko Khang Khao (North) | N 13° 07' 04.40" E 100° 48' 26.35" | Sheltered | Turbid | 4-5 | Tourism Fishery |
| Ko Khang Khao (West) | N 13° 06' 46.40" E 100° 48' 18.40" | Sheltered | Turbid | 3-5 | Fishery |
| Ko Khang Khao (Southeast) | N 13° 06' 46.30" E 100° 48' 31.10" | Exposure | Turbid | 3-6 | Fishery |
| Ao Nuan, Ko Lan | N 12° 53' 54.53" E 100° 46' 36.50" | Sheltered | Turbid | 4-7 | Tourism |
| Ko Khrok (West) | N 12° 55' 42.20" E 100° 48' 14.90" | Exposure | Turbid | 4-9 | Tourism |
| Ko Sak (Northwest) | N 12° 56' 45.64" E 100° 47' 25.77" | Exposure | Turbid | 2-5 | Tourism |
| **B) Eastern Gulf of Thailand** | | | | | |
| Hin Gurk Maa | N 11° 47' 29.25" E 102° 23' 57.56" | Exposure | Clear | 4-8 | Tourism |
| Ao Phak Weang, Ko Kut | N 11° 45' 00.71" E 102° 32' 41.31" | Sheltered | Clear | 6-8 | Fishery |
| Ao Phrao, Ko Kut | N 11° 35' 29.00" E 102° 33' 30.40" | Sheltered | Turbid | 2-6 | Fishery |
| Ao Kalang, Ko Kut | N 11° 35' 10.20" E 102° 35' 41.10" | Sheltered | Turbid | 2-4 | Fishery |
| **C) Western Gulf of Thailand** | | | | | |
| Ao Thong Tanote, Ko Samui | N 09° 24' 56.70" E 99° 56' 18.30" | Sheltered | Turbid | 1-3 | Tourism Fishery |
| Laem Sed, Ko Samui | N 09° 25' 06.75" E 99° 59' 56.26" | Sheltered | Turbid | 1-5 | Tourism, Fishery |
| Ko Tan (Northeast) | N 09° 23' 06.80" E 99° 56' 48.90" | Sheltered | Clear | 1-7 | Tourism, Fishery |
| **D) North Andaman Sea** | | | | | |
| Ao Jaak, Ko Surin North | N 09° 27' 17.65" E 97° 53' 50.53" | Sheltered | Clear | 1-17 | Tourism |
| Ao Pak Kaad, Ko Surin Tai | N 09° 22' 48.23" E 97° 52' 53.79" | Sheltered | Clear | 1-18 | Tourism |
| Ko Torinla (North) | N 09° 22' 30.17" E 97° 52' 13.17" | Exposure | Clear | 1-16 | Tourism |
| **E) South Andaman Sea** | | | | | |
| Ko Kradan (East) | N 07° 18' 24.74" E 99° 15' 34.36 | Sheltered | Clear | 1-8 | Tourism |
| Ko Chuak (East) | N 07° 24' 20.42" E 99° 13' 55.21" | Sheltered | Clear | 2-9 | Tourism |
| Ko Maa (East) | N 07° 25' 02.68" E 99° 13' 25.68" | Sheltered | Clear | 1-6 | Tourism |

*2.2. Survey method*

At each study site, three permanent belt transects of 30 x 1 $m^2$ were used. The surveys were conducted before the 2010 bleaching event in 2009, during the bleaching in 2010, and after the bleaching in February 2011 – March 2012. During the bleaching event, the corals presenting inside the permanent belt transect were classified into three categories, healthy (no apparent bleaching), partially bleached (portions of the colony bleached or pale), or completely bleached (the entire colony was white).

After the bleaching event, corals (>5 cm diameter) were classified as healthy (without apparent bleaching and subsequent mortality), or as those suffering partial or complete mortality as a result of the bleaching. For the juvenile coral study, the number of visible juvenile corals (1-5 cm diameter) were measured in three permanent belts-transects (30 x 1 $m^2$ for each). Live coral cover was also recorded in each belt-transect.

