Crab Biodiversity in Coral Reefs around Mu Koh Tao, Thailand, and the Role of Coral Crabs as Indicators of Habitat Loss Caused by Coral Bleaching

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ABSTRACT

Coral reefs provide ideal habitats for crabs and various living organisms, offering crevices, sandy bottoms, and a rich diversity of resources. Mu Koh Tao, located on the western Gulf of Thailand, boasts vibrant coral reefs and potentially high crab biodiversity. However, coral bleaching due to climate change may impact this biodiversity. This study investigates the diversity, abundance, distribution, and community structure of crabs in coral reefs around Koh Tao and Koh Nang Yuan, including 11 sampling stations with varying levels of coral bleaching. A total of 47 crab species from 34 genera and 14 families were identified. The most abundant and notable species were *Trapezia cymodoce, Tetralia nigrolineata,* and *Tetralia rubridactyla*. Additionally, two species were newly recorded in the Gulf of Thailand, and seven species were potentially first reports for Thailand. Rare species dominated, comprising 82.98% of the total. Shark Island had the highest Shannon-diversity and species richness indices, at 2.43 and 5.53, respectively, underscoring its ecological importance. The crab community structure varied with the severity of coral bleaching and the diversity of associated organisms. An in-depth study compared the abundance of coral crabs in healthy versus bleached corals, revealing that *Tr. cymodoce* did not inhabit bleached *Pocillopora damicornis*, while *Te. nigrolineata* was found in both healthy and bleached *Acropora hyacinthus*, with densities of 23.81 and 7.24 individuals per square meter, respectively. These findings suggest that coral crabs can serve as indicators of climate change-induced coral bleaching and associated habitat loss, highlighting the need for conservation efforts to protect these ecosystems.

Keywords: Climate change, Coral reef, *Tetralia, Trapezia*

INTRODUCTION

Crabs, as invertebrates, occupy a wide range of ocean habitats, ranging from coastal intertidal zones to the abyssal depths, illustrating their notable ecological adaptability (Debelius, 1999; Davie, 2021). These animals play pivotal roles in marine ecosystems: they serve as primary consumers, adept deposit feeders, and efficient decomposers, intricately integrated into the food chain and frequently forming symbiotic relationships with various organisms (Warner, 1977; Thamrongnawasawat and Wisespongpand, 2007). Additionally, crabs significantly contribute to ecosystem health by accelerating organic matter mineralization, enhancing nutrient cycling, and fostering habitat complexity for other interstitial fauna (Kristensen, 2008; Xie *et al*., 2022).

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Coral reefs, renowned for their biodiversity, serve as habitats for numerous crab species owing to abundant food resources and shelter opportunities (Debelius, 1999; Jaingam, 2013; Ryanskiy, 2020). Within these vibrant ecosystems, crabs find refuge among various sessile organisms, effectively mitigating predation risks and securing sustenance (Castro *et al*., 2004; Jaingam *et al*., 2008; Davie, 2021). The relationships crabs forge with symbiotic partners significantly contribute to the biodiversity and stability of coral reef environments (Jaingam *et al*., 2008; Stier *et al*., 2012; Limviriyakul *et al*., 2016).

Notably, scleractinian corals, pivotal ecosystem engineers, host specific crab genera such as *Tetralia* and *Trapezia* (Castro *et al*., 2004; Wisespongpand *et al*., 2022). These obligate coral symbionts engage in mutualistic relationships, defending their coral hosts against predators such as crown-of-thorns starfish (Castro, 1976; Patton, 1994; Pratchett, 2001), and contributing to sediment removal and larvae control, crucial processes for coral health (Stewart *et al*., 2006; Stier *et al*., 2012). Their presence not only supports coral resilience but also influences plankton dynamics within coral reef ecosystems (Shmuel *et al*., 2022). Indeed, the health of coral reefs can be gauged by the presence and vitality of coral crabs, underscoring their role as robust ecological indicators (Stella *et al*., 2011).

Located in the western region of the Gulf of Thailand, Mu Koh Tao comprises islands such as Koh Tao and Koh Nang Yuan, globally renowned for their coral reefs inhabited by sea turtles and diverse marine fauna (Marine and Coastal Resources Conservation Office, 2013). Koh Tao stands out as a premier diving destination, owing to its rich coral biodiversity. However, significant gaps in research persist regarding the diversity of crabs in this region, intensified by ongoing infrastructure development and coral bleaching events associated with climate change (Stella *et al*., 2011; Poltanee and Boonphetkaew, 2018).

This study aims to comprehensively analyze the diversity, abundance, distribution, and community structure of crabs across coral reef ecosystems surrounding Koh Tao and Koh Nang Yuan, considering varying degrees of coral bleaching and associated environmental factors. Specifically, it focuses on comparing coral crab abundance between healthy and bleached corals, striving for insights to guide the sustainable management and conservation of crab resources in Mu Koh Tao.

MATERIALS AND METHODS

Crab survey and sampling

A total of 11 sampling stations were surveyed in the coral reefs of Koh Tao and Koh Nang Yuan. These stations were categorized into three levels of coral bleaching: low (less than 10%), medium (11–30%), and high (31–50%) (Figure 1). The study was conducted from May to June 2023, for 7 days for each month, from 8.00 a.m. to 6.00 p.m. during the daytime and from 7.00 p.m. to 9.00 p.m. at nighttime. Crab samples were collected using SCUBA diving methods and by hand, searching for crabs hiding in rock and coral crevices, as well as those cohabiting with other organisms. Crabs inhabiting on sand, gravel, fragment corals, and those camouflaging themselves were collected by lying down and observing their movements. Some crabs concealed in rock and coral crevices were captured by photographing them. Daytime surveys focused on crabs living among various symbiotic species in coral reefs and those hidden on the seabed, while nighttime surveys targeted crabs foraging in coral reef areas and adjacent regions.

Observation on diversity, abundance and distribution of crabs

The study on species richness employed taxonomic classification methods following De Grave *et al*. (2009), and taxonomic identification was based on the works of Dai and Yang (1991), Chia *et al*. (1999), McLay (2001), McLaughlin (2002), Tan and Ng (2003), Castro *et al*. (2004), Rahayu (2006), Osawa (2007), Komai (2010), Griffin and Tranter (2013), Mendoza *et al*. (2014), Wongissarakul (2017), Poupin *et al*. (2018), and Koch *et al*. (2022). The distribution and updated classification were verified using sources such as Naiyanetr (2007), the World Register of Marine Species (WORM) website, and the Crab database.

