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EFFECTS OF SHORE SEDIMENTATION TO *Tachypleus gigas* (MÜLLER, 1785) SPAWNING ACTIVITY FROM MALAYSIAN WATERS

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Abstract: Ripraps, land reclamation and fishing jetty renovation were perturbing Balok Beach shores between the years 2011 and 2013 and visible impacts were scaled using horseshoe crab spawning yields. Initially, placement of ripraps at Balok Beach effectively reduced erosion and created a suitable spawning ground for the horseshoe crab, *Tachypleus gigas*. However sediments begun to gather on the beach onward year 2012 which increased shore elevation and caused complete shore surface transition into fine sand properties. This reduced sediment compaction and made Balok Beach less favourable for horseshoe crab spawning. During the dry Southwest monsoon, Balok River estuary retains more dense saline water which assists with sediment circulation at the river mouth section. Comparatively, the less dense freshwater during the wet Northeast monsoon channels sediments shoreward. Circa-tidal action that takes place at Balok River sorts the shore sediments to produce an elevated and steep beach. Hence, the reduced number of *T. gigas* nests and eggs retrieved during year 2013 (after comparing with yield of year 2012) at Balok Beach are indicating impacts from anthropic-caused sedimentation. Models need to be constructed and associated with *T. gigas* spawning-migration to fully understand sediment transport especially at coastal areas that need or are undergoing nourishment.

KEYWORDS: sedimentation; monsoon season; estuary; coastal processes; South China Sea

Introduction

Asian horseshoe crabs such as *Tachypleus gigas* (Liew & Tan, 2010; John *et al.,* 2016), *T. tridentatus* (Kumar & Ismail, 2008) and *Carcinoscorpius rotundicauda* (Fairuz-Fozi *et al.,* 2018a; b; c) are part of Malaysian biodiversity that reproduce using oviparous spawning strategy by burying their eggs in sediments. Alike the American horseshoe crab *Limulus polyphemus* (Chabot & Watson, 2010), Asian horseshoe crabs also rely on environmental cues that not only signal them to congregate but also, to emerge into shallow waters within intertidal zones for conducting their bi-monthly lunar-associated spawning activities (Manca *et al.,* 2016; Nelson *et al.,* 2016a; Fairuz-Fozi *et al.,* 2018d). In recent years, coastal environments are exploited for resources, recreation and used as path for vessel movement (Sale *et al.,* 2011). Unknowingly, detrimental effects are gradually taking place, just like the fate of Tanjung Selangor, Pahang (East Peninsular Malaysia) where failure to protect using legislation overruled the implementation of environmental impact assessments and permitted a 2.5 km road-bridge construction on a productive mangrove patch and horseshoe crab spawning site (Nelson *et al.,* 2015). In countries like America and China, declining horseshoe crabs populations are dealt by legislative governance, beach restorations and fisheries management after which, these endeavours are recovering their wild stocks (Beekey & Mattei, 2015; Botton *et al.,* 2015; Kwan *et al.,* 2017). Determination to protect American horseshoe crabs have reinstated *L. polyphemus* status to 'vulnerable' but unfortunately, reduced participation by Asian researchers (absence of field data from Thailand, Vietnam and Cambodia), overlapping data (same data collection period resulting to different data density) and inconsistent methodology (contribute to different outcome) maintained the status of Asian horseshoe crabs as ‘data deficient’ in the International Union for Conservation of Nature (IUCN) Red List (IUCN, 2018).

The current conservation status of Asian horseshoe crabs far-fetched their priority for legislative governance in which, perpetrator encroachment into their spawning grounds continue to remain legal (for instance, the government-liaised road-bridge project mentioned in Nelson *et al.* (2015), the riprap and jetty renovation mentioned in Nelson *et al.* (2016a) as well as the land reclamation project mentioned in Fairuz-Fozi *et al.* (2018d). The only solution to this problem is public awareness instilment which is possible after disseminating information related to horseshoe crab biology like importance of substrate to eggs; understand types of natural stress the eggs undergo during dry and arid conditions, broad temperature exposures to the eggs during day and night intervals, broad salinity exposures and, freshwater shock to the eggs during raining seasons; lengthy embryogenesis and instar growth; as well as egg predation by higher trophic animals that threaten their hatching success (Beekey *et al.,* 2013; Botton *et al.,* 2015; Nelson *et al.,* 2016b; Fairuz-Fozi *et al.,* 2018d). Moreover, the public should also understand about the function of substrate (sediment) which is not only limited to egg incubation but also, protects horseshoe crab eggs from abrasion, desiccation and to deter predator scent as well as sight.

The question is, what attracts horseshoe crabs to a particular area? While homing behaviour was thought to influence this arthropod’s longing to natal beaches (Shuster, 2015), the Malaysian *T. gigas* spawning migrates to sites with desired beach slope, elevation and sediment grain size (Manca *et al.,* 2016). Researchers working with *Limulus polyphemus* and *T. tridentatus* discovered that area and slope influences the horseshoe crab’s decision to spawn at a beach (Hsieh & Chen, 2015; Jackson *et al.,* 2014). Also, female *L. polyphemus* at Yucatan Peninsula desires spawning beaches with specific sediment grain types (Fulford & Haehn, 2012). Moreover, shore sediment composition (by percentage of gravel, sand, silt and clay) were thought to influence *T. gigas* spawning decisions at western coasts of Sarawak (Jawahir *et al.,* 2017). Thus, it is conclusive that female horseshoe crabs release their eggs in porous substrate because interstitial spaces between the granules can trap moisture and oxygen (Vasquez *et al.,* 2015) and this allows the buried eggs to breathe (Jackson *et al.,* 2010; Nelson *et al.,* 2016a). Although the knowledge on horseshoe crab biology are benchmarked, in-depth bioecological interactions remain insufficiently understood (Robert *et al.,* 2014). Unlike the *C. rotundicauda* and *T. tridentatus* that also spawns at muddy substrate, *T. gigas* spawning sites are always sandy and accessible from time to time (Tan *et al.,* 2011; John *et al.,* 2012; Nelson *et al.,* 2016a; b) rendering this arthropod most studied horseshoe crab species in Malaysia (John *et al.,* 2018a; b).

