Zoological Studies **55:** 50 (2016)
doi:10.6620/ZS.2016.55-50

Zoological Studies

Ecology of Endolithic Bivalve Mollusks from Ko Chang, Thailand

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(Received 12 February, Accepted 11 October 2016)

Cheewarat Printrakoon, Thamasak Yeemin, and Paul Valentich-Scott (2016) The objective of this study was to examine the ecology of coral boring bivalves from four islands southeast of Ko Chang, Trat Province, Thailand. A total of 11 bivalve families containing 18 species were recorded in the survey, including six reported for this first time in the region. Members of the Mytilidae comprised the highest bivalve diversity with five species recorded. The five most abundant species were *Leiosolenus lima* (Jousseaume in Lamy), *Lithophaga teres* (Philippi), *Botula cinnamomea* (Gmelin), *Coralliophaga coralliophaga* (Gmelin), and *Gastrochaena cuneiformis* Spengler. Ecological analysis showed that Ko Bai Dung had the highest density of boring bivalves, with 196.29 ± 118.24 individual/ m^2. Density of coral boring bivalves was variable; the highest density was recorded for *Coralliophaga coralliophaga* (85.18 ± 74.35 individual/m^2) at Ko Bai Dung. The highest diversity of boring bivalves was found on Ko Phrao Nok, and in dead coral. Multivariate analyses did not reveal a clear differences in the boring bivalve community composition between sites, or with coral age, or with coral species, however dead coral was well-grouped at 50% similarity. The number of species and number of specimens of boring bivalves in this study was significantly positively correlated with coral age. The maximum number of boring bivalve specimens was found in the oldest coral (11 years old) and in dead *Porites* host corals. Following the same trend of all dominant boring bivalves, corals more than nine years old showed the highest frequency distribution and the largest shell length. The distribution of shell height frequency showed *Leiosolenus lima* and *Lithophaga teres* had more variation in shell height than the other five dominant boring bivalve species. Endolithic bivalves are one of the main bioeroders in the coral biome. The ecologic data presented in this study can be used as one indicator of coral reef status, including bioerosion and nutrient recycling in coral ecosystems.

Key words: Coral boring bivalve, Endolithic, Density, Correlation, Southeast Thailand.

BACKGROUND

Ko Chang is an island in Trat Province, Eastern Thailand, near the Cambodian border. The name means Elephant Island, being named for the elephant shape of its headland of approximately 429 square kilometers in area. Ko Chang is the second largest island in Thailand and is one of the most beautiful in the country. The island topography contains high mountains, complex stone cliffs, and huge bays and beaches, with the surrounding water including numerous coral reefs and associated marine life. Ko Chang is part of a group of forty small islands called Moo Ko which is a managed National Marine Park conservation area. Ko Chang is one of Thailand's most attractive for tourism, particularly for coral diving (Natheewuttana 2007).

Coral reefs are among the most productive and biologically diverse ecosystems on earth (Crossland et al. 1991; Huang et al. 2015; Moberge and Folke 1999).The coral reef supplies many goods and services to humans, including seafood, ingredients for medicine, recreation uses, providing coastal protection, and has great aesthetic and cultural value (Peterson and Lubchenco 1997; Moberge and Folke 1999). In addition, coral is able to provide habitat for a huge community of marine

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organisms (Moberge and Folke 1999).

Large carbonate structures from scleractinian corals are well known for providing habitat for a variety of animals (Nogueira 2003). Mollusks have been recorded in the following associations with corals: as predators, as prey, boring into living and dead coral, as epizoic species, as well as providing a substrate for coral (Hadfield 1976; Morton 1983; Nielson 1986).The focus in this study is endolothic bivalves, those species which bore into coral skeletons, or occupy empty crevices and cavities, and never leave the corals (Morton 1983).

The diversity of coral boring bivalve mollusks is poorly recorded in the Indo Pacific region. In Thailand, three recent publications have described and illustrated this fauna. The highest recorded diversity included 21 species from the southeastern Gulf of Thailand (Valentich-Scott and Tongkerd 2008), followed by 18 species from Phuket, in the Andaman Sea (Nielsen 1976, 1986), and nine species from the southwestern Gulf of Thailand (Swennen et al. 2001). The main coral boring mollusk families recorded in the region includes the Mytilidae, Petricolidae, Trapezidae, Pholadidae, and the Gastrochaenidae (Valentich-Scott and Tongkerd 2008). However, in that study the identification of coral species bored by bivalves was not reported. Morton (1983) detailed the ecology and biology of coral associated bivalves.

The objective of this study was to focus on small-scale interactions of coral ecosystems. In particular, we aimed to investigate, for the first time in Thailand, the coral hosts, and to delineate their species, their life status, and their age. We also wanted to examine how these factors are associated to the diversity and population ecology of coral boring bivalve mollusks.

MATERIALS AND METHODS

Four study sites were selected at important coral diving spots in the region. The stations were located on small islets southeast of Ko Chang (Fig. 1). Subtidal corals were observed using SCUBA diving equipment from 11-12 March 2014. The age of each coral head was estimated from the data on coral growth rates in the Gulf of Thailand which were obtained by the Alizarin Red S *in situ* staining and long-term monitoring in belt-transects

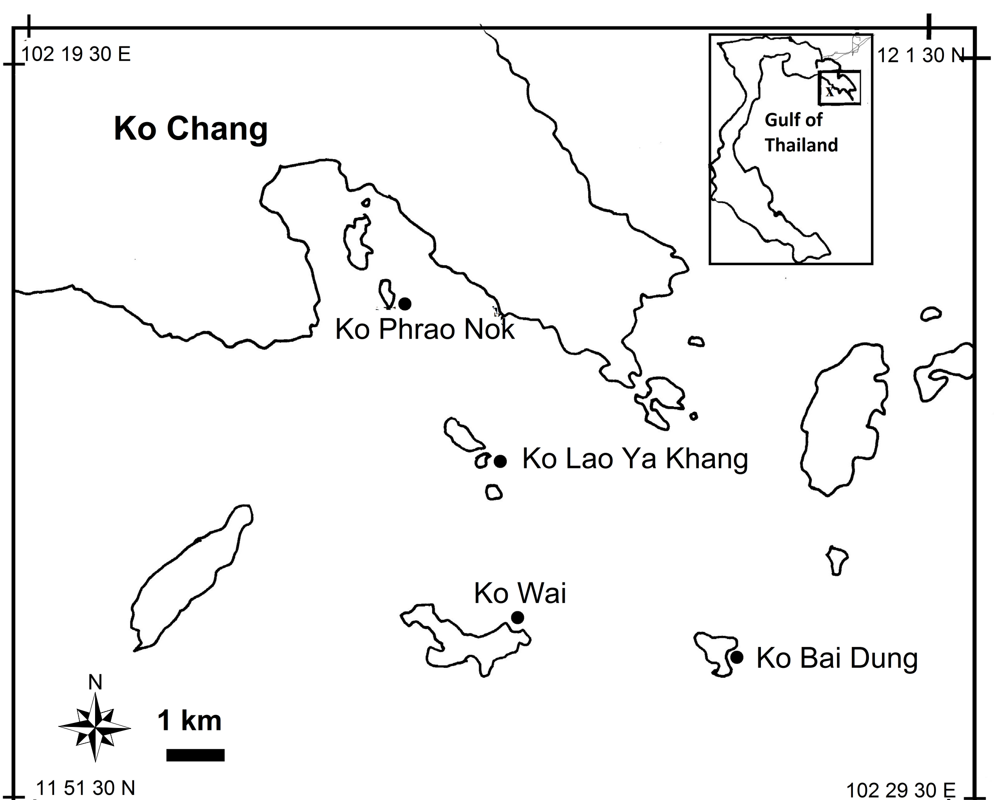

Fig. 1. Location of four study sites (circle), islands of Trat Province, Thailand.

(Sudara et al. 1991; Pengsakun and Yeemin 2011; Sangmanee et al. 2012; Samsuvan et al. 2015).

Colonies of coral species of various age and life status were randomly sampled at the four study sites and included 17 total replications. A sample of 30 × 30 cm^2 per colony was cut from whole colonies with fine mesh nylon bag placed underneath. The sample was brought to the surface in the nylon bag and then put into a 70% ethyl alcohol preservation tank in the field. Physical parameter measurements were collected at each site using YSI equipment, and included water temperature, salinity, pH, conductivity, and dissolved oxygen. Coral profiles were recorded at each site and summarized in the results section below.

All endolithic bivalves from the 17 collected colonies were extracted carefully with a hammer and chisel. Bivalves from each sample were kept separate and then identified and counted in the laboratory. Shell height and length measurements were recorded for each bivalve specimen.