Abundance assessment categorized crab numbers into three levels: low (+), moderate (++), and high (+++), representing <4, 4–10, and >10 crabs per 50 min of diving survey, respectively. Crab status was determined based on relative abundance and the percentage of survey stations where crabs were found relative to the total number of stations surveyed. Dominant species were those with ++ or +++ abundance observed in more than 75% of survey stations, common species were found in 45–74% of stations with +, ++, or +++ abundance, and rare species were present in fewer than 45% of stations with +, ++, or +++ abundance.

Analysis of crab community structure

The community structure of crabs was compared among survey stations categorized into three levels of coral bleaching (Figure 1). Species diversity was assessed using univariate methods such as the Shannon-Wiener diversity index, Simpson diversity index, species richness index, and species evenness index. Cluster analysis was conducted to evaluate spatial similarities, employing multivariate methods that classified and illustrated clustering characteristics of community diversity and abundance at each site based on the Bray-Curtis similarity matrix, which was presented as a dendrogram. Multidimensional scaling (MDS) ordination was utilized to arrange the sequence of differences among living organisms (Clarke and Warwick, 1994) using PRIMER (v.5) software from the Plymouth Marine Laboratory, UK.

Analysis of factor and environmental condition of crab habitats

The biological characteristics of the survey stations, including coral species, the percentage of bleached corals, and the presence of organisms cohabiting with crabs, were assessed. Physical and chemical factors such as air temperature (measured

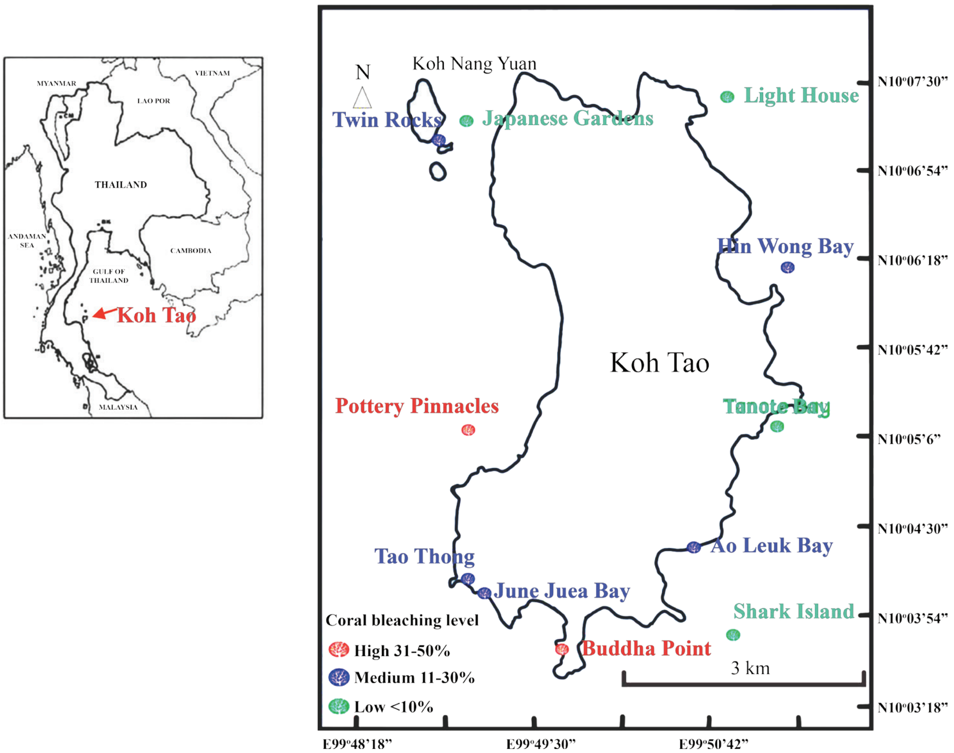

Figure 1. Locations of 11 crab survey and sampling stations with three different levels of coral bleaching around Mu Koh Tao.

with a BENETECH GM1360), water temperature, salinity, pH, and dissolved oxygen (DO) were measured using a Multiprobe (YSI Pro DSS), while levels of nitrate (HACH DR2400), ammonia, and phosphate (Grasshoff *et al*., 1999) were analyzed. Meteorological factors including sea surface conditions, wave height, wind speed, and cloud cover were also monitored (Pollution Control Department, 2001).

Comparison of coral crab abundance between healthy and bleached coral reefs

Coral crab abundance was assessed at 5 stations: June Juea Bay, Ao Luek Bay, Pottery Pinnacles, Twin Rocks, and Japanese Gardens (Figure 1), where bleached corals were observed. The study focused on two dominant coral crab species, *Trapezia cymodoce* and *Tetralia nigrolineata*, within five 50×50 cm quadrats placed at each station. The number of crabs was counted, and their density calculated (inds·m^2) to compare between healthy and bleached corals (Figure 2). The data were expressed as mean ± standard deviation. Differences between the means of the two groups were analyzed using a one sample t-test at a 99% confidence level ($p<0.01$).

RESULTS AND DISCUSSION

Biological characteristics of survey and sampling stations

The coral reefs surveyed around Mu Koh Tao were located at depths ranging from 5 to 14 meters. They predominantly consisted of coral reefs forming on underwater stone piles and sandy bottoms. The most prevalent coral species included staghorn corals (*Acropora Formosa* and *Acropora valenciennesi*), table corals (*Acropora latistella* and *Acropora hyacinthus*), fine-spined corals (*Montipora* sp.), cauliflower corals (*Pocillopora damicornis*), and hump corals (*Porites lutea*). These reefs were fertile and comparable to those documented in a 2013 survey of coral reef organisms around Koh Tao by the Office of Marine and Coastal Resources Conservation (Marine and Coastal

