ORIGINAL ARTICLE

Vegetational changes in the coral-gravelly barrier spit appearing after the 2004 Indian Ocean Tsunami at Pakarang Cape, southwestern Thailand, related to topographical changes

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ABSTRACT Vegetational change was studied during 2010–2015 in the coral-gravelly barrier spit that appeared in 2007 in association with the 2004 Indian Ocean Tsunami at Pakarang Cape, southwestern Thailand, related to topographical changes. No lichens, liverworts, or ferns were found during the study period, although lithophytic algae were widespread over the coral gravel. Several woody species, along with several creeping herbaceous species, colonized the area soon after appearance of the barrier spit. Coral gravel covering the ground surface prevented the sand movement, facilitating colonization by drifting seeds. In all, 37 species of vascular plants, comprising 21 woody and 16 herbaceous species, were recorded through 2015. Annual monitoring of the plant covered area, location, and height of all the trees taller than 20 cm along with formation process of the barrier spit using high-resolution GPS revealed that vegetation was affected strongly by topographical changes. In accordance with easterly movement of the barrier spit, vegetation largely disappeared in the western part, although it developed in the eastern part. *Casuarina equisetifolia* increased and grew significantly faster than other species, producing a thick forest in the stable central part of the barrier spit during the study period.

Key words: coastal vegetation, annual change, Thailand, tsunami

INTRODUCTION

Studies of primary and secondary successions of coastal vegetation in tropical zones have mainly examined volcanoes (e.g., Brown et al. 1917, Backer 1929, Docters van Leeuwen 1936, Tagawa 1989) or sand dunes (e.g., Campbell et al. 1988, Luisa et al. 2001, Álvarez-Molina et al. 2012). Few studies have examined coral-gravelly coasts.

The 2004 Sumatra-Andaman earthquake (Mw 9.1), which occurred on 26 December 2004, generated a large tsunami. This tsunami inflicted severe damage on coastal areas of the Indian Ocean and its surroundings. Around the Pakarang Cape, located approximately 600 km from the earthquake epicenter, the tsunami wave height was 4–9 m. They inundated areas up to 2.5 km from the coastline (Matsutomi et al. 2005, Goto et al. 2008). The strong tsunami wave once washed out 200 m of the tip of Pakarang Cape. Several barrier islands were formed offshore of the cape at least several months after the tsunami event. Then

the barrier islands were bridged by a large amount of coral debris produced by the tsunami. They connected to the Pakarang Cape in 2007, producing a barrier spit (Koiwa et al. 2016).

Damage and recovery of vegetation after the 2004 tsunami in the Andaman Sea area have been studied by Yanagisawa et al. (2009a, 2009b), Hayasaka et al. (2009, 2012), and Bayas et al. (2011). Their studies specifically examined mangrove forests and sandy beaches, but did not investigate coral-gravelly coasts generated in relation to a tsunami event.

This paper describes vegetational changes on the barrier spit on the Pakarang Cape during 2010–2015 by annual monitoring. We present discussion of the factors affecting vegetation, with special reference to topographical changes.

STUDY SITE AND METHODS

Study area and period

Field research was conducted on the barrier spit at northwestern Pakarang Cape ($8^{\circ}44'N$; $98^{\circ}13'E$) on the Andaman Sea in Phang Nga Province, 100 km north of Phuket in southwestern Thailand (Fig. 1). Climatic conditions represent the tropical monsoon climatic zone, with the mean annual temperature of $28.0^{\circ}C$, and mean annual rainfall of 2693 mm during 2008–2012 at Phuket Airport Meteorological Station (<http://www.phuket.climatemps.com>). Climatic conditions are divided into a dry season (during October–April) and a wet season (during May–September).

Topographical and vegetation studies were conducted once a year during the dry season (November or December) in 2010–2014 and the wet season (June) in 2015.

Monitoring of topographical changes

The barrier spit formation process has been studied since immediately after the tsunami by Koiwa et al. (2016). Topographical changes of the barrier spit were monitored by interpretation of sequential satellite images and high-resolution GPS (ProMark3 and ProMark120; Ashtech Inc.) measurements. In the GPS survey, kinematic measurements were done using differential GPS calculation. We calculated the location and height in post-processing using a rover

station and reference station. The accuracy of kinematic post-processing is less than 20 mm. The elevation of this study corresponds to the mean sea level calculated from average tidal height based on tidal tables at Kho Taphao Noi. Making a topographical map using data from ArcGIS 10 elicits a triangulated irregular network (TIN). The land area is calculated every year for the area higher than 1 m a.s.l. of the barrier spit north than $8^{\circ}44'13.4''N$, which corresponds to southern limit of the newly appeared barrier spit, excluding the central lagoon (Fig. 1C). The shorelines examined in the present study correspond to the same height.