The community structure of boring bivalve samples in a coral host was measured with a variety of different indices such as total number of individuals (N) and total number of species (S). To compare distributions between the four islands, we also used diversity indices based on standard formulas (Magurran 1988) including Shannon's Diversity Index (H'), and Evenness Index (J'). The population size of the five dominant boring coral species was illustrated by size frequency distribution. Sizes were ranked in 15 categories (x -axis) with 5 mm intervals, from 0 to a maximum of 69 mm. The frequency of individuals (y-axis) was grouped within four categories of coral age (a-d) that were found at our study sites; a < 6 years, b = 6-7 years, c = 8-9 years, d > 9 years, d1 = 10 years, d2 = 11 years.

Coral species, life status, and age were also combined for an analysis to answer the factors that influence the number of specimens and species of boring coral. Line regression and coefficient of determination (r^2) were used to delimit the relationship between the age of coal (x-axis), the number of specimens, and number of species. The age of coral was reported from a calculated growth rate.

The abundance of each coral boring bivalve was based on the similarity from each replicate site and was transformed to the fourth root. To further interpret the community, this figure was then placed into a group average cluster and non-metric multi-dimensional scaling (MDS) ordination in two dimensions analysis.

The hierarchical clustering (group average linking) and MDS analysis was used to show how close the abundance levels are for each species, averaged over all species.

RESULTS

Coral profiles for each site is summarized in the text below (Figs. 2 and 3)

Ko Bai Dung is located at 11.895057°N, 102.452154°E. The coral reef was at 2-6 m depth and showed the highest number of coral species (17) and included 40.32% dead coral and 38.6%

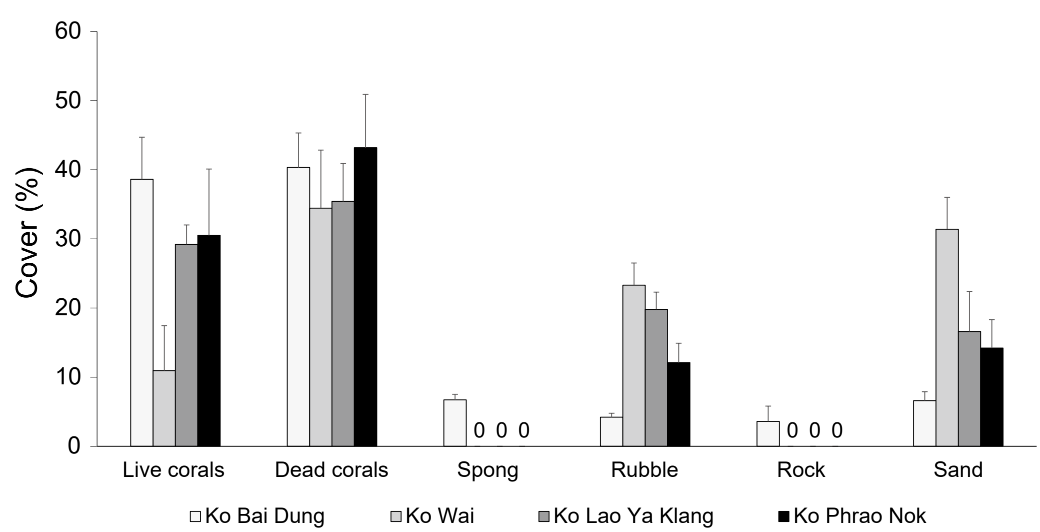

Fig. 2. Percent (%) cover of bottom composition at four study sites.

live coral. *Porites* was the dominant coral genus, comprising 81.05% of the coral cover. Sediment covered less than 10% of the bottom and primarily contained sponge, rubble rock, and sand.

Ko Wai is located at 11.902281°N, 102.415367°E. The coral reef was at 2-5 m depth and was mainly covered by 34.4% dead coral, 31% sand bed and 23% rubble respectively. Only 10% of cover comprised living coral, and this was dominated by 73.72% of *Porites* spp.

Ko Lao Ya Khang is located at 11.937625°N, 102.408896°E.The coral reef was 1-4 m depth that included coverage of 35% dead coral and 29% live coral. The dominant coral species was *Porites* spp., comprising 76.91% (combined live and dead corals). Also included in the bottom composition

	Ko Bai Dung	Ko Wai	Ko Lao Ya Klang	Ko Phrae Nok
Acropora mollepora	0.00	1.59	0.00	0.00
Acropora myriophthalma	1.09	0.00	1.71	0.77
Galaxea fascicularis	1.63	0.00	0.06	0.00
Pavona decussata	5.76	0.00	6.29	0.00
Pavona frondifera	0.26	0.00	0.00	0.00
Fungia fungites	0.82	3.47	4.29	7.36
Pectinia lactuca	0.54	0.00	0.00	0.67
Pectinia paeonia	0.00	0.00	0.00	0.33
Turbinaria sp.	0.00	1.64	0.00	0.00
Lobophyllia hamprichii	0.92	1.20	0.00	0.00
Symphyllia radians	1.17	1.44	3.43	1.14
Favia favus	0.26	0.00	0.34	0.00
Favia spp.	2.85	3.03	3.60	6.02
Favites abdita	1.14	5.76	0.23	0.00
Favites holicora	0.52	0.00	1.00	4.35
Goniastrea aspera	1.06	2.55	0.00	0.98
Platygyra sinensis	0.35	4.32	0.57	3.04
Cyphastrea sp.	0.27	0.00	0.00	0.10
Echinopora lamellosa	0.52	0.00	0.00	0.00
Porites spp.	81.05	73.72	76.91	75.49
Goniopora sp.	0.00	1.30	1.23	0.00
Number of species	17	11	12	11

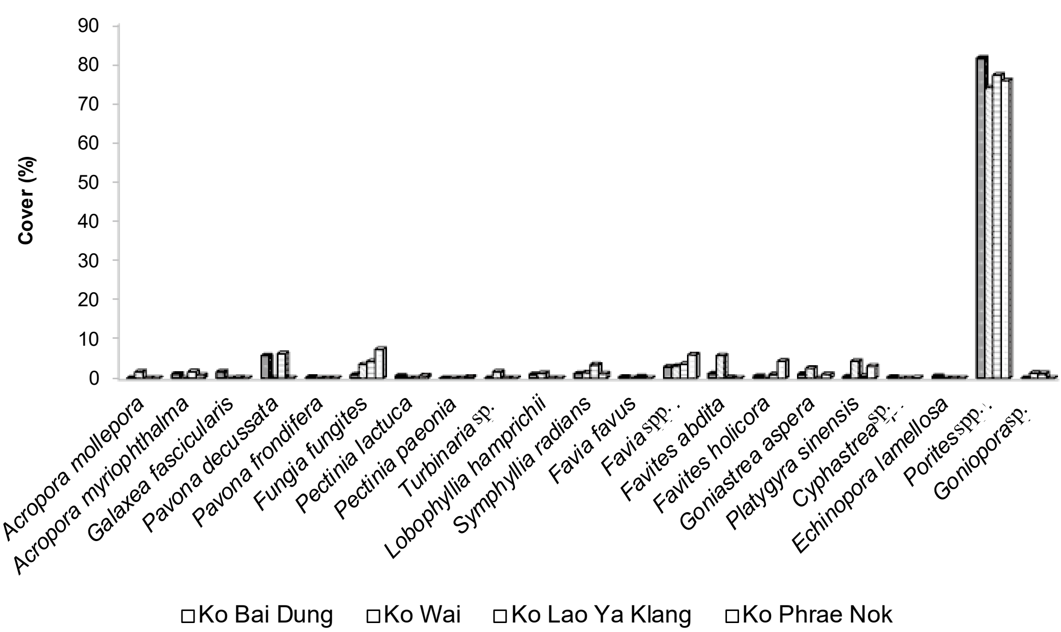

Fig. 3. Coral species composition and number of coral species at each study site.

was 19.8 % of rubble coverage, and 16.6% sand.

Ko Phrao Nok is located at 11.973046°N, 102.392599°E. The reef was at 1-4 m depth. This study site was near the mainland and it is affected by presence of freshwater and suspended solids. The coverage was composed of 43.2% dead coral and 30.5% of live coral. *Porites* spp., comprising 75.49% of the coral fauna, was the dominant species. There was little rubble or sand in the bottom coverage composition, with 12.1% and 14.2%, respectively.

Physical water measurements from the four study sites are reported in table 1. The highest values were reported at Ko Phrao Nok, including the highest water temperature (29.53°C), conductivity (55.34 ms/cm), total dissolved solid (33.07 s/l), and water pH (7.54). Ko Wai showed the highest dissolved oxygen levels at 4.76 mg/l. Salinity was nearly the same (33‰) at each of the four islands.