Additionally, identification of horseshoe crab spawning grounds are important so that year round data gathering becomes possible and contributes to the availability of background data. Yet, sediment transport assessments at Pahang Tua River are no longer possible after passive formation of landform interfered with Tanjung Selangor irrigation. Now, this area is condoned as horseshoe crab habitat because it no longer supports the arthropod’s spawning (Nelson *et al.,* 2015). Apart from feeding ecology (Razak *et al.,* 2017) and fisheries importance (Mohd-Razali & Zaleha, 2017), pilot studies are still needed to confirm that Cherok Paloh (State Pahang) is in fact another horseshoe crab choice for year-round spawning. With these limitations, the availability of research materials since 2006 made Balok Beach the most suitable spawning site in East Peninsular Malaysia (Tan *et al.,* 2012; Mohd-Razali & Zaleha, 2017; John *et al.,* 2018a; b) and applicable to understand horseshoe crab ecology and biology interactions.

Since 2011, Balok Beach underwent passive disturbances (like ripraps, parking lot construction and jetty renovation) that shifted shore sediment compositions from medium to fine sand (Nelson *et al.,* 2016a). Interestingly by 2013, this alteration has made Balok Beach favourable for horseshoe crab spawning activity (John *et al.,* 2014; Zauki *et al.,* 2018; Zauki *et al.,* 2019). Past data indicated that *T. gigas* arrives to Balok Beach and spawns at different elevations above the water-mark (Manca *et al.,* 2016; Zauki *et al.,* 2018; 2019). The spawning sites selected by *T. gigas* are loose and soft, with good moisture retention (Nelson *et al.,* 2016a). Certain horseshoe crab spawning beaches undergo sediment transition after placement of structures which result to substrate with poor air and moisture trappings (McLachlan *et al.,* 2013; Estes, 2015; Mishra & Mishra, 2015). Moreover, coastal developments alter physicochemical of water and sediment to the extent where mitigation measures such as beach recovery and beach nourishment projects are needed to re-attract horseshoe crabs (Botton *et al.,* 2001; Chen *et al.,* 2004; Mishra & Mishra, 2011; Botton *et al.,* 2018; John *et al.,* 2018a; b). However, environmental manipulations regardless regulated or not are bound to sedimentation problems like land formation, extension or erosion which again are natural sediment transport mechanism at the intertidal zone. Similar incidences were witnessed at *Limulus polyphemus* spawning sites during attempts to recondition their spawning beaches (Botton *et al.,* 1988; Jackson *et al.,* 2005; Jackson & Nordstrom, 2009; McLachlan *et al.,* 2013; Botton *et al.,* 2018). Interestingly, ecological changes at volatile beaches (subject to anthropic intervention) does not intervene with *C. rotundicauda*, *T. tridentatus* and *T. gigas* monthly spawning cycles. This is advantageous for studies that intend to contrast horseshoe crab spawning yields at disturbed and undisturbed areas (Pati *et al.,* 2017; Kwan *et al.,* 2018; Vestbo *et al.,* 2018; Rao & Patil, 2018). The ecology and biology associations that revolve horseshoe crab spawning in midst of seasonal transitions and coastal interventions are aims addressed in this study. Availability of this information enhances understanding about horseshoe crab biology (John *et al.,* 2018a; b; Zauki *et al.,* 2018; 2019) and their habitat-dependability relationships especially at their breeding grounds worldwide that constantly undergo substrate transitions because of anthropic activities that cause sedimentation.

Materials and Methods

Site descriptions

The estuary, Balok Beach is situated in State Pahang, East Coast Peninsular Malaysia and lies adjacent to South China Sea. It is the only most accessible and still surviving *T. gigas* spawning site (Lat: 3° 56′ 16.58″ to 3° 55′ 39.33″ N; Long: 103° 22′ 32.74″ to 103° 22′ 27.12″ E) (Figure 1). Balok River channels into the estuary, Balok Beach before it opens into South China Sea. Balok Beach microclimate is subject to the Malaysian monsoonal seasons Northeast (November to March) and Southwest monsoons (May to September) which are separated by two Inter-monsoon periods (April and October). The climate conditions vary between 22 °C to 38 °C and 58 % to 100 % for temperature and moisture, giving rise to hot and humid weather (Weather Underground, 2014).

The annual rainfall averages about 1759.4 mm and occurs mostly during the third-quarter (September to December). Since Balok Beach is an estuary at Balok River mouth, this area experiences mixed semidiurnal tides between 0.0 m and 3.7 m (National Hydrographic Centre, 2017). The horseshoe crab, *T. gigas* are observed spawning within the 381 m horizontal shoreline stretch (total distance from transect of Site 1 to transect of Site 3) that has gentle slope in-between high and mid tide markings. Anthropic-caused disturbances took place at Site 1 (3° 56′ 15.76″ N, 103° 22′ 33.96″ E), initiating with construction of ripraps by year 2011, land reclamation around the ripraps for parking lot construction within year 2012 and fishing jetty renovation during year 2013, which coincide with perceptions in Nelson (2015), Nelson *et al.* (2016a; b) and Zauki *et al.* (2019). These brought changes to the other spawning sites, Site 2 (3° 56′ 12.90″ N, 103° 22′ 36.62″ E) Balok River final meander used for boat docking which is situated 105 m Southwest of Site 1 and, Site 3 (3° 56′ 16.30″ N, 103° 22′ 40.36″ E) associated with anglers and recreational activities that is situated 276 m South of Site 2 (Figure 1).