In each permanent belt transect, all visible coral colonies were counted and identified to a species level, if possible, and their coverage was quantitatively estimated. Quadrats (1 m x 1 m), subdivided into 100 squares of 100 $cm^2$, were positioned along transects. The quadrats were also photographed with an underwater camera for re-investigating the data and calculating percentages of non-bleached coral, surviving coral, and live coral cover.

*2.3. Data analysis*

The data of percentages of non-bleached coral, surviving coral, and live coral following the bleaching and density of juvenile coral were tested for normality and homogeneity of variances. The data were normalized using the square root transform function. A one-way ANOVA was used to test the difference between locations. Where significant differences were found, the Tukey HSD test was employed to determine which reef site(s) differed.

**3. Results**

The percentages of non-bleached corals during the 2010 bleaching event varied significantly among the study sites (Figure 2, ANOVA, $p$<0.001). Corals at Ao Phrao (Ko Kut) in the eastern Gulf of Thailand had the highest percentage of non-bleached corals (61%) whereas Ao Jaak (Ko Surin Nua) in the north Andaman Sea had the lowest (2%). All the study sites in the Andaman Sea showed very low percentages of non-bleached coral (2-17%). There were four study sites where a percentage of non-bleached corals was over 50%, i.e. Hin Ta Sin, Ko Khrok (West), Ko Sak (Northwest) in the inner Gulf of Thailand and Ao Phrao (Ko Kut) in the eastern Gulf of Thailand.

The percentages of surviving coral following the bleaching events in 2010 varied significantly between the study sites (Figure 2, ANOVA, $p$<0.001). The highest percentage of the surviving coral was found at Hin Ta Sin in the inner Gulf of Thailand (93%) and Ao Jaak (Ko Surin Nua) in the north Andaman Sea had the lowest (4.2%). The study sites at Ao Jaak (Ko Surin Nua), Ao Pak Kaad (Ko Surin Tai) and Ko Torinla (North) in the north Andaman Sea showed very low percentages of surviving coral (4-10%).

There were significant statistical differences of the percentages of live coral coverage among the study sites after the 2010 coral bleaching event (Figure 2, ANOVA, $p$<0.001). The percentages of live coral coverage at the twenty study sites after the coral bleaching event were in the range of 3–42 %. Ao Phak Weang (Ko Kut) in the eastern Gulf of Thailand had the highest percentage (42.8%), while those at Ao Jaak (Ko Surin Nua) in the north Andaman Sea had the lowest (3%).