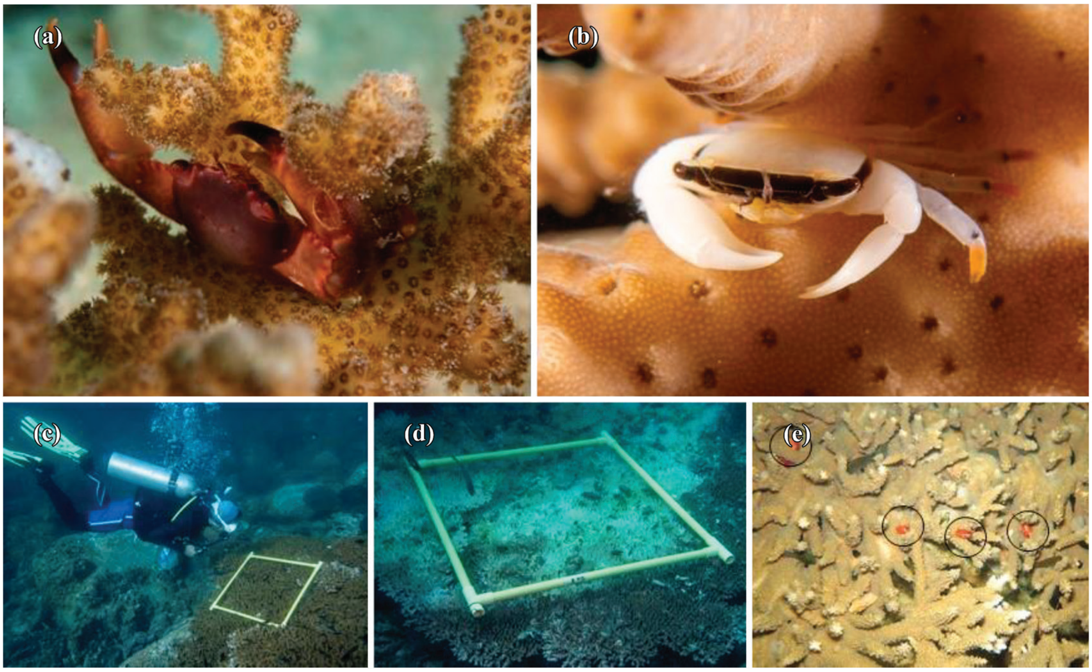

Figure 2. Figures showing: (a) *Trapezia cymodoce*; (b) *Tetralia nigrolineata*; (c) a scuba diver observing a 50×50 cm quadrat; (d) bleached coral without coral crabs; (e) healthy coral with abundant crabs (circled).

Resources Conservation Office, 2013). Particularly noteworthy survey stations included Shark Island, Japanese Gardens, and Light House due to their diverse array of organisms such as gorgonians, black corals, sea whips, soft corals, barrel sponges, and sea urchins, which are habitats where crabs typically reside. Light House and Tao Tong stations were characterized by sandy seafloors littered with coral debris and sediments. During this survey, coral bleaching was observed at a rate of approximately 50% in only two stations: Pottery Pinnacles and Buddha Point. Coral bleaching in Koh Tao's reefs between 2010 and 2016 was noted to be partial rather than severe, according to the Department of Marine and Coastal Resources (2016). The primary activities in the Koh Tao coral reefs are snorkeling and SCUBA diving, with tourist boats commonly anchored at popular diving sites.

Diversity, abundance, and distribution of crabs in coral reefs

This recent study represents a new report on the diversity and abundance of crabs in the coral reefs around Mu Koh Tao, where a total of 14 families, 34 genera, and 47 species were identified. Among these, 12 species belonged to Anomura (25.53%) and 35 species to Brachyura (74.47%). The family Xanthidae exhibited the highest diversity among the crabs surveyed (29.79%) (Table 1). Crabs from the families *Trapeziidae* and *Tetraliidae*, known as coral crabs, were particularly abundant and distributed throughout the coral reefs of Mu Koh Tao, predominantly associating with hard corals. The complex topography of the coral reef surfaces in Mu Koh Tao likely contributes to the high species richness observed, either through increased habitat diversity or expanded area (Johnson *et al*., 2003).

The three most abundant and dominant coral crabs observed were *Trapezia cymodoce, Tetralia nigrolineata*, and *Tetralia rubridactyla*. *Tr. cymodoce* primarily inhabited *Pocillopora damicornis* and *Acropora latistella* corals. *Te. nigrolineata* was predominantly found with *A. valenciennesi*, *Acropora hyacinthus*, and occasionally with *Acropora horrida* corals. *Te. rubridactyla* was associated with staghorn corals (*Acropora formosa*) and *A. horrida*. Most of these coral crab species (90%) inhabited individual coral colonies. Occasionally, two species were found inhabiting the same coral colony; for instance, 90% of *Te. rubridactyla* and 10% of *Te. nigrolineata* were found in *A. horrida* corals. Conversely, in *A. hyacinthus* corals, 90% of *Te. nigrolineata* and 10% of *Te. rubridactyla* were observed. In *A. latistella* corals, 80% of *Tr. cymodoce* and 20% of *Te. rubridactyla* were found.

At Japanese Gardens and Shark Island stations, where *Te. nigrolineata* and *Tr. cymodoce* crabs were abundant, approximately 100 crabs and 50 crabs were observed in a single coral colony, respectively. Previous studies have documented various types of coral crabs thriving in fertile coral reefs (Castro *et al*., 2004; Jaingam, 2013; Wisespongpand *et al*., 2023). Coral crabs play a crucial role in their symbiotic relationship with hard corals by protecting them from predators such as crown-of-thorns starfish, consuming mucus, removing sediment and settling larvae from coral surfaces, regulating coral reef plankton, and mitigating coral bleaching (Castro, 1976; Patton, 1994; Stewart *et al*., 2006; Shmuel *et al*., 2022).

The abundance of coral crabs in the coral reefs of Mu Koh Tao is crucial for maintaining coral health and fertility. Highlighting the significant role of coral crabs in Mu Koh Tao can enhance awareness of ecotourism initiatives, positioning them as a new iconic species alongside sea turtles. Another notable crab species inhabiting hard corals, particularly active at night, is the spiny flattened crab (*Lissoporcellana spinuligera*) (Figure 4). Over 100 individuals were observed on a single coral colony at Japanese Gardens and Shark Island stations. These crabs adapt their third maxillipeds for feeding on plankton and suspension feeders found on hard and hump corals. The relationship between the abundant spiny flattened crabs and hard corals warrants further study. Additionally, hairy hermit crabs (*Dardanus lagopodes*) were dominant along coral reefs, inhabiting both coral piles and the seafloor around Mu Koh Tao. The distribution and abundance of crab species in Mu Koh Tao coral reefs show that rare species comprise the majority at 85.11%, followed by dominant species at 10.63%, and common species at 4.26%.