A total of 11 families, represented by 18 coral boring bivalve species, including six newly reported species from southeastern Thailand are listed with the status of their coral host (Table 2). The highest number of coral boring bivalve species was recorded at Ko Wai and Ko Phrao Nok, 12 species from eight families and seven families, respectively. Eleven bivalve species from eight families were recorded at Ko Lao Ya Khang, and 11 species from seven families at Ko Bai Dung. Five species from four families were found in common at all sampling sites, and include *Chama brassica* Reeve (Chamidae), *Gastrochaena cuneiformis* (Gastrochaenidae), *Botula cinnamomea* (Gmelin)

Table 1. Physical factors at study sites

Physical factors	Ko Bai Dung	Ko Wai	Ko Lao Ya Khang	Ko Phrao Nok
Water temperature (°C)	28.46	28.54	28.79	29.53
Conductivity (ms/cm)	54.07	54.12	54.34	55.29
Total dissolved solid (s/l)	32.97	32.94	32.94	33.07
Salinity (%)	33.17	33.13	33.13	33.06
Dissolved oxygen (mg/l)	3.25	4.76	4.09	4.05
Water pH	7.49	7.47	7.49	7.54
pHmV	-76.9	-77.3	-78.6	-81.5

Table 2. Checklist and distribution of specimens of boring bivalves per coral colony

	Family	Boring bivalve species	Ko Bai Dung	Ko Wai	Ko Lao Ya Khang	Ko Phrao Nok
*	Arcidae	*Barbatia parva* (G.B. Sowerby I, 1833)	0;3^{+x}	3;5^{+x}	2;5^{+}	3;4^{x}
	Carditidae	*Cardita varigata* Bruguiere, 1792	1;3^{+}	0;5^{+x}	0;5	0;4
	Chamidae	*Chama brassica* Reeve, 1846	2;3^{x}	2;5^{x}	4;5^{+}	2;4^{+x}
	Gastrochaenidae	*Gastrochaena carteri* Nielson, 1986				
	Gastrochaenidae	*Gastrochaena cuneiformis* Spengler, 1783	2;3^{x}	1;5^{x}	4;5^{+x}	5;4^{+x}
*	Limidae	*Limaria fragilis* (Gmelin, 1791)	0;3^{+x}	3;5^{x}	0;5^{+x}	0;4^{+x}
	Mytilidae	*Botula cinnamomea* (Gmelin, 1791)	4;3^{+x}	4;5^{+}	4;5^{x}	5;4^{+x}
*	Mytilidae	*Gregariella coralliophaga* (Gmelin, 1791)	3;3^{x}	0;5	1;5^{x}	1;4^{+}
	Mytilidae	*Leiosolenus lima* (Jousseaume in Lamy, 1991)	0;3	18;5^{+x}	0;5	16;4^{+x}
	Mytilidae	*Leiosolenus malaccanus*(Reeve, 1858)	2;3^{x}	3;5^{+}	1;5^{x}	3;4^{+x}
	Mytilidae	*Lithophaga teres* (Philippi, 1846)	8;3^{x}	3;5^{+}	0;5^{+x}	18;4^{+x}
*	Noetiidae	*Arcopsis symmetrica* (Reeve, 1844)	0;3^{+x}	0;5^{+x}	1;5^{+}	0;4
	Noetiidae	*Striarca navicella* Reeve, 1844	0;3^{+x}	3;5^{x}	0;5	1;4^{+}
*	Noetiidae	*Striarca erythraea* (Issel, 1869)	0;3^{+x}	0;5	0;5	1;4^{x}
	Petricolidae	*Petricola lapicida* (Gmelin, 1791)	4;3^{x}	1;5^{+}	1;5^{x}	5;4^{+x}
	Pteriidae	*Pinctada margaritifera* (Linnaeus, 1758)	0;3^{+x}	0;5^{+x}	1;5^{x}	0;4^{+x}
*	Semelidae	*Cumingia striata* A. Adams, 1850	3;3^{x}	0;5^{+x}	2;5^{x}	5;4^{x}
	Trapeziidae	*Coralliophaga coralliophaga* (Gmelin, 1791)	23;3^{x}	1;5^{+}	0;5^{+x}	0;4^{+x}
		No. of species	**11**	**12**	**11**	**12**
		No. of families	**7**	**8**	**8**	**7**

Key: * = newly reported species from SE Thailand coral reef; (number of specimens; number of colonies); + = live coral; x = dead coral.

and *Leiosolenus malaccanus* (Reeve) (both Mytilidae), and *Petricola lapicida* (Gmelin) (Petricolidae).

Ko Phrao Nok and Ko Lao Ya Khang have four newly reported species but Ko Bai Dung and Ko Wai included only two newly recorded species. Interestingly, three of the newly reported species were only found on dead coral, namely *Cumingia striata* A. Adams (Semelidae), *Limaria fragilis* (Gmelin) (Limidae), and *Striarca erythraea* (Issel) (Noetiidae).

Amongst bivalve families, members of the Mytilidae showed the highest number of species (5), followed by Noetiidae (3), and Gastrochaenidae (2) (Table 2). The mytilids *Botula cinnamomea* and *Lithophaga teres* (Philippi), along with *Petricola lapicida* (Petricolidae) recorded higher numbers of specimens per coral colony than were found at Ko Bai Dung or Ko Phrao Nok. Whereas *Leiosolenus lima* recorded higher number of specimens per available coral colony than were found at Ko Wai or Ko Phrao Nok. Moreover, *Coralliophaga coralliophaga* had the highest number of specimens (23) per coral colony at Ko Bai Dung.

The five most abundant species in rank are illustrated in figure 4. Three of these species belong to the Mytilidae, namely *Leiosolenus*

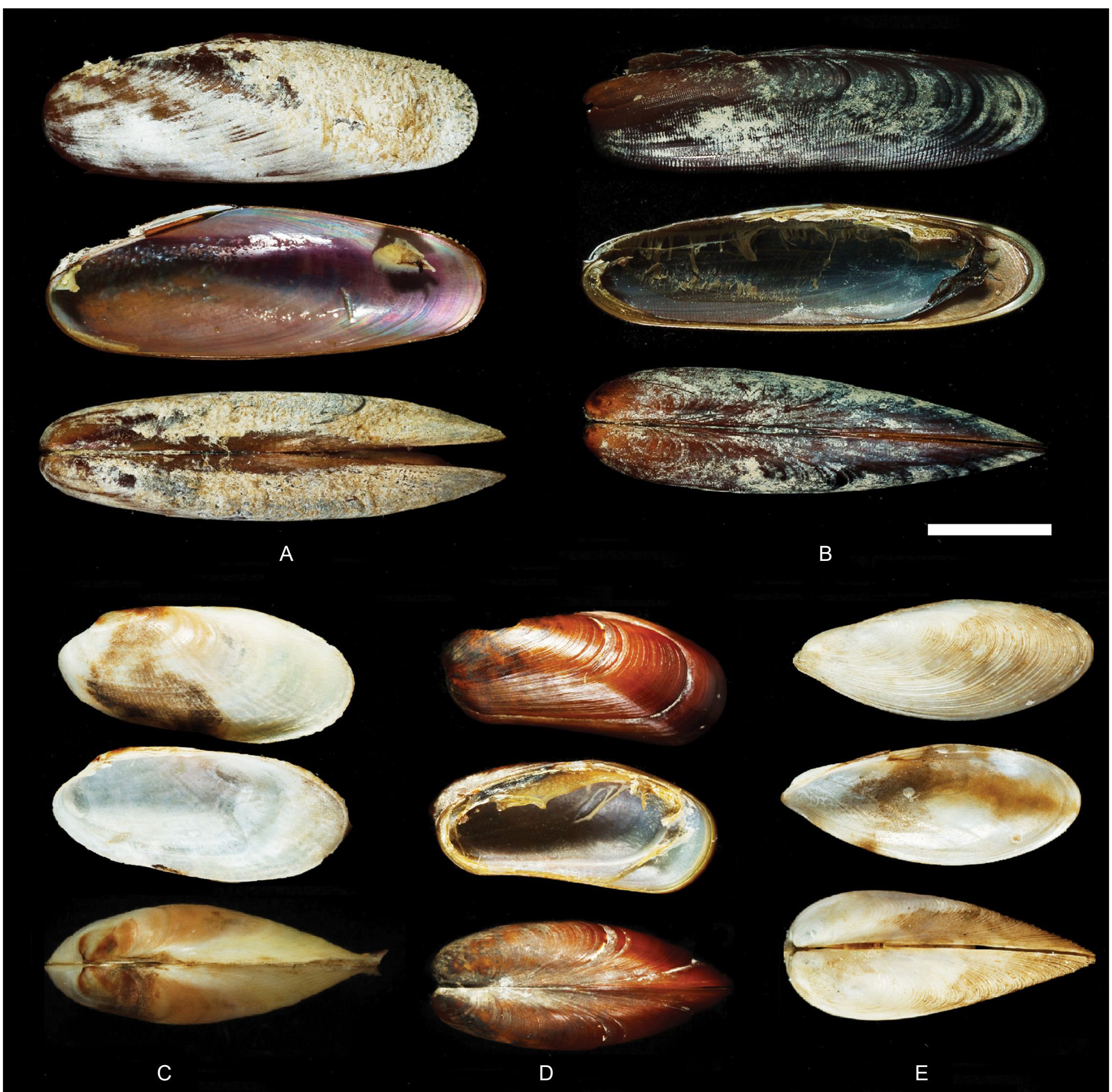

Fig. 4. Top five species in abundance at the study sites. 1. *Leiosolenus lima* (A); 2. *Lithophaga teres* (B); 3. *Coralliophaga coralliophaga* (C); 4. *Botula cinnamomea* (D); 5. Gastrochaena *cuneiformis* (E). Each set of species photographs are in the following orientation (top to bottom); exterior view, interior view, and dorsal view of the shell morphology. (scale bar = 1 cm).

lima, *Lithophaga teres* and *Botula cinnamomea*. Also included in the top five are *Coralliophaga coralliophaga* and *Gastrochaena cuneiformis*.