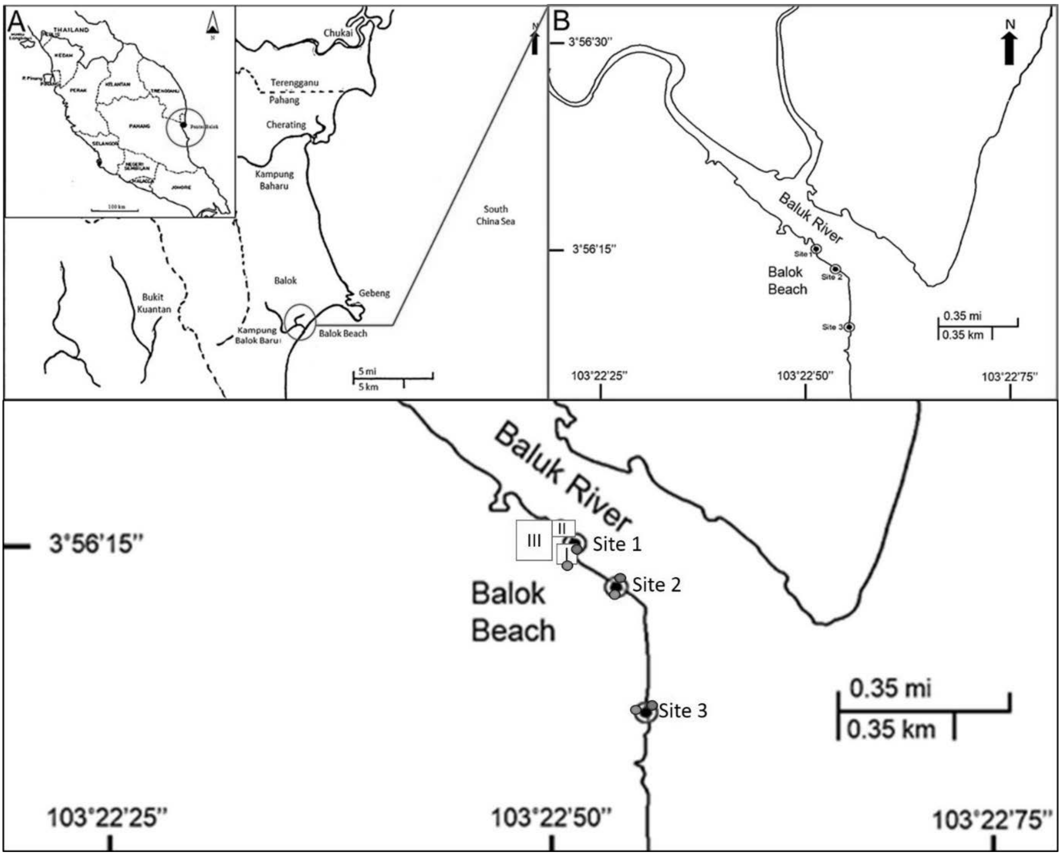

Figure 1: The location of Balok Beach on (A) East coast of Peninsular Malaysia. Description of sampling sites (Sites 1 to 3) at the vicinity (B) and man-made structures such as rip raps (I), fishing jetty (II) and Balok Wet Market (III) at the beach (C). The red circle ● indicates area for current meter deployment (between 0 m and 1 m depth) and the green circle ● indicates location for wind speed measurement using portable anemometer (in between 1 m and 2 m above sea level).

Field and laboratory activities

Bi-monthly visits were carried out to Balok Beach covering full and new moon spring tides of May 2012 until May 2013. At each visit, *T. gigas* nests were searched by observing horseshoe crab carapace imprints on the sand. It should be noted that *T. gigas* nests are limited to the 250 m2 transect boundary (Horizontal x Vertical = 50 m x 5 m) at each site. Horseshoe crab nests were never observed outside these transects because beach slope beyond these sections are steep and sediments are tightly compacted. After exhumation and measuring the nests, counting of horseshoe crabs eggs and returning the eggs into respective nests, 2 to 3 *Avicennia* sp. twigs with peeled barks were placed horizontally in each nest to avoid double counting. Notably, horseshoe crab eggs in clutches (newly fertilized eggs aged between 0 and 5 days) and uni-coloured green eggs (5 to 9 days of age) are considered for data collection. Important information such as beach elevation (via dumpy surveyor instrument - Sokkia C4 10), current speed (via current meter - Valeport 106, UK) and wind speed (using anemometer - Extech 45160, USA) were recorded whereas 1 litre (*l*) water samples (for total suspended solid analysis) and approximately 400 g of sediment (for mean and sorting properties) were collected from each site.

Additional information like rainfall, humidity and, wind and current direction were retrieved from the weather station repository records (Weather Underground, 2014). Balok Beach elevation and slope measurements were adopted from Saghravani *et al.* (2009) and applied to demarcate tide markings (depicted as high and intermediate markings) between the water and vegetation lines on the shore.

Analysis of suspended solids were adopted from Greenberg *et al.* (1992). In this protocol, 1 l water from each site were filtered in situ on pre-weighed Gf/c 47 mm microfiber filter (Whatman PLC, UK) attached to filtering apparatus (DURAN® 25.710.54.51, Germany) and diaphragm pump (GAST DOA-P504-BN, USA). Each microfiber filter was washed with 10 ml 10^8 Ohm deionized (DI) water. Three-series repetitions were carried out and this procedure completes when all DI has passed the filter. The samples were then transferred into separate petri dishes before storing in an ice-box for later analysis. At the laboratory, the filtrate were heated by pool at 105 °C for one hour before their weights were individually recorded. The heating continues until constant weights were achieved with <0.5 mg or 4 % total weight error. Suspended solid composition in all water samples were calculated using the proposed equation:

$$\text{Suspended solids [mg } l^{-1}\text{]} = \frac{\text{Sample + filter weight [mg]} - \text{filter weight [mg]}}{\text{Sample volume [}l\text{]}}$$

Estimation of mean grain size and sediment sorting adopted protocols of Blott and Pye (2001) whereby pre-weight sediments (c.a. 100 g) were transferred into petri dish, oven dried for three days at 45 °C, then transferred into a series of 13 sieves ranging from 4 mm to 0.063 mm on a mechanical shaker set to operate at 9 g acceleration for 30 minutes. After measuring weight of retained sediments in each sieve, the Logarithmic Method of Moments is used to estimate mean grain size and sediment sorting properties (Zauki *et al.,* 2018; 2019). While height of the dumpy lens, foresight and backsight measurements are used to calculate the shore elevation, Pythagorean Theorem ($\cos\theta = \frac{\text{adjacent}}{\text{hypothenus}}$) and gradient equation ($y = mx + c$) are adopted to calculate the slope angle at each point elevation was measured.

The topography of Balok Beach were examined in year 2011 as initial and, during 2012 and 2013 to overview changes for shore layout. Topographical layouts were prepared using ArcGIS v.10 by cross-referencing 'Base Maps' obtained from Google Earth images. Cross-referencing these base maps allow precise calibration of GPS coordinates. All map coordinates were synchronised using the system Kertau UTM Zone 47N before measuring the annual (average) shoreline changes. On the other hand, since the present study focuses on *T. gigas* spawning and their relationships with changing shorelines, only the periods when horseshoe crabs eggs were discovered at Balok Beach are considered to explain the findings. The supplementary data may be referred for additional data during periods of no nests. Statistical analyses are carried out using Biological-Environment Step-wise (BEST) with amalgamation of Spearman's Correlation in the Primer v.6 (Clarke & Gorley, 2006) software.