Table 1. Species diversity, abundance, and distribution of crabs in coral reefs around Mu Koh Tao.

Scientific name	status	Pottery Pinnacles	Buddha Point	Twin Rocks	June Juea Bay	Ao Leuk Bay	Tao Thong	Hin Wong Bay	Japanese Gardens	Shark Island	Tanote Bay	Light House
1. Family Galatheidae Samouelle, 1819 (1 genus 1 species)												
Galathea sp.	rare	-	-	-	-	-	-	-	+	+	-	-
2.Family Porcellanidae Haworth, 1825 (4 genera 5 species)												
Aliaporcellana kikuchii Nakasone and Miyake, 1969	rare	+	-	-	-	-	-	-	-	-	-	-
Lissoporcellana spinuligera (Dana, 1853)	dominance	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++
Aliaporcellana sp.	rare	-	-	-	-	-	-	-	+	-	-	-
Pachycheles sp.	rare	-	-	-	-	-	-	-	-	+	-	-
Polyonex sp.	rare	-	-	-	-	-	-	-	-	-	-	+
3.Family Diogenidae Ortmann, 1892 (4 genera 5 species)												
Clibanarius cruentatus (H. Milne Edwards, 1848)	rare	-	-	-	-	-	+	-	+	++	-	-
Dardanus lagopodes (Forskål, 1775)	dominance	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++
Dardanus megistos (Herbst, 1804)	common	-	+	-	-	-	-	+	++	++	-	+
Paguristes runyanae Haig and Ball, 1988	rare	-	-	-	-	-	+	-	+	+	-	-
Diogenes sp.	rare	-	-	-	-	-	-	-	+	-	-	-
4.Family Paguridae Latreille, 1802 (1 genus 1 species)												
Pagurixus rubrovittatus Komai, 2010	rare	-	-	-	-	++	-	-	+	+	-	+
5.Family Dromiidae De Haan, 1833 (1 genus 1 species)												
Cryptodromia hilgendorfi De Man, 1888	rare	-	-	-	-	-	-	+	-	-	-	+
6.Family Epialtidae MacLeay, 1838 (4 genera 6 species)												
Hoplophrys oatesii Henderson, 1893	rare	-	-	-	-	-	-	-	-	++	-	-
Hyastenus diacanthus (De Haan, 1839)	rare	-	-	-	-	+	-	+	++	++	-	-
Hyastenus borradailei (Rathbun, 1907)	rare	-	-	-	-	-	-	-	+++	+++	-	++
Menaethius monoceros (Latreille, 1825)	rare	-	-	-	-	-	-	+	-	+	-	+++
Xenocarcinus conicus (A. Milne-Edwards, 1865)	rare	-	-	-	-	-	-	-	-	++	-	+
Xenocarcinus tuberculatus White, 1847	rare	-	-	-	-	-	+	-	-	+	-	+
7. Family Majidae Samouelle, 1819 (2 genera 2 species)												
Micippa platipes Rüppell, 1830	rare	-	-	-	-	-	-	+	-	-	-	+
Schizophrys aspera (H. Milne Edwards, 1831)	rare	+	-	-	-	-	+	-	+	+	-	+
8. Family Parthenopidae MacLeay, 1838 (1 genus 1 species)												
Certolambrus pugilator (A. Milne-Edwards, 1873)	rare	-	-	-	-	-	-	-	+	-	-	-
9. Family Pilumnidae Samouelle, 1819 (2 genera 2 species)												
Echinoecus pentagonus (A. Milne-Edwards, 1879)	rare	+	-	-	-	-	-	-	-	+	-	-
Pilumnus sp.	rare	-	-	-	-	-	-	-	-	+	-	-
10. Family Portunidae Rafinesque, 1815 (3 genera 5 species)												
Goniosupradens acutifrons (De Man, 1879)	rare	-	-	-	-	-	-	-	++	++	-	-
Thalamita admete (Herbst, 1803)	rare	-	-	-	-	++	+	-	-	-	-	-
Thalamita prymna (Herbst, 1794)	rare	-	-	-	-	-	-	-	-	+	-	-
Thalamita spinimana Dana, 185	rare	-	-	-	-	-	-	-	-	-	-	+
Xiphonectes longispinosus (Dana, 1852)	rare	-	-	-	-	+	-	-	+	+	-	-

Table 1. Continued.

Scientific name	status	Pottery Pinnacles	Buddha Point	Twin Rocks	June Juea Bay	Ao Leuk Bay	Tao Thong	Hin Wong Bay	Japanese Gardens	Shark Island	Tanote Bay	Light House
11. Family Tetraliidae Castro, Ng & Ahyong, 2004 (1 genus 2 species)												
Tetralia nigrolineata Serène and Pham, 1957	dominance	+++	+++	+++	+++	+++	+++	+++	+++	+++	+++	+
Tetralia rubridactyla Garth, 1971	dominance	++	++	++	++	++	++	++	++	++	++	-
12. Family Trapeziidae Miers, 1886 (1 genus 1 species)												
Trapezia cymodoce (Herbst, 1801)	dominance	++	+++	++	++	++	++	+++	++	+++	++	++
13. Family Xanthidae MacLeay, 1838 (11 genera 14 species)												
Actaeodes mutatus Guinot, 1976	rare	-	-	-	-	-	-	-	+	-	-	-
Atergatis floridus (Linnaeus, 1767)	rare	-	-	-	-	-	-	-	+	+	-	-
Atergatis integerrimus (Lamarck, 1818)	rare	-	-	-	+	-	-	-	+	+	-	-
Chlorodiella nigra (Forskål, 1775)	common	++	-	++	-	+	+	+	-	++	-	+
Cymo melanodactylus Dana, 1852	dominance	++	-	++	-	++	++	++	++	++	++	-
Etisus electra (Herbst, 1801)	rare	+	-	-	-	+	+	-	-	+	-	-
Etisus utilis Jacquinot in Jacquinot and Lucas, 1853	rare	-	-	-	-	-	-	-	-	+	-	-
Euxanthus exsculptus (Herbst, 1790)	rare	-	-	-	-	-	-	-	+	+	-	-
Liomera loevis (A. Milne-Edwards, 1873)	rare	-	-	-	-	-	+	-	-	-	-	-
Liomera rugata (A. Milne-Edwards, 1834)	rare	-	-	-	-	+	-	+	-	-	-	++
Lophozozymus edwardsi Odhner, 1925	rare	+	-	-	-	+	-	-	-	-	-	-
Palapedia integra (De Haan, 1835)	rare	-	-	-	+	-	-	-	-	-	-	-
Neoxanthop lineatus (A. Milne-Edwards, 1867)	rare	-	-	-	-	-	-	-	-	+	-	-
Leptodius sp.	rare	-	-	-	-	-	-	-	+	+	-	-
14. Family Varunidae H. Milne Edwards, 1853 (1 genus 1 species)												
Varuna yui Hwang and Takeda, 1986	rare	-	-	-	-	-	++	-	-	+	-	-
Total 14 families 37 genera 47 species		12	6	7	7	13	15	13	25	33	6	17