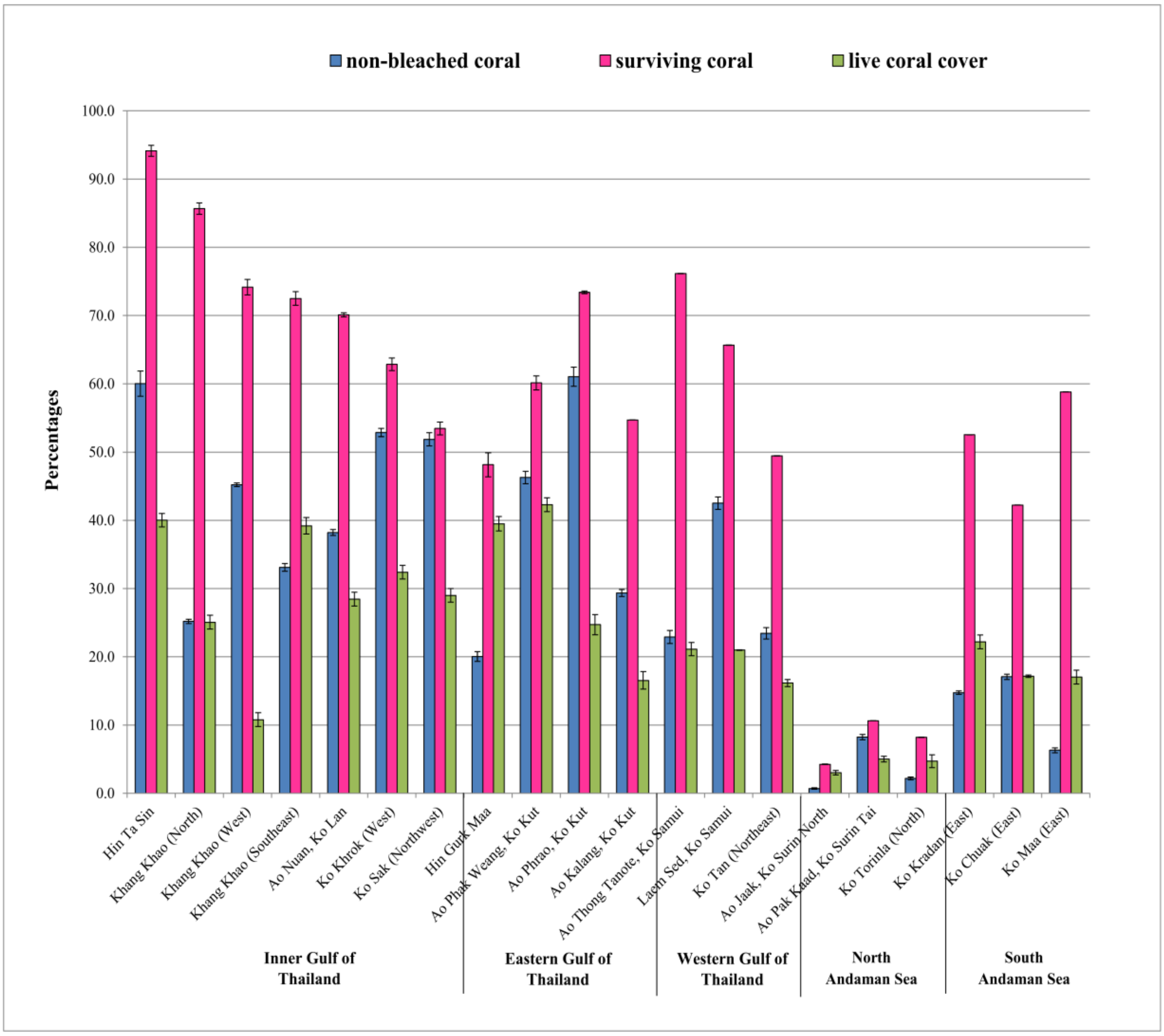


**Figure 2.** Percentages of non-bleached corals and surviving corals during the 2010 coral bleaching event and percentages of live coral coverage after the 2010 coral bleaching at the 20 study sites (Means±SE).

The density of juvenile corals following the 2010 bleaching event was significantly different among the study sites (Figure 3-4, ANOVA, $p$<0.001).The highest average density of juvenile corals 1.8 juveniles/$m^2$)was in Ao Jaak (Ko Surin Nua) in the north Andaman Sea (while the lowest was in Ko Khang Khao (North) in the inner Gulf of Thailand (0.2 juveniles/$m^2$). All study sites of Ko Surin in the north Andaman Sea showed a relatively high average density of juvenile corals (1.3-1.8 juveniles/$m^2$).

Non-bleached colonies (%), surviving colonies (%), live coral following the bleaching event (%), and juvenile coral density among the study sites were significantly different (Table 2, ANOVA, $p$<0.001).