Results

Horseshoe crab spawning activity

Horseshoe crabs like *T. gigas* adopt oviparous spawning by releasing and fertilizing eggs in the external environment. In this case, the buried fertilized eggs were only available for period of seven months at Balok Beach, in comparison to the total field visit duration of thirteen-months that lasted between the years 2012 and 2013. While these seven months include May, June, July and August for year 2012 and February, March and April for year 2013, a total of 3977 *T. gigas* eggs were retrieved from 32 nests. From these, vast majority comprising of 2978 eggs and 21 nests were recorded during year 2012 (Table 1) in contrast to the three-fold reduction of 999 eggs after unearthing 11 nests during year 2013 (Table 2). The spawning activity of *T. gigas* are considerably higher during lunar (full moon) spring tides, achieving a total of 3343 eggs and 24 nests. Taking into account the month-wise changing circa-tidal clocks and seasons, the *T. gigas* preferred conditions during July 2012 (Southwest monsoon) because 1687 eggs and 12 nests were discovered at Balok Beach. On the contrary, almost two-fold *T. gigas* spawning yield reductions were obtained during March 2013 (onset Northeast monsoon season), because this arthropod only laid 840 eggs in 6 nests at Balok Beach (Table 2). Observations at the field noted Southwest monsoon (May, July and August) to bring hot and arid climate. The calm weather during Southwest monsoon reduced Balok River downstream flow (between 11.1 kph and 12.4 kph) which then allowed seawater penetration up to 623 ± 15 m (point on river when salinity was ± 1 ‰) upstream. Precipitation taking place in February and March 2013 during the Northeast monsoon brought rain to Balok Beach and increased the downstream discharge of Balok River (between 15.0 kph and 18.5 kph). The vigorous exchange between sea- and freshwater during Northeast monsoon was less favourable to *T. gigas* because it only laid 967 eggs and made 10 nests. Also, this arthropod did not favour Balok Beach during Inter-monsoon periods (April and October) because only 32 eggs were discovered from 1 nest (Tables 1 and 2). The *T. gigas* strategy to choose certain sections on the beach for their spawning is not coincidence but, reflects on the beach conditions during that time. This arthropod carried out local spawning migrations, limiting its spawning to Site 1 (human-infringed section) and Site 2 (Balok River final meander located 105 m apart and associated with artisanal fisher boat docking) during Southwest monsoon. Then, the *T. gigas* included Site 3 for its spawning after discovery of buried eggs within this transect area (adjacent to open sea, frequently visited by anglers and is perturbed by recreational beachgoers) during Northeast monsoon. Ultimately, eggs and nests of *T. gigas* are available throughout the 381 m spawning zone on Balok Beach during year 2013

Table 1: Balok Beach and Baluk River characteristics coinciding with period of successful *T. gigas* spawning during new moon spring tides of 2012 and 2013.

	2012			2013					
	June			February			March		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Nest (nos.)	0	2	0	0	2	0	4	0	0
Egg (nos.)	0	169	0	0	47	0	418	0	0
Xw (Phi)	2.43	2.62	2.57	2.57	2.60	2.41	2.46	2.47	2.41
Xm (Phi)	2.59	2.59	2.56	2.58	2.56	2.35	2.54	2.50	2.47
Xv (Phi)	2.59	2.50	2.52	2.50	2.48	2.54	2.53	2.53	2.63
Sw (σ_1)	0.62	0.55	0.51	0.53	0.64	0.49	0.63	0.73	0.56
Sm (σ_1)	0.51	0.53	0.61	0.53	0.68	0.64	0.55	0.73	0.51
Sv (σ_1)	0.53	0.59	0.64	0.62	0.77	0.45	0.59	0.67	0.50
Slope v-m (^{o})	18.45	19.34	18.63	18.27	17.72	17.78	19.57	19.30	18.66
Slope m-w (^{o})	15.09	15.03	14.57	14.40	14.86	13.71	14.13	13.37	14.13
Elevation v-m (m^{-1})	1.92	2.31	1.89	2.11	2.27	2.23	1.86	1.89	2.04
Elevation m-w (m^{-1})	2.60	3.15	2.74	2.94	2.88	3.18	2.97	3.19	3.01
SS-LT (mg l^{-1})	29.73	23.77	17.54	95.44	109.46	87.35	105.36	112.67	109.62
SS-HT (mg l^{-1})	21.24	16.98	12.53	129.99	149.08	118.97	77.32	82.68	80.44
Current LT (kph)	0.20	0.11	0.13	0.02	0.01	0.01	0.11	0.08	0.02
Current HT (kph)	0.98	0.55	0.61	0.23	0.21	0.25	0.19	0.14	0.09
Wind (kph)	10.54	11.11	12.38	18.47	21.22	24.08	12.96	18.52	20.37
LT (m)	1.15	1.15	1.15	0.43	0.43	0.43	0.7	0.7	0.7
HT (m)	2.73	2.73	2.73	1.89	1.89	1.89	2.11	2.11	2.11

*Criteria abbreviations include nos. = numbers, X = mean grain size, Phi = mean grain size coefficient, S = sediment sorting, w = water (lowest tide mark), m = mid-tide mark, v = vegetation (highest tide mark), v-m = highest to mid-tide mark, m-w = mid to lowest tide mark, σ_1 = sorting coefficient, SS = suspended solids, LT = low tide and, HT = high tide. Units are abbreviated as; m = meters, mm = millimetre, mg l^{-1} = milligram per litre and, kph = kilometres per hour.

Table 2: Balok Beach and Baluk River characteristics coinciding with period of successful *T. gigas* spawning during full moon spring tides of 2012 and 2013.