Monitoring of vegetational changes

Vegetational change was studied for all areas of the barrier spit north of $8^{\circ}44'13.4''N$ (Fig. 1C). Species composition of the vascular plants, plant covering area, location, and growth of woody plants were monitored on each research occasion. Locations of all woody plants taller than 20 cm were determined using GPS as described above. Their natural heights were measured individually. In the 2011 study, all woody plant individuals studied were tagged for individual recognition with plastic labels showing specific numbers on the trunk. From 2012 surveys, the heights of labeled individuals were measured, although new labels were assigned and the locations and heights were measured for young unlabeled individuals or plants with damaged labels. For marked individuals, the annual growth rates in six dominant woody plant species were estimated

Fig. 1. Location of the barrier spit studied at (C) Pakarang Cape (B) and southwestern Thailand (arrow in A).

The dotted area in B shows the newly appeared barrier spit after the tsunami; it corresponds to C. Line 1 in C corresponds to the transection line for which a vegetation map is portrayed in Fig. 7.

Fig. 2. Views of ground and vegetation at the barrier spit on Pakarang Cape: A, view from north to south near the lagoon in Nov. 2010; B, the same, on 16 Dec. 2011; C, the same on 23 Nov. 2013; D, western storm ridges of the barrier spit on 2 July 2015, from south to north. A dead *Casuarina equisetifolia* was found at the top; E, turned over coral gravel at the barrier spit, showing attached lithophytic cyanobacteria.

by the change in height between two successive years during the study period. Locations and area of plant coverage in the spit were determined by tracing with the GPS on the fringe of the vegetation. Differences in annual growth rates between woody plant species were evaluated for significance using Tukey-Kramer tests. Scientific names of the plant species used in this study followed the system reported by Yonekura and Kajita (2003–). In addition, to examine lithophytic algal flora on the coral gravels in the barrier spit (Fig. 2E), colored materials attached to the gravel were scraped using a toothbrush while adding tap water. Then the suspensions were fixed with 3% formalin solution in the field. They were examined qualitatively in the laboratory using optical microscopy.

Environmental factors

Photon flux density was measured around noon without clouds with an illuminance meter (TM205; Tenmars Electronics Co. Ltd.) at 88 points beneath 12 different plant communities along with neighboring open sites in the 2014 survey. Electric conductivity and pH were measured for surface layers of land deposits collected from 23 vegetated and 9 non-vegetated sites in 2014 and 2015. Each 10 g of

the deposit sample was dipped with 50 ml of deionized water for 3 hr. Then the supernatant liquid was measured for pH (α Pack Test; Narika Corp.) and electric conductivity (CM14P; Toa Corp.). Salinity was measured in the surface water of the lagoon in the study spit using a refractometer (Master-S/Mill α ; Atago Co. Ltd.) in the 2013 survey. The significance of differences between environmental factors (habitat elevation, electric conductivity and pH of deposits) and distribution of plants was tested using ANOVA.

RESULTS

Topographical changes

The barrier spit consisted of coral gravels and coral or other kinds of mineral sands filling the gaps between gravel particles (Fig. 2). The ground surface in the barrier spit was covered with coral gravel of some 50 cm in diameter in the wide range, although no such large gravel covering was found in some places, especially at the southeastern part of the barrier spit.

Micro-landforms of two types were observed: washover fan and storm ridge (SR; Yamano et al. 2007).

The washover fan was composed of gravels and/or medium to coarse sand transported landward by waves. This landform had 5–8 m width, 5–10 m length, and 0.5–1 m a.s.l. height. The storm ridge (Fig. 2D) was narrow and elongated (5–200 m long and less than 2 m wide), and extended in a linear or arc shape on the barrier spit. Heights of the storm ridges were 1.5–2.3 m a.s.l., which agreed with the level of high tide at the time of the spring tide. The storm ridges were higher at the western part facing the Andaman Sea than at the eastern part of the barrier spit.