Note: Abundance: +++ (more than 10 crabs); ++ (4–10 crabs); + (less than 4 crabs) per station in 50 min of SCUBA diving; – indicates no crabs found

Seven rare crab species were identified in this study, marking their first reported occurrence in Thailand: *Paguristes runyanae, Pagurixus rubrovittatus, Cryptodromaia hilgendorfti, Certolambrus pugilator, Xiphonectes longispinosus, Actaeodes mutatus,* and *Lophozozymus edwardsi*. The distribution of these species includes various regions: *P. runyanae* has been reported in the northern seas of Australia and eastern Indonesian waters (Haig and Ball, 1988; Rahayu, 2006), *P. rubrovittatus* in the Indo-West Pacific (Komai, 2010), *C. hilgendorfi* in Indonesian and Australian waters (McLay, 2001), *C. pugilator* in Guam, Singapore, Japan, New Caledonia, and Western Samoa (Tan and Ng, 2003), *X. longispinosus* in the Indian Ocean (Spiridonov, 2016), *A. mutatus* in the Indo-West Pacific, southern Japan, and French Polynesia (Iwasa-Arai *et al*., 2015), and *L. edwardsi* in the Indo-West Pacific, Mayotte Island, Guam, and French Polynesia (Poupin *et al*., 2018).

Additionally, two symbiotic crab species were identified: the candy crab (*Hoplophrys oatesii*), associated with soft corals (*Dendronephthya* sp.), and the sea urchin crab (*Echinoecus pentagonus*), found with sea urchins (*Echinothrix* sp.). These species were previously reported in the Andaman Sea of Thailand (Naiyanetr, 2007; Thamrongnawasawat and Wisespongpand, 2007; Jaingam, 2013) and are now documented for the first time in the Gulf of Thailand. The candy crab (*H. oatesii*) is widely distributed in the Indo-West Pacific, including the Western Indian Ocean, Japan, Indonesia, Philippines, Fiji, and Eastern Australia (Griffin and Tranter, 2013), while *E. pentagonus* ranges from the Red Sea and East Africa to the Hawaiian Islands and French Polynesia (Chia *et al*., 1999).

Several rare crab species in the family Epialtidae were found inhabiting gorgonians and sea whips. Most small crabs in the family Xanthidae hide beneath the seabed and are patchily distributed among table corals and sand mixed with coral debris. The family Porcellanidae includes four species of flattened crabs that live in sponges but are less abundant compared to those living in hard corals. These small and colorful crabs often conceal themselves within Koh Tao's tourist attractions, providing a challenge for divers interested in observing small marine organisms.

The majority of crabs found in Mu Koh Tao were associated with other animals in coral reefs, comprising 42.55% of the total species. Shark Island exhibited the highest crab diversity, with 33 species (70.21%), followed by Japanese Gardens with 25 species (53.19%) (Table 1). These stations were rich in various organisms that crabs typically associate with, including barrel sponges, soft corals, gorgonians, black corals, sea whips, corallimorphs, zoanthids, sea urchins, and sea cucumbers. In addition to coral crabs, which were the most abundant group living with hard corals, flattened crabs, hairy crabs, and hermit crabs were commonly found residing with sponges. The candy crab (*H. oatesii*) was exclusively found at Shark Island, where spiny soft corals (*Dendronephthya*) provided ideal camouflage with their thorny appearance and coloration. *Echinoecus pentagonus* crabs inhabited sea urchins (*Echinothrix calamaris*), while *Xenocarcinus conicus* and *Xenocarcinus tuberculatus* crabs lived with gorgonians and wire coral, respectively. Crabs living symbiotically with other organisms in coral reefs utilize them for shelter, food sources, camouflage, and defense mechanisms (Jaingam *et al*., 2008), contributing to the high biodiversity observed among crabs in these habitats.

Coral reefs in Mu Koh Tao are recognized for their rich biodiversity and abundance of crabs, with a total of 47 species identified. Research on crab biodiversity in Koh Tao has been limited, with the Checklist of Crustacea fauna in Thailand focusing mainly on nearby areas such as Koh Phangan and Koh Samui (Naiyanetr, 2007). According to reports from the Marine and Coastal Resources Conservation Office (2013), the most abundant hermit crabs in Koh Tao's coral reefs are *Dardanus lagopodes* and *Dardanus megistos*. Mu Koh Tao exhibits a crab species richness comparable to other coral reefs in Thailand, such as Mu Koh Lan (62 species), Mu Koh Surin National Park (62 species), and Mu Koh Racha (48 species), surpassing that of Mu Ko Kam (23 species) and Koh Talu-Koh Sing-Koh Sung (22 species) (Wisespongpand *et al*., 2007; 2010; 2011; 2016; 2022). As a world-class diving destination, Koh Tao's sustainable tourism development should emphasize the importance of crab biodiversity through guidelines for tourists and divers. Incorporating biological resource information into the formulation of a master plan and action plan for Mu Koh Tao's development is crucial for achieving sustainable tourism goals and maintaining a balance between tourism utilization and conservation efforts.