Criteria	2012									2013								
	May			July			August			February			March			April		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
Nest (nos.)	0	6	0	8	4	0	1	0	0	2	0	0	4	1	1	0	1	0
Egg (nos.)	0	868	0	1074	613	0	254	0	0	80	0	0	418	108	314	0	32	0
Xw (Phi)	2.13	2.15	2.32	2.29	2.26	2.42	2.34	2.37	2.18	2.47	2.50	2.35	2.07	2.37	2.26	2.50	2.56	2.44
Xm (Phi)	2.50	2.47	2.45	2.42	2.35	2.30	2.39	2.41	2.33	2.50	2.44	2.51	2.44	2.44	2.38	2.55	2.59	2.59
Xv (Phi)	2.65	2.52	2.60	2.45	2.49	2.11	2.51	2.41	2.22	2.54	2.57	2.56	2.52	2.56	2.44	2.58	2.53	2.49
Sw (σ_I)	0.91	0.87	0.81	0.96	0.90	0.85	0.89	0.92	0.94	0.68	0.71	0.70	1.14	0.85	0.67	0.61	0.65	0.58
Sm (σ_I)	0.60	0.76	0.68	0.83	0.95	0.94	0.82	0.89	0.88	0.62	0.74	0.45	0.73	0.77	0.59	0.52	0.63	0.43
Sv (σ_I)	0.44	0.63	0.64	0.76	0.64	1.15	0.58	0.88	0.82	0.59	0.52	0.60	0.61	0.69	0.51	0.51	0.77	0.62
Slope v-m (°)	15.55	18.51	18.76	16.31	17.13	14.86	17.75	19.47	21.65	19.54	19.27	19.01	19.57	17.93	17.65	18.99	18.83	18.13
Slope m-w (°)	13.88	14.33	14.08	12.81	13.02	9.74	16.17	14.94	17.98	14.76	13.23	14.57	14.13	13.61	14.92	14.07	13.07	13.88
Elevation v-m (m^{-1})	2.34	2.31	2.96	2.4	2.33	3.17	1.81	1.74	2.77	1.83	1.91	1.94	1.86	1.87	1.95	2.04	2.03	2.19
Elevation m-w (m^{-1})	2.78	3.20	3.96	3.35	3.37	5.18	2.12	2.62	3.30	2.81	3.21	2.85	2.97	2.87	2.53	3.08	3.36	3.14
SS-LT (mg l^{-1})	50.22	54.65	61.08	18.77	37.65	26.90	40.45	48.92	56.74	109.72	121.34	147.28	105.36	77.54	63.67	33.23	26.27	21.32
SS-HT (mg l^{-1})	27.90	30.36	33.93	16.53	33.16	23.69	20.94	25.32	29.37	157.58	174.27	211.52	77.32	92.54	75.99	54.47	43.06	34.95
Current LT (kph)	0.02	0.02	0.04	0.04	0.06	0.07	0.14	0.12	0.10	0.83	0.92	1.04	0.11	0.05	0.09	0.02	0.01	0.02
Current HT (kph)	0.04	0.04	0.07	0.05	0.08	0.10	0.38	0.32	0.27	1.46	1.51	1.73	0.19	0.18	0.25	0.12	0.15	0.15
Wind (kph)	9.08	7.65	9.26	9.37	11.93	12.52	18.52	14.82	16.67	14.58	18.52	24.08	12.96	14.76	20.37	5.23	9.82	13.37
LT (m)	0.93	0.93	0.93	0.31	0.31	0.31	0.69	0.69	0.69	0.79	0.79	0.79	0.7	0.89	0.89	0.59	0.59	0.59
HT (m)	2.81	2.81	2.81	3.25	3.25	3.25	3.03	3.03	3.03	1.79	1.79	1.79	2.11	2.11	2.11	2.51	2.51	2.51

*Criteria abbreviations include nos. = numbers, X = mean grain size, Phi = mean grain size coefficient, S = sediment sorting, w = water (lowest tide mark), m = mid-tide mark, v = vegetation (highest tide mark), v-m = highest to mid-tide mark, m-w = mid to lowest tide mark, σ_I = sorting coefficient, SS = suspended solids, LT = low tide and, HT = high tide. Units are abbreviated as; m = meters, mm = millimetre, mg l^{-1} = milligram per litre and, kph = kilometres per hour.

Changing Beach Morphology

The horseshoe crab *T. gigas* confines its spawning to the 381 m sandy shore stretch at the south-most section of Balok River that lies adjacent to South China Sea. Perhaps because Balok River is covered with sand-like grains at the mouth, the Balok Beach estuary became accessible to fishermen for fish landing and boat docking. Initially, the fisher community erected a wooden jetty to transport their catch into the wet market (located 50 m inland at Site 1). Heeding the Pahang state Department of Fisheries initiative to upgrade fishing services through blueprints of Economic Transformation Program 2010, Balok Beach had to be reinforced before the wooden jetty is renovated. Hence by end of 2011, ripraps were erected at Site 1 with purpose to reduce erosion and create landforms naturally. Instead, the ripraps were destructive to Balok Beach as it perturbed the substrate while gradually collecting sand at Site 1. As observed in 2012, Balok Beach begun to have medium-fine to fine sediment grain (1.5 Phi to 2.7 Phi) domination. Perturbation continued the following year and fine sediment (2.0 Phi to 2.7 Phi) became dominant at Balok Beach. This infringed section of Balok Beach became steep (during the low tide observations), reducing the unsubmerged land (water ward) from the average 67.2 m in year 2011 (Figure 2A) to about 54.8 m by year 2012 (Figure 2B). This explains the absence of horseshoe crab spawning at this site in later months. However in 2013, the unsubmerged land at Site 1 became extended by 10.82 m and contrasts the corrosion taking place at the opposite banks (Figure 2C). Additionally during year 2012, the Balok River meander section at Site 2 became eroded by 9.17 m. Nevertheless by year 2013, this sandy shore gained additional unsubmerged land by 18.89 m. In 2012, the open sea section (Site 3) received unremitting landform-sedimentation which extended its shorelines by 6.90 m followed by additional 1.12 m in the following year. Overall, these Balok Beach water ward-shoreline extensions severely reduced Balok River girth (up to 18.09 m) especially at the confluence section located North of Site 1 (Figure 2D).

Balok Beach was impacted by changing seasons that brought winds of different speeds. Moderate breeze up to 16 kph blew South-westward in August of year 2012, an indication that season was going to change from Southwest to Inter-monsoon before entering into the Northeast monsoon. Simultaneously, Balok River current flow increased (from 0.12 kph to 0.38 kph) and headed South-south-eastward. Onset Northeast monsoon of 2013, the breeze reached 24 kph and headed Northward (Figure 2E, Table 1). The surface water currents of Balok River increased its flow (from 0.83 kph to 1.73 kph) during February 2013 and shifted towards North-north-eastward direction (Figure 2F, Table 1). When surface currents of Balok River increased, sediment deposits were made along Balok Beach span (Figs. 2, D to G). In February 2013, precipitation during the Northeast monsoon leeched sediments into Balok River and increased the abundance of fluvial-laden suspended solids (up to 211.52 mg l^{-1}) (Table 1). While the overall combined yield of suspended solids in Balok River during low and high tides of year 2012 were between 18 mg l^{-1} and 61 mg l^{-1}, it increased to between 21 mg l^{-1} and 211 mg l^{-1} by 2013. Indications like increased suspended solids and elongated shorelines at Balok Beach by 2013 is in agreement with land accretion that took place at Sites 1 and 3 and also the beach corrosion at Site 2 during that time.