During the study period, the land area of the barrier spit changed from 24,124 m² in 2010 to 29,509 m² in 2015, showing neither a remarkable increase nor decrease (Fig. 3). Severe erosion occurred on the western part of the barrier spit, although remarkable progradation was observed on the eastern part. A minor change was found by which small hooks developed, extending southward. The hooks comprise deposits derived from the upper side during the dry season in 2014–2015. Judging from the lack of significant change of total area and simultaneous topographic change of erosion and deposition, it is considered that topographic change during this period was mainly redistribution by barrier spit deposits. The most significant change of the barrier spit occurred before 2011, as described by Koiwa et al. (2016).

Environmental parameters

The electric conductivity of the land deposits were 10–103 mS m⁻¹, ranging 10–61 mS m⁻¹ at the vegetative sites.

No significant difference was found in electric conductivity among specific vegetation. pH of the deposits was 6.5–9.1. No significant difference was found between vegetated and vegetation-free sites. The lagoon water in the spit was brackish, with salinity of 22‰.

In the 2014 survey, the photon flux density at the open sites of the barrier spit was 1796–2074 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Relative density lower than 10%, on average, of neighboring open sites was found beneath four plant community stands (*Casuarina equisetifolia*, *Hibiscus tiliaceus*, *Scaevola taccada*, and *Morinda citrifolia*). The shading effect was most prominent in *C. equisetifolia* stands, with the minimum value of the relative density as low as 0.6%.

Flora of the barrier spit

During the study period, a total of 37 species of vascular plants, consisting of 21 woody and 16 herbaceous species, were recorded at the barrier spit (Table 1). Eighteen species occurred at the beginning of the study in 2011. Then 3–7 species were added every year until 2014, with a few disappeared ones. Ten woody and 7 herbaceous species continued to occur throughout the study period. The woody plant community was dominated by six species throughout the study period: *Cocos nucifera*, *Terminalia catappa*, *C. equisetifolia*, *H. tiliaceus*, *S. taccada*, and *Dendrolobium umbellatum*. Herbaceous plant communities were dominated by *Ipomoea pes-caprae*, *Vigna marina*, *Canavalia lineate*, and some poaceans throughout the study

Fig. 3. Annual changes in the form of the barrier spit studied, showing vegetated areas as shaded. Land and vegetated areas are also shown for respective years.

Table 1. Occurrence of plant species in the study area in Pakarang Cape, during 2011 and 2015.

All the plant species occurred in the study area are listed. Numerals for each taxon in the upper part of the table indicate individual number of alive trees in the study area; + indicates the occurrence.

Family name	Species name	Dec. 2011	Nov. 2012	Nov. 2013	Nov. 2014	Jun. 2015
Woody plant						
Pandanaceae	<i>Pandanus odoratissimus</i> L. f.		16	4	3	3
Arecaceae	<i>Cocos nucifera</i> L.	37	21	17	14	14
Combretaceae	<i>Terminalia catappa</i> L.	93	121	77	47	63
Clusiaceae	<i>Calophyllum inophyllum</i> L.	4	6	5	2	2
Rhizophoraceae	<i>Rhizophora mucronata</i> Lam.		2	+	+	1
Fabaceae	<i>Dendrolobium umbellatum</i> (L.) Benth.	+	1	37	29	37
Fabaceae	<i>Sophora tomentosa</i> L.				1	1
Fabaceae	<i>Caesalpinia crista</i> L.	+	+	+	+	3
Casuarinaceae	<i>Casuarina equisetifolia</i> L.	37	80	91	96	112
Malvaceae	<i>Hibiscus tiliaceus</i> L.	53	68	89	135	199
Malvaceae	<i>Thespesia populnea</i> (L.) Sol. ex Correa		3	3	2	2
Lecythidaceae	<i>Barringtonia asiatica</i> (L.) Kurz.		19	14	4	4
Rubiaceae	<i>Morinda citrifolia</i> L.	4	3	22	25	17
Apocynaceae	Apocynaceae sp. R		2	1	+	1
Verbenaceae	<i>Clerodendrum inerme</i> L.	+	1	4	3	4
Goodeniaceae	<i>Scaevola taccada</i> (Gaertn.) Roxb.	84	92	113	126	169
unknown	sp. K		9	3	4	6
unknown	sp. P		1	3	1	1
unknown	sp. V			1	+	+
unknown	sp. BA					2
unknown	sp. BB					1
Herbaceous plant						
Lauraceae	<i>Cassytha filiformis</i> L.				+	+
Poaceae	<i>Digitaria ciliaris</i> (Retz.) Koeler				+	+
Poaceae	<i>Eleusine indica</i> (L.) Gaertn.			+	+	+
Poaceae	<i>Pseudoraphis sordida</i> (Thwaites) S.M.Phillips et S.L.Chen	+	+	+	+	+
Poaceae	<i>Thuarea involuta</i> (G.Forst.) R.Br. ex Sm.				+	+
Poaceae	Poaceae sp. W	+	+	+	+	+
Cyperaceae	Cyperaceae sp. S				+	+
Cyperaceae	Cyperaceae sp. L				+	+
Aizoaceae	<i>Sesuvium portulacastrum</i> (L.) L.	+	+	+	+	+
Passifloraceae	<i>Passiflora foetida</i> L. var. <i>hispida</i> (DC. ex Triana et Planch.) Killip		+	+	+	+
Fabaceae	<i>Canavalia lineata</i> (Thunb.) DC.	+	+	+	+	+
Fabaceae	<i>Vigna marina</i> (Burm.f.) Merr.	+	+	+	+	+
Convolvulaceae	<i>Ipomoea pes-caprae</i> (L.) Sweet	+	+	+	+	+
Verbenaceae	<i>Stachytarpheta jamaicensis</i> (L.) Vahl				+	+
Asteraceae	<i>Melanthera biflora</i> (L.) Wild	+	+	+	+	+
Asteraceae	<i>Crassocephalum crepidioides</i> (Benth.) S.Moore	+		+		
Number of species						
Number of woody plant species		10	17	18	19	21
Number of herbaceous plant species		8	8	10	15	15
Total		18	25	28	34	36