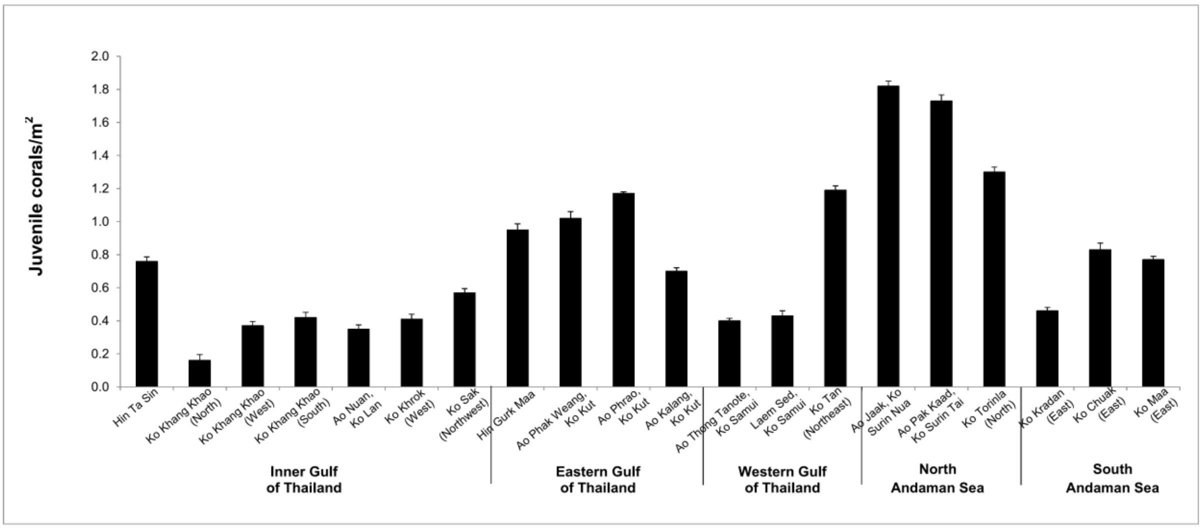


**Figure 3.** Juvenile coral densities following the 2010 coral bleaching event at the study sites (Means±SE).

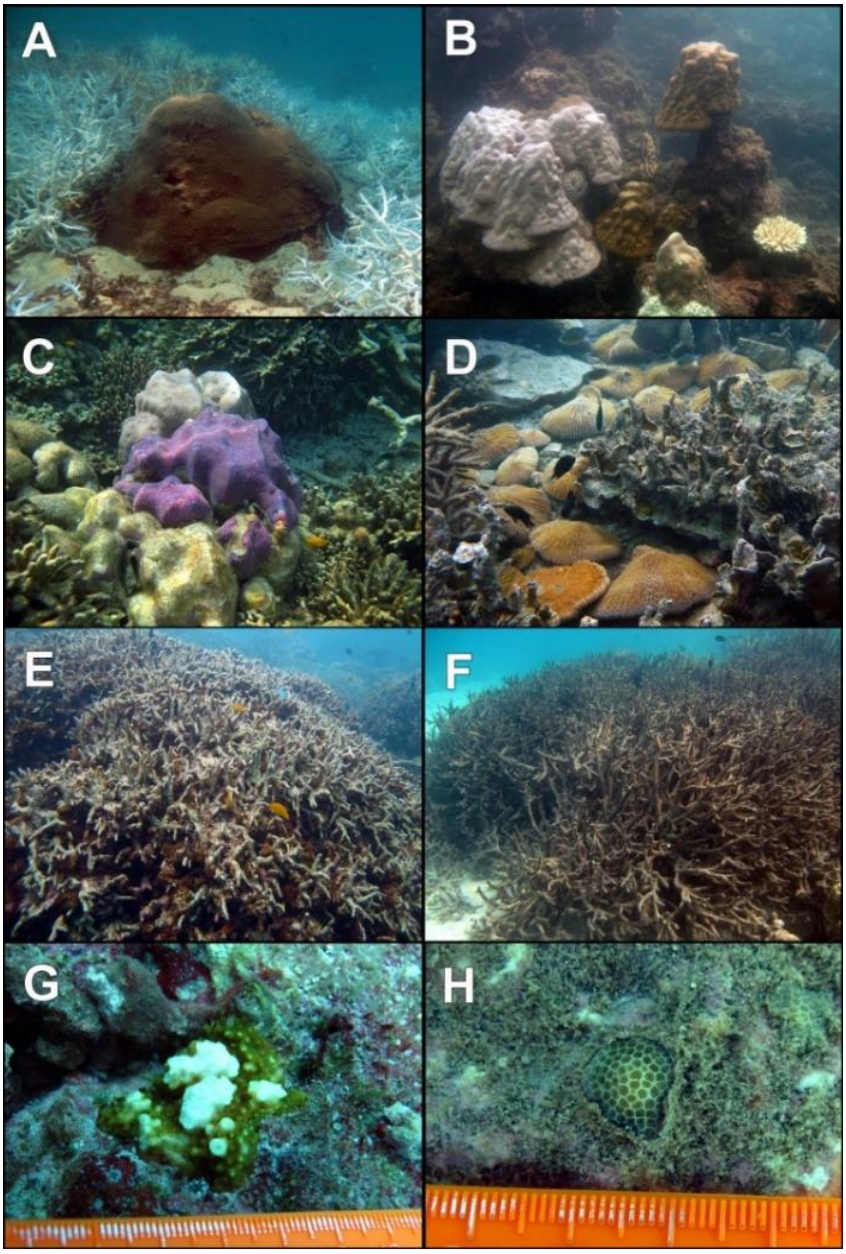


**Figure 4.** Coral colonies at the study sites: (A) non-bleached *Diploastrea heliopora* colony in the Andaman Sea, (B) non-bleached *Porites lutea* colony in the Gulf of Thailand, (C) surviving *Porites lutea* colony in the Andaman Sea, (D) surviving *Fungia fungites* in the Gulf of Thailand, (E) dead *Porites cylindrica* colony in the Andaman Sea, (F) dead *Acropora muricata* colony in the Gulf of Thailand, (G) juvenile *Acropora* colony in the Andaman Sea and (H) juvenile *Porites* colony in the Gulf of Thailand

**Table 2.** A result of one-way ANOVA testing for differences in (A) non-bleached colony (%); (B) surviving colony (%); (C) live coral following the bleaching event (%) and (D) juvenile coral density among study sites.

| Source of variation | SS | df | Mean square | *F* | *p* |
|---|---|---|---|---|---|
| A) Non-bleached colonies | | | | | |
| Among sites | 20641.381 | 19 | 1086.388 | 1.822 | <0.001* |
| Within sites | 23.847 | 40 | 0.596 | | |
| Total | 20665.227 | 59 | | | |
| B) Surviving colonies | | | | | |
| Among sites | 34050.389 | 19 | 1792.126 | 3.740 | <0.001* |
| Within sites | 19.166 | 40 | 0.479 | | |
| Total | 34069.555 | 59 | | | |
| C) Live coral following the bleaching event | | | | | |
| Among sites | 8193.394 | 19 | 431.231 | 479.632 | <0.001* |
| Within sites | 35.964 | 40 | 0.899 | | |
| Total | 8229.358 | 59 | | | |
| D) Juvenile coral density | | | | | |
| Among sites | 12.307 | 19 | 0.648 | 777.288 | <0.001* |
| Within sites | 0.033 | 40 | 0.001 | | |