Community structure of crabs in coral reef ecosystems in Mu Koh Tao

According to the study on the community structure of crabs across 11 stations with varying levels of coral bleaching, Shark Island station and June Juea Bay station exhibited the highest and lowest Shannon diversity indices of 2.43 and 1.26, respectively. Meanwhile, the Simpson diversity index ranged from its highest at Light House station (0.89) to its lowest at June Juea Bay (0.63) (Table 2). The Shannon diversity index emphasizes species richness and the presence of rare species, whereas the Simpson diversity index emphasizes species evenness and the dominance of particular species (Nagendra, 2002). Therefore, Shark Island station, with its highest Shannon diversity index and a species richness index of 5.53, plays a significant ecological role in the coral reef ecosystem of Mu Koh Tao. In contrast, Light House station, with the highest Simpson diversity index (0.83) is important for understanding the dominance patterns and the evenness of crab species in Mu Koh Tao.

Table 2. Indices of crab diversity from 11 stations in coral reef around Mu Koh Tao.

No.	Station	Total species	Total individuals	Species richness index	Peilou's evenness index	Shannon-diversity index	Simpson diversity index
1	Pottery Pinnacles	12	99	2.39	0.80	1.98	0.83
2	Buddha Point	6	66	1.19	0.88	1.57	0.79
3	Twin Rocks	7	75	1.39	0.92	1.79	0.82
4	June Juea Bay	7	187	1.15	0.65	1.23	0.63
5	Ao Leuk Bay	13	104	2.58	0.82	2.09	0.85
6	Tao Thong	15	217	2.60	0.63	1.71	0.72
7	Hin Wong Bay	13	91	2.66	0.79	2.04	0.85
8	Japanese Gardens	25	246	4.37	0.64	2.07	0.78
9	Shark Island	33	327	5.53	0.69	2.43	0.85
10	Tanote Bay	6	69	1.18	0.91	1.62	0.79
11	Light House	17	57	3.40	0.83	2.36	0.89

Note: The level of coral bleaching in each station: 1–2 = high; 3–7 = medium; 8–11 = low

The community structure of crabs in Mu Ko Tao as shown in dendrogram (Figure 3a) indicating the percentage of similarity between communities. At 80% of similarity, the structure of crabs communities in coral reef of Mu Koh Tao were categorized into 5 groups; group 1 (Lighthouse), group 2 (Japanese Gardens and Shark island), group 3 (Ao Leuk Bay and Hin Wong Bay), group 4 (June Juea Bay and Tao Thong) and group 5 (Pottery Pinnacles, Buddha Point, Twin Rocks and Tanote bay). MDS was considered the distance between the communities that are represented graphically would be proportional to the similarity between the communities (Figure 3b). The communities of crabs from MDS also categorized into 5 groups as dendrogram at 80% of similarity. A value of 0.05 stress coefficient would correspond to a very reliable interpretation of MDS graphical representation in this study.

The community structure of crabs in Mu Koh Tao can be categorized into 5 groups (Figure 3). Coral bleaching significantly influenced the community structure of crabs, resulting in distinct groupings between areas with low, moderate, and high levels of coral bleaching. Stations with low levels of coral bleaching formed two distinct groups: the Shark Island-Japanese Garden community and the Light House community. These stations exhibited higher Shannon diversity indices (ranging from 2.07 to 2.43) compared to others and harbored a variety of crab symbionts likely influencing their community structure. Particularly, the Light House community stood out due to noticeable differences, possibly due to sediment presence on corals and sea floors, as well as coral debris resulting from strong storms.

The largest community structure similarity encompassed four stations with varying levels of bleaching: Pottery Pinnacles (high), Buddha Point (high), Twin Rocks (medium), and Tanote Bay (low). These stations showed lower diversity of associated organisms with crabs and appeared less affected by coral bleaching that did not spread extensively across the area. The impact of coral bleaching seemed more pronounced on coral crabs living with hard corals compared to other crab groups. Factors such as the abundance of symbionts and the morphology of the reef also play crucial roles in shaping the similarities among crab communities in Mu Koh Tao coral reefs, alongside coral bleaching levels and sediment presence.

The physical and chemical factors recorded at sampling stations in the coral reefs of Mu Koh Tao generally met the criteria for seawater quality conducive to coral reef conservation (Office of the

National Environment Board, 2021). Air temperature averaged 33.74±2.65 °C, water temperature 29.45±0.50 °C, pH 8.25±0.10, salinity 30.24±0.44 psu, dissolved oxygen (DO) 6.57±0.56 mg·L^{-1}, ammonia 0.02±0.01 mg·L^{-1}, nitrate 2.95±0.35 mg·L^{-1}, and phosphate 0.01±0.01 mg·L^{-1}. The water temperature observed was relatively lower compared to sandy and rocky beaches around Mu Koh Tao, which averaged 32.08±0.89 °C, likely due to greater water depth and absence from the intertidal zone. Meteorological factors such as sea surface state, wave height, wind speed, and cloud cover were not considered detrimental to the coral reef ecosystem.

The abundance of coral crabs in healthy and bleached corals

Global warming, driven by climate change, poses a severe threat to life on earth, manifesting in seawater temperature rising and ocean acidification. One of its significant consequences is coral bleaching, which profoundly impacts marine biodiversity. Changes in crab habitats due to climate change also affect the biodiversity, distribution, community structure, behavior, and productivity of crabs (Stella *et al*., 2011; Asakura, 2021; Szuwalski *et al*., 2021; Alaerts *et al*., 2022; Liu *et al*., 2022).