Ko Bai Dung showed the highest density of boring bivalves, 196.29 ± 118.24 individuals/m^2, followed by Ko Phrao Nok (180.55 ± 86.94 individuals/m^2), Ko Wai (97.77 ± 36.75 individuals/m^2), and Ko Lao Ya Khang (48.88 ± 17.07individuals/m^2) (Table 3).The density of coral borers varied from completely absent at some sites to the highest density of 85.18 ± 74.35individuals/m^2 (*Coralliophaga coralliophaga* from Ko Bai Dung, in 11 year old dead *Porites*.) *Lithophaga teres* and *Leiosolenus lima* had densities of 50.00 ± 39.68 individual/m^2 and 44.44 ± 23.57 individuals/m^2, respectively at Ko Phrao Nok.

Not surprisingly, not all species were found all sites. *Cardita variegata* Bruguiere, was only found at Ko Bai Dung (3.70 ± 3.70 individual/m^2). Three species were only found at Ko Wai, namely *Limaria fragilis* (Gmelin) (6.67 ± 6.67 individual/m^2), *Arcopsis symmetrica* (Reeve) and *Pinctada margaritifera* (Linnaeus) (the latter two species at 2.22 ± 2.22) (Table 3).

The community structure of the four sampling sites showed Ko Phrao Nok with the highest diversity index (H' = 2.209), the highest values of Margalef's richness index (d = 3.235), and Pielou's evenness index (J' = 0.9212), and had the highest number of individuals (65) and species number (12) (Table 4).

All dead corals had a high Shannon Wiener diversity index (H') above 1. The highest diversity of coral boring was recorded in seven-year-old, dead *Porites* at Ko Phrao Nok (H' = 1.887), whereas five and seven-year-old live *Porites* sp. from Ko Wai and Ko Lao Ya Khang, respectively showed the lowest boring bivalve diversity, as no specimens were collected at these sites. However,

Table 3. Density (mean ± SE) of boring bivalve species from four sampling sites (number per m^2)

Family	Boring bivalve species	Ko Bai Dung	Ko Wai	Ko Lao Ya Khang	Ko Phrao Nok
Arcidae	*Barbatia parva* (G.B. Sowerby I, 1833)	0.0 ± 0.0	6.67 ± 2.72	4.44 ± 4.44	8.33 ± 8.33
Carditidae	*Cardita varigata* Bruguiere, 1792	3.70 ± 3.70	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Chamidae	*Chama brassica* Reeve, 1846	7.41 ± 3.70	4.44 ± 4.44	8.89 ± 5.44	5.56 ± 3.21
Gastrochaenidae	*Gastrochaena carteri* Nielson, 1986	3.70 ± 3.70	4.44 ± 2.72	2.22 ± 2.22	0.0 ± 0.0
Gastrochaenidae	*Gastrochaena cuneiformis* Spengler, 1783	7.41 ± 3.70	2.22 ± 2.22	8.89 ± 4.15	13.89 ± 5.32
Limidae	*Limaria fragilis* (Gmelin, 1791)	0.0 ± 0.0	6.67 ± 6.67	0.0 ± 0.0	0.0 ± 0.0
Mytilidae	*Botula cinnamomea* (Gmelin, 1791)	14.81 ± 3.70	8.9 ± 8.9	8.89 ± 4.16	13.89 ± 6.99
Mytilidae	*Gregariella coralliophaga* (Gmelin, 1791)	11.11 ± 11.11	0.0 ± 0.0	2.22 ± 2.22	2.78 ± 2.78
Mytilidae	*Leiosolenus lima* (Jousseaume in Lamy, 1991)	0.0 ± 0.0	40.0 ± 37.71	0.0 ± 0.0	44.44 ± 23.57
Mytilidae	*Leiosolenus malaccanus* (Reeve, 1858)	7.41 ± 7.41	6.67 ± 4.44	2.22 ± 2.22	8.33 ± 5.31
Mytilidae	*Lithophaga teres* (Philippi, 1846)	29.63 ± 29.63	6.67 ± 6.67	0.0 ± 0.0	50.00 ± 39.68
Noetiidae	*Arcopsis symmetrica* (Reeve, 1844)	0.0 ± 0.0	0.0 ± 0.0	2.22 ± 2.22	0.0 ± 0.0
Noetiidae	*Striarca navicella* Reeve, 1844	0.0 ± 0.0	6.67 ± 6.67	0.0 ± 0.0	2.78 ± 2.78
Noetiidae	*Striarca erythraea* (Issel, 1869)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.78 ± 2.78
Petricolidae	*Petricola lapicida*(Gmelin, 1791)	14.81 ± 14.81	2.2 ± 2.2	2.22 ± 2.22	13.89 ± 1.52
Pteriidae	*Pinctada margaritifera* (Linnaeus, 1758)	0.0 ± 0.0	0.0 ± 0.0	2.22 ± 2.22	0.0 ± 0.0
Semelidae	*Cumingia striata* A. Adams, 1850	11.11 ± 11.11	0.0 ± 0.0	4.44 ± 2.72	13.89 ± 10.52
Trapeziidae	*Coralliophaga coralliophaga* (Gmelin, 1791)	85.18 ± 74.35	2.22 ± 2.22	0.0 ± 0.0	0.0 ± 0.0
	Mean ± sd	196.29 ± 118.24	97.77 ± 36.75	48.88 ± 17.07	180.55 ± 86.94

Table 4. Community structure at four sampling sites. Including the number of species (s), total number of individuals (N), Margalef's richness index (d), Pielou'seveness index (J'), the Shannon- Wiener diversity index (H')

Station	s	N	d	J'	H' (log e)	1-Lamda
Ko Bai Dung	11	53	2.519	0.7855	1.884	0.7808
Ko Wai	12	44	2.907	0.8202	2.038	0.814
Ko Lao Ya Khang	11	22	2.635	0.8345	2.074	0.8462
Ko Phrao Nok	12	65	3.235	0.9212	2.209	0.9134

no patterns were found correlating species diversity index with coral condition (live or dead), age, or species (Fig. 5).

A cluster analysis was performed to group the abundance of each coral boring bivalve based on the similarity from each replication site with the fourth root transformed. Dendrograms were constructed to display the results of the cluster analysis; a group of seven stations (in square) showed similarity in abundance of coral boring bivalves at a 50% level (Fig. 6A).

Multivariate analysis did not reveal clear differences at 50% community composition between sites (Figs. 6 A, B) or coral age (Fig. 6E). A similar result was found with coral species, although less well defined (Fig. 6 D). However, coral status, particularly dead coral, was well grouped at 50% similarity with boring bivalve abundance (Fig. 6 C).

After gathering results from the cluster analysis and the MDS, we then focused on coral status and the coral species sampled. The number of bivalve species and specimens increased with increasing coral age (Fig. 7). The number of bivalve species specimens was significantly positively correlated with the age of the coral with *p* valve = 0.013 and p valve = 0.001 respectively. The number of bivalve species and specimens increased with increasing coral age with the linear equations y = 0.823x-2.186 and y = 3.96x-20.532, respectively. The number of specimens was more correlated to coral age (r^2 = 0.53) than the number of species (r^2 = 0.348) (Figs. 7A, B).

The age of *Porites* had a significant positive correlation to the number of boring bivalve specimens (r^2 = 0.536, p = 0.04) than that of the other two coral species with the linear equation y = 3.644x-17.911 (Fig. 7C). The maximum number of specimens (40) was found in the oldest (11 years old) *Porites* from Ko Bai Dung (Fig. 8B), which was similar to the number bivalve specimens (38) found in *Favia* of the same age at Ko Phao Nok (Fig. 8A).