period. The former three species fringed the vegetated area widely. No significant differences were found between the distribution and habitat elevation for any plant species.

Lichens, liverworts, and ferns could not be found in the barrier spit during the study period. Lithophytic algae dominated by unidentified filamentous cyanobacteria were widespread on the underside of the coral gravels on the land, making the gravel surfaces light green (Fig. 2E). *Oscillatoria* sp. and other algae were also found on the upper side of the gravel particles with dark-gray or blackish

color (Fig. 2A).

Vegetational change

During the study period, the vegetated area of the barrier spit fluctuated between 7,978 m² in 2012 to 10,769 m² in 2011 (Fig. 3). The ratio of the vegetated area to the barrier spit area fluctuated from 41.6% in 2014 to 54.6% in 2011. The vegetated area and the ratio did not

Fig. 4. Annual change in the individual distribution (left) and individual numbers between west and east areas (right) of five dominant tree species in the study area during December 2011 and June 2015.

Dead trees are not included. West and east areas are separated by the longitudinal line of 98°13'12.2" E, which corresponds to the western limit of the barrier spit in 2015.

increase or decrease constantly.

The total individual number of woody plants higher than 20 cm in the study area changed from 312 in 2011 to 642 in 2015, increasing about twice during the study period (Table 1). Vegetation developed year by year in accordance with the increase of plants during the study period (Figs. 2A–2C).

The barrier spit moved eastward. The fate of trees depended largely on their location on the barrier spit (Fig. 4). Between western and eastern parts of the barrier spit, separated by a longitudinal line at the west margin of the spit in 2015 ($98^{\circ}13'12.2''\text{E}$), all tree individuals in the western part disappeared until 2014, although the individual numbers in the eastern part increased 2.7 times during 2011

Fig. 5. Annual change in the height distribution of six dominant tree species in the study area at Pakarang Cape during Dec. 2011 and June 2015. Dead trees are not included.

–2015. The highest increase rate was found for *H. tiliaceus*, for which the individual number increased 3.8 times during the study period (Table 1, Fig. 4). It was followed by *C. equisetifolia* (3.0 times) and *S. taccada* (2.0 times). Two woody species, *T. catappa* and *C. nucifera*, continued to decrease in number, and 32% and 62% of individuals disappeared during the study period, respectively. After 2013, many dead *T. catappa* were found at the western fringe of the barrier spit in accordance with landform changes of severe erosion and storm ridge formation (Fig. 2D).

Rapid change in the population structure was found for *C. equisetifolia*, in which taller trees appeared every year along with small individuals (Fig. 5). The population became denser in the central part of the barrier spit during

Fig. 6. Comparison of annual mean growth rate (height) for six dominant tree species in the study area at Pakarang Cape. Growth rates are calculated based on the trace in labeled individuals during 2012–2015. The vertical line represents the standard deviation. Abbreviations of plant species: Cn, *Cocos nucifera*; Tc, *Terminalia catappa*; Du, *Dendrolobium umbellatum*; Ce, *Casuarina equisetifolia*; Ht, *Hibiscus tiliaceus*; St, *Scaevola taccada*.

the study period (Figs. 2, 4). In two other woody species with increased individual numbers, *S. taccada* and *H. tiliaceus*, the annual changes in the population structures were not so great as in *C. equisetifolia*, for which more than 60% of the populations were composed of small trees of lower than 120 cm height as well as larger individuals appearing every year in the study period (Fig. 5). For *C. nucifera*, few new individuals were found during the study period. Live individuals grew slowly.