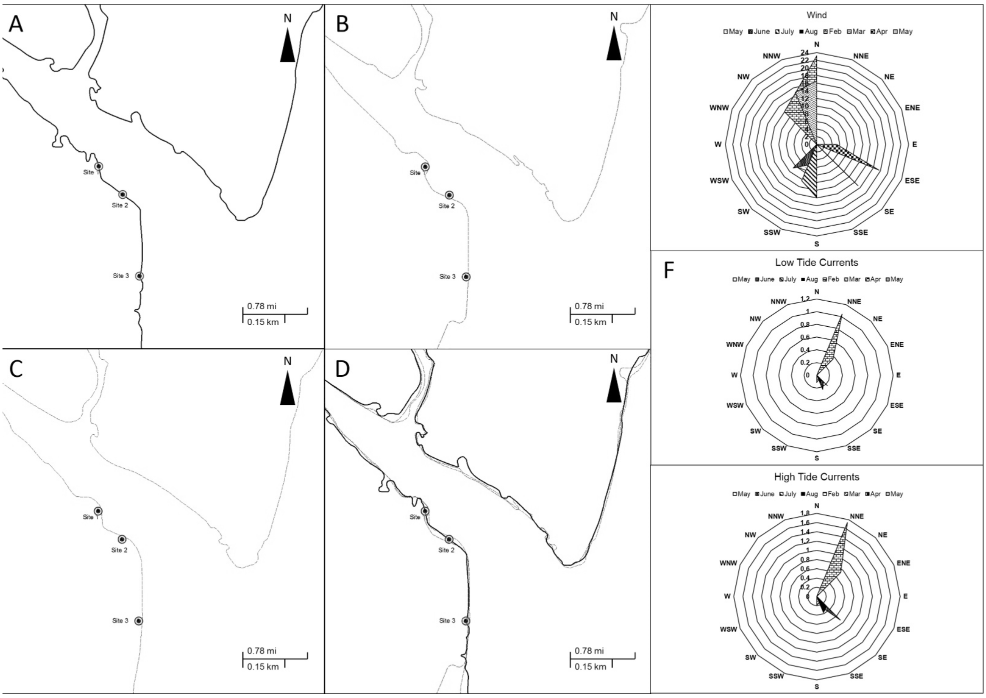

Figure 2: Changing Balok Beach shorelines during from 2011 to 2013 and the intensity of wind and water currents from 2012 to 2013. Annual Balok Beach shoreline mark initiating with (A—) 2011, (B...) 2012, (C---) 2013, and (D) overall-view for changes between 2011 and 2013. Speed (measured as kilometres per hour, kph) and direction of (E) wind, (F) low tide and (G) high tide currents.

Horseshoe crabs did not bury their eggs at Site 3 of Balok Beach during year 2012 despite the gradual steepness (between 9 ° and 14 °) because beach elevation was greatly reduced (in-between 3 m and 5 m). On the other hand, decreasing beach elevation (up to 3.5 m) between vegetation and water-mark made the beach very steep (slope angles were in-between 13° and 19°) during the month of March for year 2013. Yet, *T. gigas* eggs were exhumed from all three Balok Beach study sites. While the results were tested using BEST analysis at 95 % and 99 % confidence, high correlations at 0.954 (rho 95 %) and 0.965 (rho 99 %) were achieved for criteria beach slope (mid-tide mark to water mark), suspended solids and wind speed when tested against *T. gigas* egg yields during the 7 months of successful spawning between years 2012 and 2013.

Discussion

Sediment Transport at Balok Beach

The horseshoe crab, *T. gigas* were thought to spawn at shores with medium to medium-fine sand (Zaleha *et al.,* 2012; Nelson *et al.,* 2015) properties. Presently, this perception changed after *T. gigas* nests were also discovered at areas with fine sediments, specifically at Balok Beach during year 2013 (Nelson *et al.,* 2016a; Zauki *et al.,* 2019). At that time, sand-imprints resembling *T. gigas* carapace were sighted on soft sediment areas in Balok Beach, specifically within the high to intermediate tide shoreline marks. Past studies associate American horseshoe crab, *L. polyphemus* egg deposition with soft and loose sand regardless sand types and sand sizes (Ellingsen, 2002; Jackson *et al.,* 2007). In this case, porosity is the reason for horseshoe crab spawning in loosely packed sediments. The similar is also applied to other oviparous arthropods (turtles and crocodiles) that use sediments for egg incubation. Porous substrate ease digging especially when constructing deep pits (Wooster *et al.,* 2008). Eggs of *L. polyphemus* and *T. gigas* were uncovered from sandy pits between 9 cm and 25 cm whereas eggs of *C. rotundicauda* and *T. tridentatus* were uncovered from muddy pits between 4 cm and 10 cm deep (Smith *et al.,* 2002; Chiu & Morton, 2003; Chen *et al.,* 2004; Zaleha *et al.,* 2012; Robert *et al.,* 2014; Fairuz-Fozi *et al.,* 2018d). The differences between nest depths are indications of sediment compaction that can effectively trap moisture and allow oxygen exchange to support horseshoe crab embryogenesis (Vasquez *et al.,* 2017).

The erection of ripraps (in year 2011), land reclamation for parking lot (in year 2012) and fish jetty renovation (in year 2013) at Site 1 of Balok Beach resulted to surface sediment transitions whereby the medium-fine sediment properties during year 2011 (Nelson *et al.,* 2016a) were transformed into fine sediment properties by year 2013 (Zauki *et al.,* 2019). While high shore morphology and bottom shore sediment composition reflects the beating of wind and water currents, bottom shores composing of fine sand (just above the water mark) indicates horizontal breaking from weakened tides that make way into the estuary. During horizontal breaking, beach slope reduces gradient and the shore becomes accreted with sediments. Similar incidences were also reported to take place at Long Beach, New Jersey (Lemke & Miller, 2017) and Maresme coast, Spain (Ballesteros *et al.,* 2018) in the presence of horizontal breaking. Additionally, Balok River fluvial discharge during the calm Southwest monsoon brought fine sand downstream and deposited them throughout Balok Beach. This did not only extend the shore (by increasing its elevation) through land formation but also, made the river mouth width become narrow (increasing the elevation gradient at all horseshoe crab spawning sites). Hence by 2013, the whole shoreline of Balok Beach were deposition sites for fine sediments.