When considering the coral status, the age of the dead coral had a significant positive correlation to the number of boring bivalve specimens (r^2 = 0.518, p = 0.044) (Fig. 7D) whereas the number of boring bivalve specimens was not significant correlated to live coral (p = 0.068). The maximum

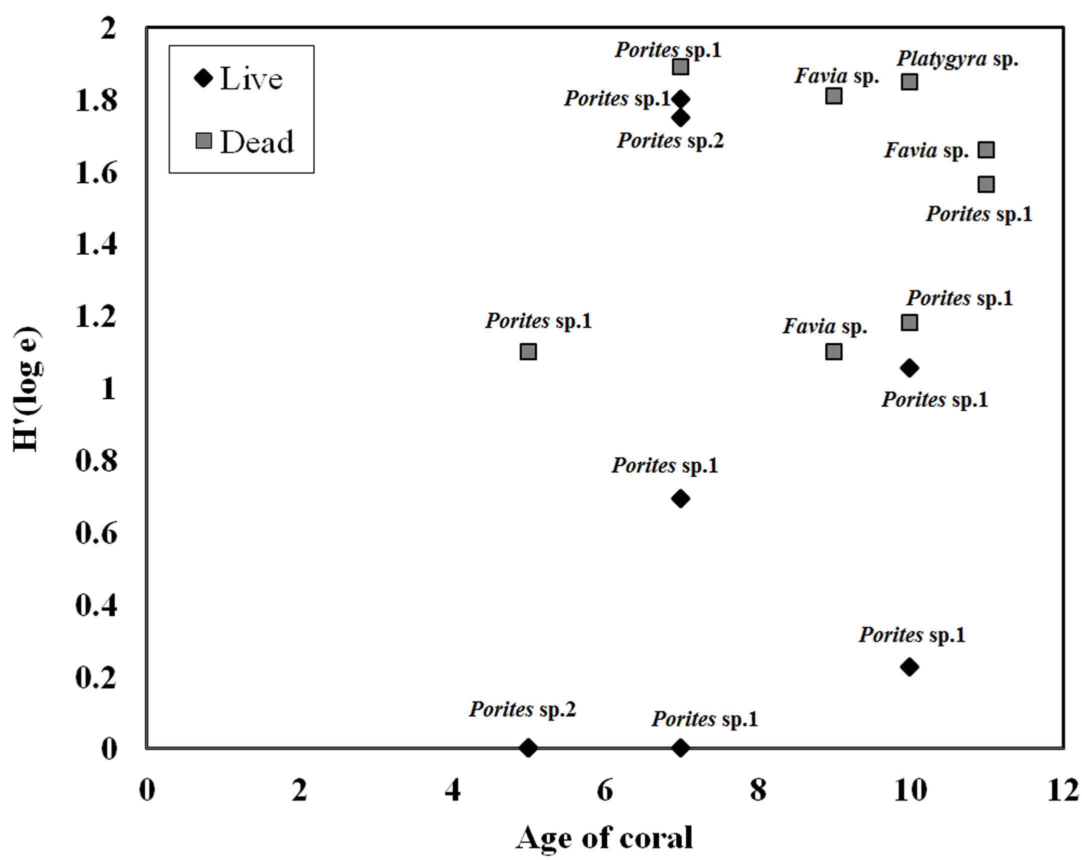

Fig. 5. Shannon Wiener diversity index Value (H') of coral boring bivalves by different coral age, coral species, and coral status.

number of boring bivalve specimens came from the oldest dead host coral (11 years old). We examined two examples of dead and live of *Porites* colonies of the same age (7 years old). The live coral had from one to 11 boring bivalve specimens and these were only bored at the lower base of the coral (Fig. 9A), whereas the dead coral showed 12 bivalve specimens from seven species, and these bored into the middle of the coral colony (Fig. 9B).

The distribution of bivalve shell height frequencies of the five dominant coral boring bivalve species is shown in figure 10. Large mytilid species exhibited more variation in shell height than other groups, including *Leiosolenus lima* that ranged from 3.73 to 66.97 mm (mean ± SD, 34.95 ± 16.39) and *Lithophagus teres* that fluctuated from 17.57 to 86.67 mm (mean ± SD, 33.02 ± 14.84). However, the small boring mytilid bivalve, *Botula cinnamonea*, had a narrow size range with a shell height from 8.31 to 23.76 mm (mean ± SD, 17.08 ± 4.64) and *Coralliophaga coralliophaga* had a shell height minimum of 6.7 mm and a maximum

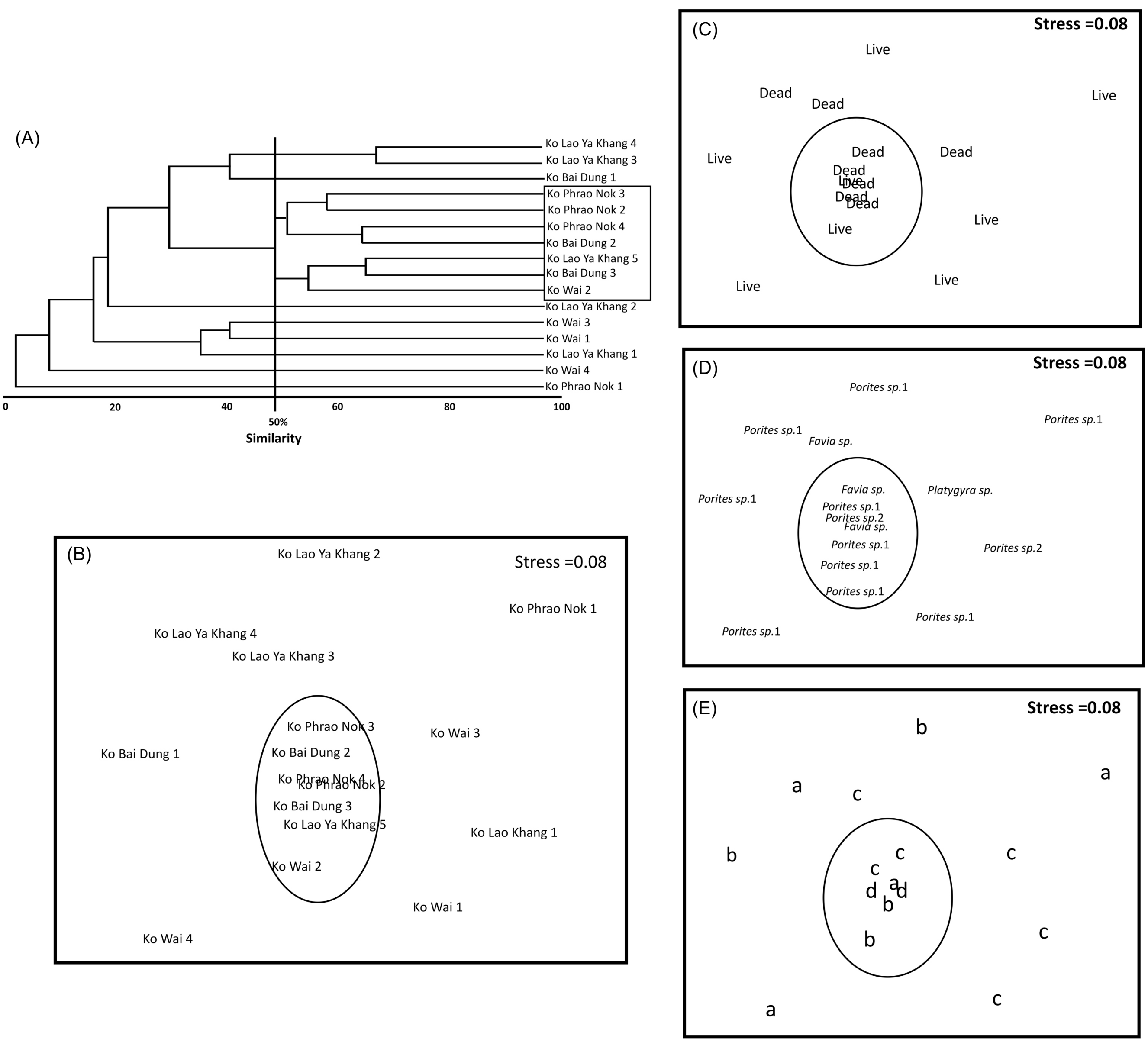

Fig. 6. Sixteen stations by species abundance based on Bray-Curtis similarity and fourth root transferred shown in the dendrogram hierarchical clustering (group-average linking) (A) and the 2-dimensional MDS (stress 0.08) (B) at 50% similarity level in Group (circle). MDS ordination of same data, 50% similarity in Group (circle) under different factors. Boring bivalve abundance by coral status (dead and live) (C) by 4 coral species (D) and four classes of coral ages, a < 6 y, b 6-7 y, c 8-9 y, d > 9 y (E).