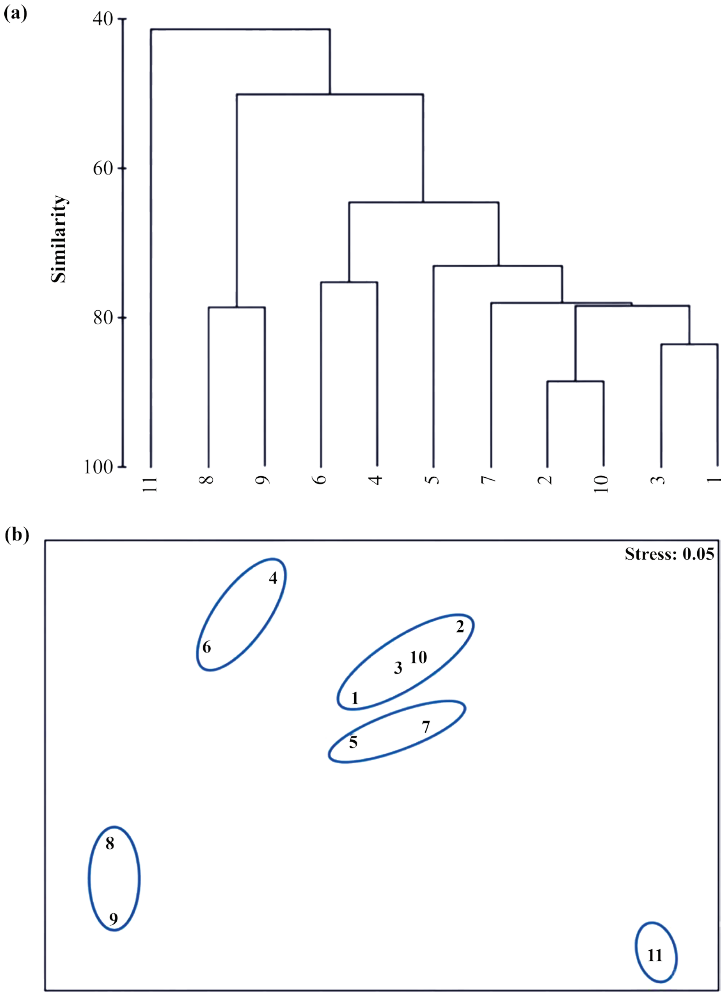

Figure 3. A dendrogram (a) and PCA ordination for MDS (b) comparing the structure of crab communities at three levels of coral bleaching in coral reef around Mu Koh Tao.

Note: Numbers indicate levels of coral bleaching in each station: 1–2 = high; 3–7 = medium; 8–11 = low

Physical and chemical factors and environmental quality of sampling stations

Corals serve as critical and threatened habitats for a diverse array of reef-associated animals, particularly coral crabs. Crabs belonging to the families Tetraliidae and Trapeziidae utilize corals as shelters to evade predators. The occurrence of coral bleaching directly impacts these coral crabs. Conversely, some studies suggest that coral crabs may play a role in mitigating coral bleaching (Stewart *et al*., 2006; Stella *et al*., 2011; Wisespongpand *et al*., 2023).

According to this study on the abundance of coral crabs living with hard corals in Mu Koh Tao, *Tr. cymodoce* and *Te. nigrolineata* were identified as significant species. Comparing the density of these coral crabs between colonies of healthy corals and bleached corals across 5 stations revealed significantly denser populations in healthy coral colonies compared to bleached ones ($t = 3.15$, $df = 24$, $p = 0.004$) (Table 3). On average, *Te. nigrolineata* exhibited a density of 21.2 inds·m^{-2} in healthy corals, whereas only 6.08 inds·m^{2} were found in bleached corals. *Tr. cymodoce*, predominantly associated with cauliflower corals at Ao June Juea station, showed a density of 7.5 inds·m^{-2} in healthy corals, with none found in bleached corals. This suggests that *Tr. cymodoce* may be more sensitive to coral bleaching compared to *Te. nigrolineata*, which appear more resilient to these environmental changes.

Previous studies conducted by on coral reefs in Thailand, specifically Koh Lan in Chonburi province and Koh Kam in Ranong province, support these findings, indicating that Tetralia crabs are more commonly found in bleached coral reefs compared to *Trapezia* crabs (Wisespongpand *et al*., 2016; 2022; 2023). Studies from Australia have also reported that coral bleaching affects not only the abundance of coral crabs like *Tr. cymodoce* but also the size of coral crab eggs. Moreover, *Tr. cymodoce* displaced from bleached corals to new habitats, potentially competing with original host crabs in unbleached corals due to habitat loss caused by coral bleaching driven by climate change (Stella *et al*., 2011). Accordingly, coral crabs can serve as indicators of habitat loss due to climate change in coral reefs, highlighting their potential role in monitoring ecosystem health under changing environmental conditions.

The occurrence of sediment and coral fragmentation on coral reefs, attributed to man-made construction and severe storms exacerbated by climate change, directly impacts coral health. This study observed a sparse presence of coral crabs on corals covered by sediment at Light House station, whereas corals inhabited by coral crabs did not exhibit sediment cover. Tao Tong and Light House stations also showed numerous fragmented corals with a minimal presence of coral crabs. This finding aligns with a study conducted on shallow coral reefs at Panwa Cape in Phuket, which experienced higher populations of *Tr. cymodoce* and *Trapezia septata* crabs on corals located outside the shorelines, where corals were less covered by sediment following the 2004 tsunami (Wisespongpand *et al*., 2009). Research indicates that coral crabs actively remove sediment from coral surfaces, particularly targeting larger particles that can damage coral tissue and contribute to bleaching events. The presence of coral crabs is associated with healthier coral colonies

Table 3. The density of two coral crabs (inds·m^{-2}) in heathy coral and bleached coral in five stations of coral reef around Mu Koh Tao.

Species	Station	Healthy coral	Bleached coral	p-value
Tetralia nigrolineata	Ao Leuk Bay	52.80±15.85	17.60±10.81	
	Pottery Pinnacles	7.20±4.38	0.80±1.79	
	Twin Rocks	17.60±14.59	4.00±6.93	
	Japanese Gardens	15.20±13.08	4.80±5.22	
Trapezia cymodoce	Ao June Juea	10.40±2.19	0	
	overall	20.64±19.82	5.60±8.64	0.004

and reduced instances of coral bleaching, as they contribute to sediment removal, which is crucial for coral feeding and respiration (Stewart *et al*., 2006).