| Total | 12.340 | 59 | | | |

*Significant difference ($p<0.001$), df: degree of freedom

## 4. Discussion

Our field studies across five coral reef regions in Thai waters contrasted in their level of environmental conditions and anthropogenic disturbances. The observations before, during and after the 2010 bleaching event allow us to assess reef resilience to coral bleaching based on direct factors rather than indirect ones. The percentages of non-bleached coral in this study included corals which were avoidant or resistant to the 2010 coral bleaching event. The percentages of surviving coral following the bleaching events in 2010, or the tolerance, varied significantly among the study sites. The most tolerant site was at Hin Ta Sin in the Inner Gulf of Thailand while the lowest one was at Ao Jaak (Ko Surin Nua) in the north Andaman Sea. This agrees with a previous report by Yeemin et al. (2012a) indicating sea surface temperature anomalies between the 30-34°C recorded during March-June 2010 in the Andaman Sea and the Gulf of Thailand, and further resulting in widespread and severe coral bleaching of over 80% at several reef sites. Coral bleaching in the Andaman Sea was more severe and extensive than in the Gulf of Thailand, with the inner Gulf of Thailand exhibiting the lowest bleaching impact. The most susceptible coral taxa were *Acropora* spp. and *Pocillopora* spp. (Sutthacheep et al. 2012; Yeemin et al. 2012b). The most highly resistant sites harbored *Porites* spp. and *Pavona* spp. The patterns of seawater temperature anomalies in five regions of coral reefs in Thai waters were obviously different (Yeemin et al. 2010; Pengsakun and Yeemin 2011; Yeemin et al. 2012b).