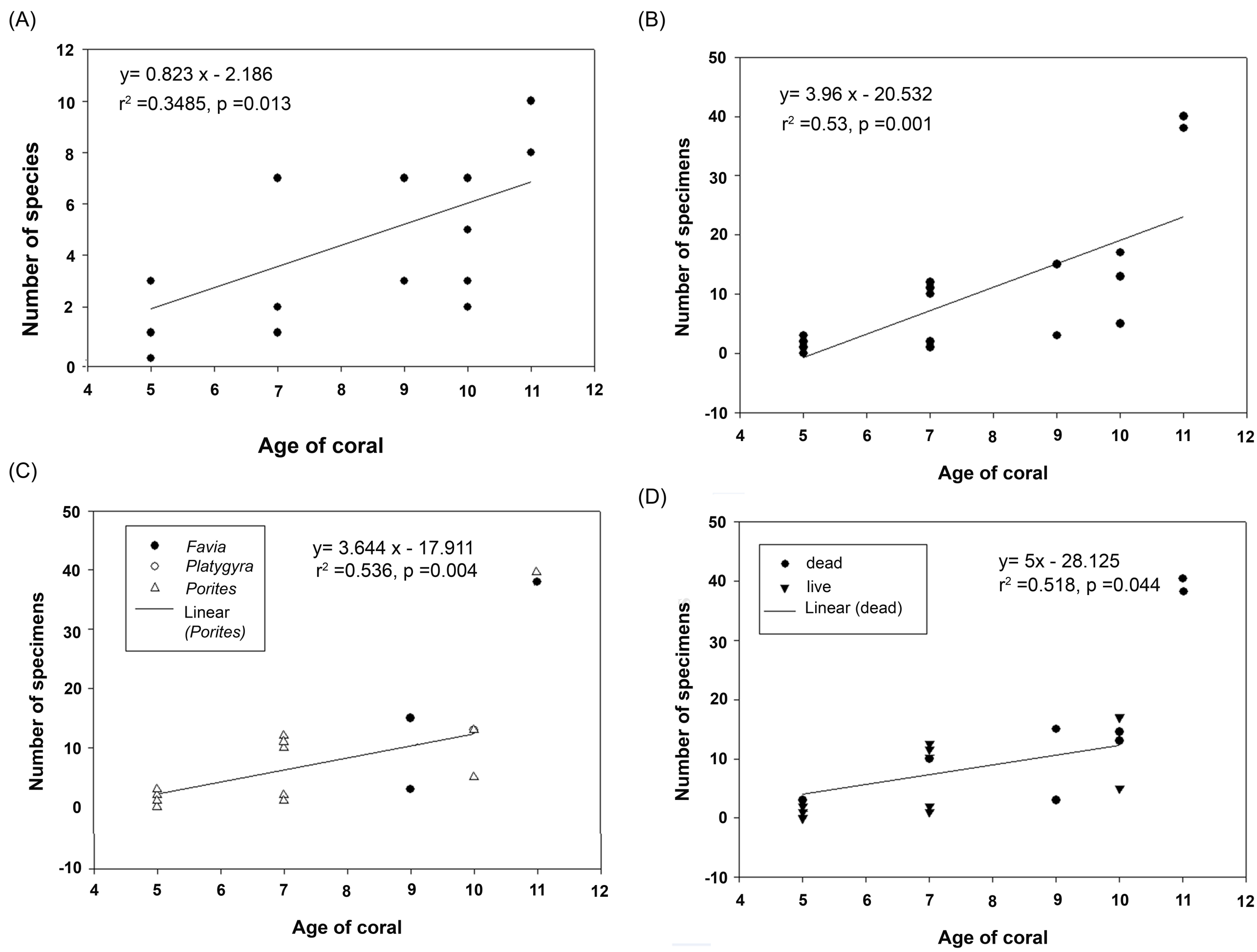

Fig. 7. Line regression with least square means for the relationship between the age of the coral (x-axis) and number of boring coral species (y-axis) (A) and number of boring coral specimen (y-axis) (B). Line regression with least square means for the relationship between age of the coral (x-axis) and number of boring coral specimens (y-axis) by three coral species (C) and by two types of coral statuses (D).

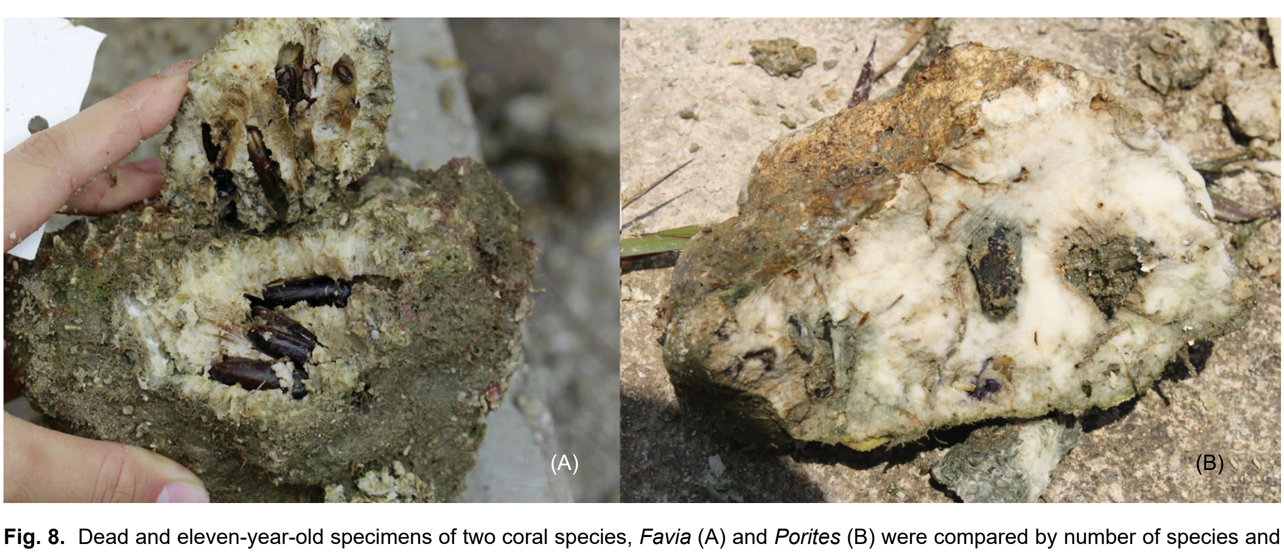

Fig. 8. Dead and eleven-year-old specimens of two coral species, *Favia* (A) and *Porites* (B) were compared by number of species and number of specimens.

of 33.31 mm, with average of 13.60 ± 5.59 mm (mean ± SD). *Gastrochaena cuneiformis* showed shell heights with average of 15.41 ± 5.59 mm.

The differences in coral age patterns and bivalve shell heights reflected changing shapes in the size frequency distribution. All dominant boring bivalves in corals with an age of more than nine years old showed larger shell lengths when compared to those in younger coral.

Moreover, corals in age Class d, those more than nine years old, showed the highest frequency distribution of almost bored coral except with *Botula cinnamomea* (Class b, highest frequency in 6-7 year old corals) (Fig. 10 D). Interesting, *Botula cinnamomea* and *Gastrochaena cuneiformis* were found in all age classes of coral, whereas *Leiosolenus lima*, *Lithophagus teres* and *Coralliophaga coralliophaga* were distributed in corals more than 6 years old (Fig. 10)

DISCUSSION

Coral reefs are one of the most productive marine systems in Thai waters and are mainly found around fringing islands. Coral reefs around the islands in the east part of the Gulf of Thailand are usually shallow, and extend to depths of approximately 2-5 m (ONEP 2004). Three groups of massive corals have mainly colonized these habitats; *Porites* spp., *Platygyra* sp., and *Favia* spp. Coral colonies are very complex, with their dead undersides and branches offering shelter and provide protection for mollusks and other animals (Moberg and Folke 1999; Hadfield 1976).

Endolithic Bivalve Diversity

Eighteen species from 11 families reported in this study represents moderate levels of coral boring bivalves for the Gulf of Thailand. Eight species are reported herein for the first time in the region. The number of species was lower than in the southeastern Gulf (Valentich-Scott and Tongkerd 2008) but higher than the southwestern region (Nielson 1976) where 21 and nine species were reported, respectively. However this study reported a higher number of species than comparable temperate localities (Valentich-Scott and Dinesen 2004; Riccia et al. 2015).

When compared to boring bivalve species reported from southeastern Thailand (Valentich-Scott and Tongkerd 2008), our study had eight species in common. These include: two gastrochaenids, *Gastrochaena carteri* and *Gastrochaena cuneiformis*; four mytilids, *Botula cinnamomea*, *Leiosolenus lima*, *Leiosolenus malaccanus*, *Lithophaga teres*; one petricolid, *Petricola lapicida*; and one trapeziid, *Coralliophaga coralliophaga*. These species are also common coral boring bivalves in western Thai waters (Nielson 1976, 1986; Tantanasiriwong 1979). This group of boring bivalves appears to be specific shallow water habitats in the region. *Leiosolenus*

Fig. 9. The number of boring bivalve species and specimens from two seven-year-old *Porites* corals with different coral statuses were compared, live coral (A) and dead coral (B).