The relationship between coral crabs and hard corals is a vital symbiotic partnership. Coral crabs utilize corals as their home, seeking refuge from predators and feeding on mucus and organic matter present on coral surfaces. In return, coral crabs play a crucial role in protecting corals from predation by crown-of-thorns starfish; they use their sharp claws to deter these starfish by grasping their tubular feet (Castro, 1976; Patton, 1994; Pratchett, 2001). Additionally, coral crabs help maintain coral health by clearing sediment and removing aquatic larvae that settle on coral surfaces, thereby aiding in the recovery of corals following bleaching events (Stewart *et al*., 2006; Stier *et al*., 2012). Coral crabs also contribute to ecosystem balance by consuming zooplankton such as amphipods, copepods, and isopods on the sea bottom beneath the corals where they reside, thus regulating plankton populations in coral reef environments (Shmuel *et al*., 2022). Corals lacking symbiotic relationships with coral crabs are more susceptible to bleaching and mortality compared to those that host these crabs (Stewart *et al*., 2006). Overall, the diverse presence of coral guard crabs is essential for the resilience and biodiversity of coral reef ecosystems, highlighting their critical role in coral reef sustainability and biodiversity enhancement.

Our study also observed three crab species inhabiting partially bleached table corals in distinct patterns. The coral crab (*Te. nigrolineata*) predominantly resided in unaffected coral areas, while the xanthid crab (*Cymo melanodactylus)* was found within bleached coral regions. The spiny flattened crab (*L. spinuligera*) was observed inhabiting dead coral sections during nighttime (Figure 4).

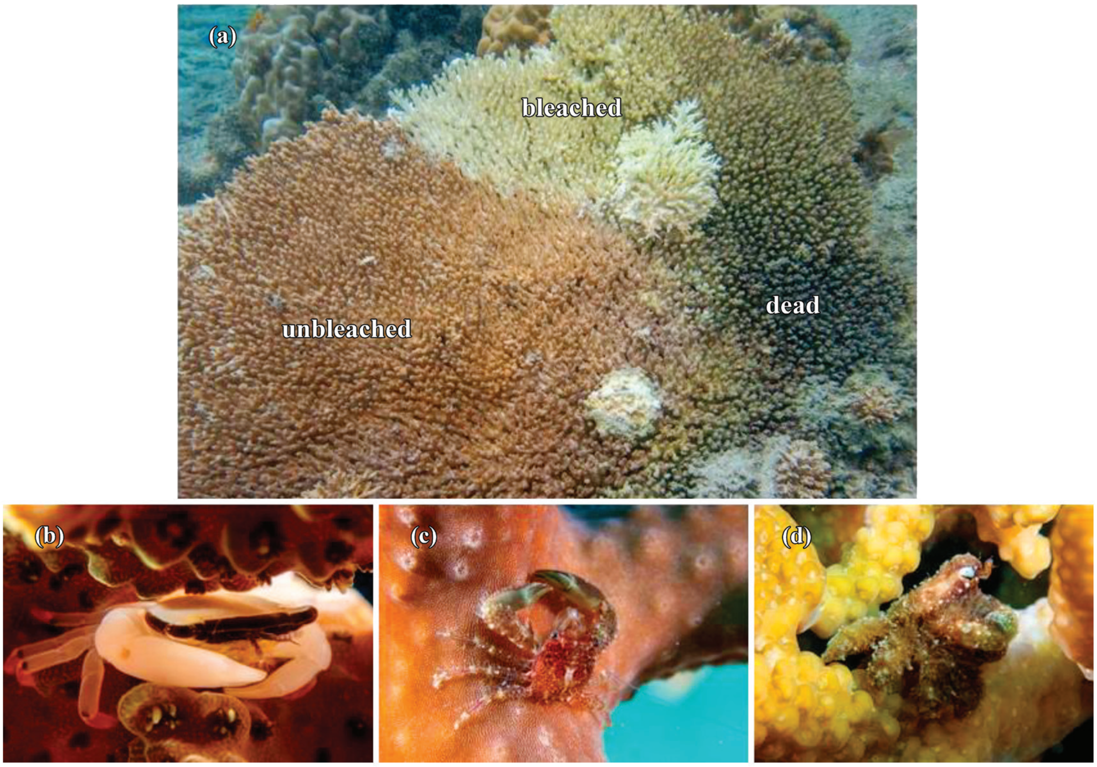

Figure 4. Figures showing: (a) a partially bleached and dead table coral; (b) *Tetralia nigrolineata* inhabiting the unbleached part; (c) *Cymo melanodactylus* inhabiting the bleached part; (d) *Lissoporcellana spinuligera* inhabiting the dead part.

The presence of multiple crab species within coral habitats enhances the resilience of both the host corals and the symbiotic crabs. Each crab species likely plays a unique role in coral protection, thereby enhancing functional diversity crucial for the persistence of coral reef ecosystems (McKeon and Moore, 2014).

The interaction facilitated by the cohabitation of corals and coral crabs plays a crucial role in protecting corals from physical damage and bleaching caused by climate change and human threats. With rising sea temperatures contributing to widespread coral bleaching incidents, such as those observed in the Great Barrier Reef and numerous coral reefs in Thailand, it is increasingly likely that the abundance of coral crabs, integral to the symbiotic relationship with hard corals, will be affected. Ensuring the preservation of this relationship is essential. Effective measures and guidelines are urgently needed to safeguard both corals and coral crabs amidst these challenges. Conservation efforts must focus on maintaining the health and resilience of coral reefs, fostering conditions that support the continued coexistence and mutual benefits of coral crabs and hard corals.

CONCLUSIONS

The coral reefs of Koh Tao and Koh Nang Yuan are rich in biodiversity, with 47 crab species, including the dominant *Trapezia cymodoce* and *Tetrlia nigrolineata*. These reefs host many rare species, making up 82.98% of the total, with seven newly recorded in Thailand, including two from the Gulf of Thailand. Shark Island and Japanese Gardens are biodiversity hotspots, with 33 and 25 species, respectively. Crabs living with other organisms account for 42.55% of the species. Densities of *Tr. cymodoce* and *Te. nigrolineata* were higher in healthy corals than in bleached ones. These crabs are crucial indicators of habitat health, emphasizing the urgent need for conservation guidelines to protect crab biodiversity and support sustainable tourism. This research provides essential biological data to inform comprehensive master planning efforts that balance tourism development with conservation imperatives, ensuring the long-term sustainability of the region.

Ethical statements

The animal care and use protocol in this research has been approved by the Kasetsart University Animal care and use committee by ID# ACKU66-FIS-012 under license No. U1-03503-2559.

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