Among six dominant woody plant species described above, *C. equisetifolia* showed the highest annual mean growth rate in height (174.0 cm year⁻¹) (Fig. 6). The annual mean growth rate was significantly higher than that of four other woody species (22.8–8.9 cm year⁻¹) ($P = 3.02 \times 10^{-16}$), for which no significant difference was found in the annual mean growth rate.

The zonal distribution became clear from 2013. Herbaceous plants dominated by *I. pes-caprae*, *V. marina*, and *C. lineata* were found at western and eastern seaward locations; a *C. equisetifolia* forest was colonized and accompanied by some poaceans at the central area (Fig. 7). No vegetation was found on or near new storm ridges at the west and prograde sandy beach at the east.

DISCUSSION

Characteristics of vegetational change in the study area

Plant communities found on the barrier spit of Pakarang Cape were fundamentally composed of pantropical plants with sea-drifting seeds (Miryeganeh et al. 2014). Almost all species are common in tropical coasts and were also found on neighboring Phuket Island (Hayasaka et

Fig. 7. Schematic distribution of plant species on line 1 in Fig. 1C.

Western-most (left) and eastern-most (right) areas without vegetation respectively correspond to a storm ridge and sandy progradation. The vertical scale is only for landforms. Abbreviations of plant names: Ce, *Casuarina equisetifolia*; Ht, *Hibiscus tiliaceus*; St, *Scaevola taccada*; Ip, *Ipomoea pes-caprae*; Po, Poaceans.

al. 2009). In the present study, 37 species of vascular plants were recorded from the barrier spit at Pakarang Cape in 2015, 8 years after the barrier spit appeared. Among them, 19 species were common to coastal vegetation of Krakatau Islands (Backer 1929, Tagawa 1989), where the occurrence of the most common 19 species took 23 years after the 1883 catastrophic eruption. The rapid invasion of the plant species in the present barrier spit might be attributable to the close and contiguous location of the main Pakarang Cape, which provided frequent and easy access of seeds from many plant species to the newly occurred barrier spit.

It is noteworthy that woody species colonized soon after the appearance of the barrier spit studied, without accompanying lichens, liverworts, or ferns. In vegetational studies of tropical sand dunes or sand beaches, the plant communities are dominated by grass or shrubs. The radicoid form is important for their establishment (Luisa et al. 2001, Hayasaka et al. 2009). At the barrier spit at Pakarang Cape, coral gravel covering the ground surface can prevent sand movement, facilitating its colonization by the drifted seeds.

Factors affecting vegetational changes in the study area

This study found no significant distributional differences in elevation of the habitat in any plant species. Electric conductivity and pH of the deposits were not significantly different between vegetated and non-vegetated areas in the barrier spit. Consequently, it seems clear that the fates of the plant individuals depend strongly on their locations on the barrier spit. Significance of movement and transformation of landform on the succession and composition of plant communities were also pointed out in tropical sand dunes (Luisa et al. 2001) where sand movement was correlated with the species distribution. At the present study area, topographical changes by erosion occurred rapidly in the west and by progradation in the east of the barrier spit. As a result, the central part of the barrier spit has remained stable. Vegetation developed well there. In such a stable environment, *C. equisetifolia* grew rapidly and shaded other plants. In addition, *C. equisetifolia* has been known to have symbiotic nitrogen-fixing actinomycetes (Huang 1989), and to release inhibiting allelochemicals from the roots (Nakahira and Ohira 2005). Furthermore, litter of *C. equisetifolia* on the ground decomposed slowly, with the accumulated litter layer inhibiting germination of other plants (Hata et al. 2009). These characteristics might be related to the predominant

occurrence of *C. equisetifolia* on the present barrier spit. The rapid development of alien *C. equisetifolia* and its suppression of other indigenous plants have been reported for many tropical areas (e.g., Abe et al. 2011).

Although the barrier spit is unpopulated, many local people and tourists visit the barrier spit for fishing or sightseeing. Some anthropological factors such as planting or mounding can affect the colonization of some species in the study area, especially for *C. nucifera* or *T. catappa*. Local people are accustomed to the plant.

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