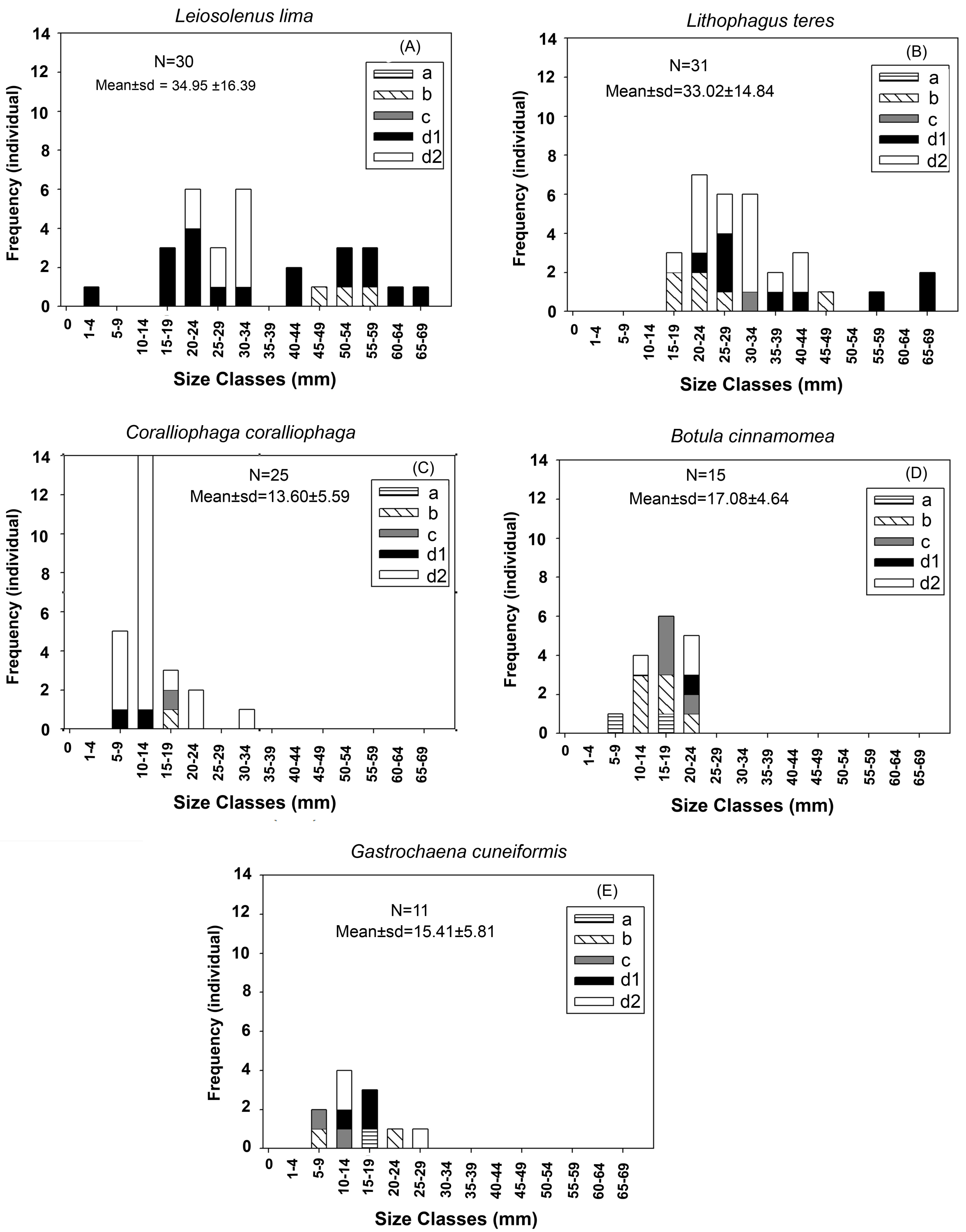

Fig. 10. Size frequency distribution (shell height) with mean ± sd of the five dominant species. Five intervals of size classes (0-69 mm); N = total sample; legend box of age classes, a < 6 years, b = 6-7 years, c= 8-9 years, d1 = 10 years, d2 =11 years.

lima and *Gastrochaena cuneiformis* were wider spectrum borers, in that they colonized all three coral species sampled in this study. Similar to previous reports our study found *Leiosolenus lima* in a wide range of corals, including Faviidae, Acroporidae and Fungiidae (Wilson 1979; Kleemann 1980; Scott 1980; Morton and Scott 1980; Kleemann and Hoeksema 2002).

The giant clam, *Tridacna maxima* (Cardiidae), byssally attaches to the upper surface of coral colonies and in crevices. The coral scallop, *Pedum spondyloideum* (Gmelin) (Pectinidae), is found in narrow crevices in massive coral in Indo-Pacific (Morton 1983; Scaps and Denis 2007). However, neither species was included in this study. The giant *Tridacna* is illegal to collect in Thailand. We observed *Pedum* at almost all sites but they were deeply imbedded in huge massive live colonies of *Porites* and impossible to collect.

We have added 10 coral associated bivalve species to the Gulf of Thailand. These include *Barbatia parva* (Arcidae), *Chama brassica* (Chamidae), *Gregariella coralliophaga* (Mytilidae), *Limaria fragilis* (Limidae), three members of the Noetiidae, *Arcopsis symmetrica*, *Striarca navicella* and Striarca *erythraea*, *Pintada margaritifera* (Pteriidae) and *Cumingia striata* (Semelidae) (Morton 1982; Nielson 1976; Tantanasiriwong 1979; Valentich-Scott and Tongkerd 2008).

Ko Phrao Nok was important locality for boring bivalve diversity. The high diversity of boring bivalve species in Ko Phrao Nok can be explained by the character and type of reef coral. This site has a high composition of massive corals (*Porites* spp, 75.49% coverage) providing large surface of coral skeletons for bivalves to live within or on, which may affect the diversity. Larger massive coral assemblages provide shelter and protection for a diverse range of taxa (De Vantier and Endean 1988). Kleeman (2009) demonstrated that a big colony of fossil coral can have a high number of boring bivalve species. Scott (1980) indicated that very few borers were found on branching corals. Massive corals provide large amounts of space for many species to colonize with less interspecific competition.

Environmental Factors

Physical factors, particular the highest amount of total dissolved solids in Ko Phrao Nok (related to organic loading from the mainland in sea water column) may affect an increase in the mass of coral (Risk et al. 2001; Floros et al. 2005) and the feeding of bivalves in coral host (Newell 2004). Londoño-Cruz et al. (2003) suggested that sediment deposition may affect the diversity and abundance of bored coral. High sediment load may directly affect the living conditions for the borers by deteriorating the habitat for settlement, and thus yielding low abundance. Kleemann (1992) detailed coral communities, mainly species of *Porites* and *Acropora*, which had coral-bivalve associations in the northern Red Sea. He suggested that it was typical for specific reef areas to be correlated to the food supply for the bivalves. The lowest numbers of coral associated species have been found at the most pristine sites (Scaps and Denis 2008).

Ko Bai Dung showed the highest density of bored corals. This could be explained by the high complexity of the coral habitat at the site, which included a variety of bottom sediment and coral covers. Coral cover is important for understanding the abundance of coral-dwelling species, as well as species that use coral habitat for recruitment (Booth and Beretta 1994; Munday et al. 1997; Munday 2002). Although Ko Bai Dung was an important site for boring bivalve density it had the lowest diversity value. Crowded populations of boring bivalve species may affect interspecific competition for space and food, whereas low abundance of boring species might yield a high diversity community. Kleeman (2009) suggested that the advantage of dense settlement in hosts is assumed to include substantially increased reproductive success because simultaneous spawning can occur at a closer range. In this study, *Coralliophaga coralliophaga* was one of the species with high numbers, and was seemingly highly successful at competing for space and food. The extremely high density at only one specific site could be explained by the availability of an optimal space for larvae settlement. Also, high populations of this nestling bivalve species could be a function of available crevices in dead *Porites*, or in empty burrows of the coral- boring lithophagines (Morton and Scott 1980; Nielson 1986; Morton 2014).

Importance of Lithophagine Mussels

In the southeastern Gulf of Thailand lithophagines are an important coral boring group (total density 195.37 individuals/m^2, 30% of total population density). This is similar to other studies, such as the Brazilian coast where over 50% of the corals were colonized by the lithophaginae, *Lithophaga bisulcata* (Nogueira 2003). Further, *Lithophaga simplex* is found to inhabit scleractinian corals in high densities (density of 0.22 ± 0.11 bivalves/cm^2) in the northern part of the Gulf of Eilat in the Red Sea (Mokady et al. 1998).

The reefs around the islands of Hoga and Kaledupain the Tukang Besi Archipelago along the southeastern coast of Sulawesi in the Banda Sea, in Indonesia, had an exceptionally high 73% coral infestation by lithophagids (Scaps and Denis 2008). Interestingly, when comparing lithophaginean densities, the southeastern Thailand densities were higher than those in the southeastern Banda Sea (Scaps and Denis 2008).

Members of the Family Mytilidae are one of the most important coral borer groups in terms of abundance and density, not only the shallow waters sampled in this study, but also in coral ecosystems at all depths (Bromley 1978; Morton and Scott 1980; Morton 1983; 1990; Nielson 1986; Kleemann and Hoeksema 2002; Nogueira 2003; Valentich-Scott and Tongkerd 2008). In this study, two mytilid coral borers, *Lithophaga teres* and *Leiosolenus lima* had the highest abundance and density.