The density of juvenile corals following the 2010 bleaching event differed significantly among the study sites. Ao Jaak (Ko Surin Nua) in the north Andaman Sea had the highest average density of juvenile corals whereas it was the least resistant and tolerant site. The live coral cover at Ao Jaak (Ko Surin Nua) was only 3%. Coral coverage may have a negative association with the density of juvenile coral and appear that a larger local stock of adult coral does not result in a higher density of recruits (Mumby et al. 2012). The dominant juvenile corals in the Andaman Sea were *Acropora* spp. and *Fungia* sp. and their densities were relatively low compared with other reef sites in Maldives and the Pacific (McClanahan 2000; Roth and Knowlton 2009; Yucharoen and Yeemin 2012). The drivers of coral recruitment are complex and may include effects of coral cover, macroalgal biomass, corallivore abundance and canopy of algal turfs (Yeemin et al. 2009; Mumby et al. 2012). While it is too early to assess the long-term impacts of the 2010 coral bleaching event, we expect that the coral communities in the North Andaman Sea may regrow gradually, at least based on the abundance of juvenile corals we have found at the study sites (Adjeroud et al. 2009; Yucharoen et al. 2015).

Studies on coral reef resilience have been conducted intensively in the last decade. There are several available assessment methods that were developed and applied at many reef sites (Smith et al. 2008; Obura and Grimsditch 2009; Maynard et al. 2010; Bachtiar et al. 2011; Swain et al. 2017). Some methods for assessing coral reef resilience require many variables or high expertise that includes a long list of indirect factors, therefore. it is difficult to practice in developing countries. In the present study, we attempt to provide a simple set of data on coral conditions using empirical data from the studies on the impact of the 2010 coral bleaching event in the Gulf of Thailand and the Andaman Sea. All three study sites at Mu Ko Surin, the north Andaman Sea, had very low resistance and tolerance, although these study sites are in the marine protected area which has an implemented management plan (Yeemin et al. 2012a). In contrast, the most resilient site was in the Inner Gulf of Thailand where there are no any coral reef management plans and the water in relatively turbid (Klinthong and Yeemin, 2010; Pengsakun and Yeemin, 2010). Our findings can stimulate local managers in the Andaman Sea to seriously consider the appropriate way for building and enhancing coral reef resilience at certain sites, particularly the tourist hot spots.

The management of coral reefs usually requires a broader context of social and environmental issues other than coral bleaching. Coral reef resilience gives a way to plan for these in the same framework as coral bleaching, incorporating their impacts on and contributions to functional diversity (Obura, 2005). Reef sites possessing threats other than those related to coral bleaching events have their own needs for management which may be planned based on resilience in a similar pattern as has been done for coral bleaching. The major issues involve tourism, fisheries, conservation and other socio-economic activities currently related to coral reefs (McClanahan et al. 2002; Samsuvan and Yeemin 2012). The management of coral reefs is very important because they are intensively used by local communities, and concern for the well-being of local people dependent on coral reef ecosystem services is essential. Social resilience issues should be also included in the coral bleaching management in Thai waters as it relates to the social vulnerability to the resilience of the coral reefs and natural resources on which they depend (Marshall and Schuttenberg 2006, Obura 2005, Sutthacheep et al. 2012; Tkachenko 2017). The present study provides insights into the degree to which coral communities in Thai waters are resilient to climate change based on empirical scientific evidence.

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