Similar incidences took place at Puducherry and Tamil Nadu (India) whereby the presence of structures accumulated sediments around it and within one year extended the shoreline length-wise (Muthusankar *et al.,* 2017). With regard to horseshoe crab preference for sheltered areas having negligible tides (Chabot & Watson, 2010), the irregular surface water current speeds of Balok River (0.02 kph to 1.73 kph depending on tides and season) were sufficient to transport sediment within its channel. In fact, suspended solids are part of Balok River fluvial transport and its movement increased during the wet Northeast monsoon. Hence, the fine fluvial sediments in Balok River are constantly shifted around and as claimed by Nelson *et al.* (2016a), sediment transport transitioned the surface sediments at Balok Beach from medium to fine sand at all three sites during their 2012 and 2013 data collection period.

Wind speeds did correlate well with horseshoe crab egg yields in BEST analysis but, was this solely responsible to transport sediment throughout Balok Beach? While the breeze was moderate (up to 24 kph) during the wet Northeast monsoon, the calmer winds (< 17 kph) experienced during other seasons were still classified as moderate breeze. Aeolian transport model for Valdevaqueros littoral zone (Spain) demonstrated that fresh breeze and strong gale (between 30 kph and 42 kph) can move 0.28 mm sediment grains when blowing at 0.6 m heights (Navarro *et al.,* 2015). Additionally, the light to moderate breeze (between 6 kph and 24 kph) at Tramore Beach (Ireland) can transport 0.19 mm sediment grains at rates from 7 g min^{-1} to 23 g min^{-1} when blowing 0.5 m above the surface layer (Smyth *et al.,* 2014). As observed by Nelson (2015) and Nelson *et al.* (2016a), Balok Beach is particularly abundant with 0.125 and 0.180 mm grains and wind speeds were measured using anemometer at 1.7 m height (eye level). Perhaps, Aeolian transport equally contributed as indirect but played a major role to transport, shift and scatter of fine sediments throughout Balok Beach.

Wind speed influences wave amplitude and surface current directions at an estuary (Hunt *et al.,* 2015), in the same manner the light to moderate breeze altered directions of Balok River current flow. While moderate breeze blew Northward during the Northeast monsoon, the surface water of Balok River moved North-north eastward. At Batu Pahat (Malaysia), unidirectional movement of winds and river currents transported fine sediments into its direction (Mohtar *et al.,* 2017). Hence, the sediment deposits at Sites 1 to 3 (at Balok Beach) are possibly caused by Balok River surface water current speeds that range between 0.01 kph and 0.38 kph during the Southwest and Inter-monsoon season. In this case, hydrodynamics allowed fluvial transportation of fine sand up- and downstream (Bravard *et al.,* 2014) whereby, bed-load sediment deposit into shallow waters through collision between waters of different densities (Yang *et al.,* 2016). With regard, the turbid seawater from open sea came into contact with silt and clay-laden freshwater from Balok River. It resulted to sediment retention at the open sea cum recreational section (Site 3) of Balok Beach.

A different scenario takes places during Northeast monsoon whereby stronger river currents (up to 1.73 kph) also laden with fine sediments headed downstream Balok River. The collision between fresh- and seawater allowed gravity to deposit sediments onto the bed. Residual currents from the collision transported sediments along its path and this resulted to sedimentation effects throughout Balok Beach vicinity. Thus, some sections of Balok Beach like Sites 1 and 2 underwent corrosion whereas Site 3 became accreted with sediments during year 2012. Prolonged and continued ecological turbulences have made Balok Beach experience accretion at all sites during 2013. In a separate scenario, Doce River, Brazil has increased flow rate during raining seasons. The increased river flow rate did not only corrode upstream banks but also brought fluvial sediments downstream which were then deposited along the river passage and caused modification of existing landforms (Aprile *et al.,* 2016). Hence, the combination of environmental expressions like wind speed and fluvial discharge resulted to multi-directional currents that scattered fine sediments throughout the Balok River estuary (Sites 1 to 3) by 2013.

Changing Beach Morphology and Tachypleus Gigas Spawning Yield

The average Balok Beach shore elevation between vegetation and mid-tide line marks were demarcated as high tide mark and, between mid-tide and water line marks were demarcated as intermediate tide mark during year 2012. In this case, the elevation of high tide mark was 1.43 m^{-1} (slope = 6.79 ^{o}) whereas intermediate tide mark was = 3.06 m^{-1} (slope = 8.24 ^{o}). After unremitting sedimentation that persisted until year 2013, shore elevation for high tide mark became 0.36 m^{-1} (slope = 1.92 ^{o}) whereas intermediate tide mark became 1.18 m^{-1} (slope =1.85 ^{o}). Clearly, Aeolian transport has construed responsibility for inland sediment transitions at Balok Beach shorelines by assisting the accumulation of sediments on the shore face (slope peak). Since slope angles between 0 and 25o retard wind flow at the slope toe and resulted to gravitational accumulation of sediment at the slope peak (Smyth & Hesp, 2015), the horseshoe crab, *T. gigas* were stimulated to lay more eggs in 2012 when the high-tide slope was gradient (< 18 ^{o}) than it did during year 2013 when the same slope became steep (> 18 ^{o}). In short, slope angles directly influence sediment accumulation at the high-tide shorelines after breeze pounding (in Aeolian transport). Also, the moderate breeze up to 14 kph at Balok Beach assisted with local transportation of fine sand along the shorelines and interfered with shore surface sediment compositions.