Londoño-Cruz et al. (2003) suggested that the pioneering behavior of lithophagid mollusks might be very important in the successional pattern of the coral boring community on the Pacific coast of Colombia. The success of the Lithophaginae might derive from their capacity to colonize in a large range of coral substratum, including completely dead coral, the dead portion of living coral, and also live coral (Morton 1983; 1990). Lithophaginaes have mechanisms to erode and deconstruct a wide range of calcareous skeletons by using well-developed functional boring glands found in the mantle margin (Yonge 1955; Morton and Scott 1980).

Living versus Dead Corals as a Substratum for Endolithic Bivalves

Many boring bivalves are associated with both dead and live coral. This study found a higher diversity of boring species in dead versus living coral, similar to previous ecological studies of boring bivalves (Kleeman 1980, 1992; Morton 1983; 1990; Nielsen 1986; Nogueira 2003; Scott 1980; Valentich-Scott and Dinesen 2004; Valentich-Scott and Tongkerd 2008), thus supporting the hypothesis that dead coral is a more easily colonized substratum compared to live corals. Some species were found mainly associated with dead corals, such as *Cumingia striata*, *Striarca erythraea*, and *Pinctada margaritifera.* Dead coral colonies provide a substratum for high abundance and density of boring bivalves, as well as epizoic bivalves that settle in dead corals or inhabit crevices in corals (Morton and Scott 1980; Morton 1983; Nielson 1986). Epizoic bivalves in this study, either byssally attached or cemented to the coral, included members of the families Arcidae, Carditidae, Pteriidae, and Chamidae. Taylor (1971), who studied the corals of the lagoon shore of Diego Garcia in the Indian Ocean, showed that byssate species (*e.g. Barbatia helblinggi*, *Isognomon legumen*, *Septifer bilocularis*, *Lima lima*, and *Gloripallium pallium*) were common in coral crevices and on dead coral branches.

Londoño-Cruz et al. (2003) suggested that dead coral colonies provided important physical characteristics, such as an adequate substratum where borers can settle. Boring bivalves are similar to euendoliths (boring microflora including cyanobacteria, chlorophytes, rhodophytes, and fungi), which colonize live and dead substrates, but have been shown to have higher densities in dead corals (Le Campion-Alsumard et al. 1995).

Higher boring densities in dead corals could explain why Ko Phrao Nok was an endolithic bivalve diversity hotspot, as that site showed the highest percentage of dead coral cover in our study. A succession of boring bivalve communities in the coral host is the likely explanation for the higher diversity in older corals. There were positive correlations between coral age and the number of specimens.

Boring bivalves may induce some coral die off, but they do not disturb overall growth of corals. De Vantier and Endean (1988) showed slow growth in massive corals at 0.5-1 cm per year. Massive corals usually have a longer life span, such as a colony host coral *Porites lutea* (Dai and Yang 1995); therefore boring animals inhabiting such corals might have a higher fitness (Hunte et al. 1990).

Coral Species and Endolithic Bivalves

The massive coral *Porites* has been reported by many authors to be infested with many bivalve species (Nielson 1976; 1986; Tantanasiriwong 1979; Valentich-Scott and Tongkerd 2008).This coral genus is the most successful in recolonizing and is the most abundant group of corals in Thailand and the Indo-Pacific (Scoffin et al. 1992; Veron 1986; 1995). However, this study has demonstrated that *Favia* and *Platygyra* are also key groups in the coral ecosystem, as they both support a high diversity and abundance of boring bivalves. By not focusing solely on *Porites* colonies, we have expanded the known bivalve/coral associations. Notably, *Limaria fragilis* was found only on 10 year old dead *Platygyra* from Ko Wai. *Striarca erythraea* was found at only on *Favia* and *Platygyra.* Morton (1983) showed *Favia* was an important coral for the lithophaginaes such as *Lithophaga simplex*. Kleeman (1992) further suggested that the frequency of coral-bivalve occurrence in coral community was dependent on factors such as the coral growth form, growth rate, skeletal density, and lifespan.

The colony morphology of the genera *Favia* and *Porites* is plocoid corallite (Veron and Stafford-Smith 2000). Wielgus et al. (2006) reported that boring spionid worms generally infested plocoid coral species (corallites with their own walls) with small polyps which may facilitate infestation by providing sufficient surface areas. *Favia* has discretely separated walls that may provide an advantage for coral boring larvae settling, or an easier path to infestation (Veron 1986). The position of the boring bivalve site might also be determined by the coral species. Faviid species are more frequently bored by bivalves on the upper surface, whereas *Porites* was attacked at the base of colony (Morton 1983). Since *Favia* and *Platygyra* have low bottom coverages in Thai waters, we are unable to definitively state that they are more important in the coral boring bivalve community when compared to *Porites*, especially in the context of global coral ecosystems.

Endolithic Bivalve Distribution

Coral boring bivalve abundance is not clearly grouped by different localities or coral species but was closed related to coral status (boring within dead or live coral). All four island study sites were located within Ko Chang National Park, and environmental factors and coral species were not different between sites. It is possible that endolithic bivalve species were not specific to a coral host but rather needed a massive coral for successful colonization.

The succession of boring organisms in the coral community has been demonstrated in number of species, with a variety of abundance and biomass (Karlson 1999; Osborne 2000). In this study, we have demonstrated that a host coral over 9 years old may represent the beginning succession point for the boring bivalve community.

The productivity of a population can vary because of the fluctuation in its density, size structure, and growth characteristics (Caetano et al. 2006). Cardoso and Veloso (2003) suggested that smaller bivalve individuals have rapid growth and a short life span, whereas large individuals have slower growth. The larger boring bivalve species, *Leiosolenus lima* and *Lithophagus teres* showed more variation in shell height when compared to other boring species. This may be related to their higher density, higher growth rate, and higher lifetime reproductive success when compared to other mytilids.

The distributions of shell height frequency and mean of shell height of the five dominant species of this study were more variable than previously reported from the Gulf of Thailand (Valentich-Scott and Tongkerd 2008). This may be a function of the size or health of the coral hosts in Trat Province is better than Chantaburi Province (ONEP 2004). Brickner et al.(1993) suggested that significant differences in maximal boring bivalves shell dimensions may be caused by the different size of host corals, or possibly the bivalves were limited by the thickness or mass of the boring substratum (Bagur et al. 2013).

Bioerosion

Bioerosion is an important part of coral dynamics, producing reef sediments (rubble, sand, silt, and clay) (Trudgill 1983), and plays an important role in regulating coral reef growth (MacGeachy and Stearn 1976). Coral boring bivalves are one of the main marine bioeroders in this ecosystem (Hutchings 1986; Kiene and Hutchings 1992). Mokady et al. (1998) considered that the symbiotic association between boring bivalves and their host coral to be mutualistic. The boring bivalve *Lithophaga simplex* has been shown to produce ammonium as nitrogenous waste products, which are then recycled by the coral host and may account for a significant portion of the coral / zooxanthellae nitrogen requirements.

The most abundant members of the Mytilidae, Trapeziidae and Gastrochaenidae play a significant bioerosion role in destruction of dead coral at Ko Chang, Thailand. Large mytilid species, particularly lithophagians, are important bioeroders (Riccia et al. 2015) and affect the rate of erosion (Scott and Risk 1988; Scaps and Denis 2008; Bagur et al. 2013). *Leiosolenus lima* and *Lithophagus teres* were primary boring bivalve species in this study, their larger size, ability to bore into live or dead massive corals, make them keystone species for bioerosion of corals in the region.

Thus, boring bivalves can, and should, be used as one indicator of coral reef status, including bioerosion and nutrient recycling in coral ecosystem.

CONCLUSIONS

Coral reefs are one of the most productive marine systems in Thai waters and are mainly found around fringing islands. In this study 18 coral boring bivalve species from 11 families represents moderate levels for the Gulf of Thailand and includes eight newly reported species. The high diversity and density of endolithic bivalve species was more related to the character or type of coral host, such as coral age or coral status (live or dead), rather than the locality. Our findings suggest that a host coral over 9 years old may represent the beginning succession point for the endolithic bivalve community. Corals over that age represent the highest diversity with the highest frequency distribution and size of boring bivalves.

This study of boring bivalves and their coral hosts provides one indicator in bioerosion coral reef ecosystems. Members of the bivalve families Mytilidae, Trapezidae, and Gastrochaenidae play a significant bioerosion role in destruction of dead coral in the region.

Acknowledgments: We acknowledge the Department of Biology, Faculty of Science, Ramkamhang University and the Department of Zoology, Faculty of Science, Kasetsart University (Visiting Professor Fund) who provided financial support. We deeply thank the staff of Ko Chang National Park who allowed us to conduct field research. We also thank students from the Marine Biodiversity Research Group, Ramkhamhaeng University, and the Department of Zoology, Faculty of Science, Kasetsart University for field collection assistance and laboratory sorting of specimens.

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