Sediment accumulation on the slope face and toes are co-joint effects from wind and water current action which alters beach elevation gradually and until a certain balance is achieved (the cycle repeats). On the other hand, changing elevation directly alters shore slope to create another cycle in which, substrate corrosion and accretion would take place at Balok Beach during falling and ebb tides (circa-tidal) to balance out the sedimentation cycle. These transitional ecological sets were thought to indicate the likelihood for horseshoe crab spawning to take place. As observed, regular river currents and breeze does not change shoreline rise more than 25 % its original height (Ruessink *et al.,* 2016). However, wind speed and water currents throughout Balok vicinity were above ambiance during Inter-monsoon and Northeast monsoon because shore elevation at that time were beyond 25 %. This took place especially at Site 3 during year 2012 and at Site 2 during year 2013. Coincidently, *T. gigas* did not spawn at Site 3 during the Northeast monsoon of year 2012 but, it continued to spawn at Site 2 in the following year despite the increased shoreline elevation.

Beach corrosion gradually erodes shore elevation (Jackson *et al.,* 2014). Balok Beach underwent severe corrosion between mid-tide and water line marks (intermediate-tide mark) than between the vegetation and mid-tide line marks (high-tide mark) from years 2012 to 2013. Beach sections that constantly undergo corrosion have tendency to be hypoxic and also have maintained (but elevated) surface sediment temperatures because of increased surface area exposure to heat (Bush *et al.,* 2015; Smith *et al.,* 2017). For this reason, horseshoe crabs do not spawn at corroded shores as well as during the low tide periods. As observed, the *T. gigas* of Balok Beach only spawned at high tide marks between vegetation and mid-tide sections (Manca *et al.,* 2016; Zauki *et al.,* 2018; Zauki *et al.,* 2019). However, the *T. gigas* nests at high tide marks on the shores were containing blackened and red-stained eggs which were surrounded by carnivorous worms (Nelson *et al.,* 2016b). This clear-cut indication revealed that horseshoe crab nests at Balok Beach are prone to extreme heat exposures that can cause egg desiccation. But, such incidences were hardly heard off in the past, especially at Balok Beach when horseshoe crabs shifted their spawning towards higher sections of the beach (Nelson *et al.,* 2016a; Zauki *et al.,* 2019).

Thus, in the present situation, horseshoe crab egg survival is directly related to the height of their nests on the shoreline (Fulford & Haehn, 2012; Bakker *et al.,* 2016) and sediment compaction determines the depth of nests which female *T. gigas* were able to dig (between 8 cm and 18 cm deep). Also, it should be noted that Malaysia undergoes transitional weathering with some periods of the year having hot and arid climate capable to cause heat retention in shallow and deep waters (Chatterji *et al.,* 2012). Water circulation during falling and ebb tides reduces heat retention in sediments but, this nullifies when sand is left directly exposed to the scorching sun. Yet beneficial, periods with heated sediments offer temperature shocks that actually speeds-up the horseshoe crab embryogenesis (Vasquez *et al.,* 2015). This in fact is accountable for the different horseshoe crab egg hatching durations, in particular with *T. gigas* from Balok Beach (Nelson, 2012; 2015). After combining all facts, it is affirmed that *T. gigas* eggs in shallow nests at high shores have higher chances of desiccation (Nelson *et al.,* 2016b) and this risk reduces when nests are dug deeper in lower shores. With this, all female horseshoe crabs are biologically programmed to spawn at areas that support embryogenesis and maximize hatching. That is why horseshoe crab species like *C. rotundicauda*, *L. polyphemus* and *T. gigas* migrate their spawning locally depending on the season at that time and, their preferred spawning sites differ from time to time (Jackson *et al.,* 2010; Smith *et al.,* 2011; Nelson, 2012; Nelson, 2015; Nelson *et al.,* 2015; 2016a; Fairuz-Fozi *et al.,* 2018d; John *et al.,* 2018a; b; Zauki *et al.,* 2019).

In addition to the observations that *T. gigas* dug deep nests (up to 18 cm) at the high-tide shore line than it did between the mid-tide and low-tide line markings (8 > cm), depth of eggs in nests depends on digging capability of horseshoe crabs. Also, digging capability of horseshoe crabs depends on the texture or hardness of the surface sediment layer. If the sediment layer is compacted, horseshoe crab eggs are more vulnerable to the predation by scavenging and carnivorous worms. This situation was explained in Nelson *et al.* (2016b) whereby shallow *T. gigas* nests contained desiccated eggs and became food source to scavenging and carnivorous worms. It was noted that beach sections containing horseshoe crabs nests were loosely-packed and leave 2 cm to 5 cm imprints when stepped-upon. Since horseshoe crabs avoid areas with sediment corrosion, the *T. gigas* spawning at Balok Beach are limited to shorelines that undergo accretion. In fact, the reason for *T. gigas* to spawn at sites that undergo accretion pertains to its favour for loosely packed sediments as this provided adequate oxygenation to the buried eggs (Vasquez *et al.,* 2015). Hence, sediment transport either by wind or by water provides natural balance to retain the role Balok Beach as spawning grounds for *T. gigas* during unremitting sedimentation.

Conclusions and Recommendations

The horseshoe crab *T. gigas* was observed to spawn at the 381 m sandy patch of Balok Beach for period of 7 months, maximising its spawning during the Southwest monsoon and full moon circatidal. Absence of *T. gigas* spawning activity during other months were subject to shore changes after placement of ripraps during year 2011. In less than one year, it is learnt that ripraps stimulated a sediment deposition zone at Balok River mouth whereby sediments gathered around this structure and contributed to the overall increase of sediment circulation within the Balok Beach estuary. At the same time, suspended solid circulation measured as fluvial deposits were increased with clear demarcations during the Northeast and Inter-monsoon seasons. Also, increased sediment circulation within Balok River resulted to total shoreline accretion at all *T. gigas* spawning sites by year 2013. While the *T. gigas* only favoured upstream sections (Sites 1 and 2) for its spawning during year 2012, this situation changes after Aeolian transport moulded slopes with < 18 ° gradient during year 2013. Hence, this arthropod spawned throughout the sandy patch sections (Sites 1 to 3) of Balok Beach. These changes not only motivated the female *T. gigas* to increase its spawning yield per nest but also restrict its spawning to sections between high and intermediate-tide marks on the shore in favour of reduced sediment compaction. Additional research is needed to fully comprehend the horseshoe crab spawning biology. The construction of Balok Beach Aeolian transport model is needed to measure intensity and distance of sediment movement, a direct factor that is associated with emergence and spawning of *T. gigas* and *C. rotundicauda* that coexist at Balok Beach. Similarly, this model is also applicable to understand horseshoe crab behaviour at other regions of Asia for effective implementation of shore recovery measures at designated horseshoe crab safeguarding areas.

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