JEE Journal of Ecological Engineering

Journal of Ecological Engineering 2022, 23(12), 273–284
https://doi.org/10.12911/22998993/154846
ISSN 2299–8993, License CC-BY 4.0

Received: 2022.09.09
Accepted: 2022.10.18
Published: 2022.11.01

From Descriptive to Accurate Horseshoe Crab Size Variations in Wild Populations

Li Yu Chan[1], Akbar John[2,3], Salwa Shahimi[1], Lusita Meilana[4],
Chong Ju Lian[1], Loh Ing Hoe[5], Wong Chee Ho[6], Jayaraj Vijaya Kumaran[7],
Siddhartha Pati[8], Bryan Raveen Nelson[9,*]

[1] Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[2] Institute of Oceanography and Maritime Studies, Kulliyyah of Science, International Islamic University Malaysia, Kuantan, Malaysia
[3] IIUM molecular and cellular biology research cluster (iMoleC), International Islamic University Malaysia, Jalan hospital campus 25100, Kuantan, Malaysia
[4] College of Environment and Ecology, Xiamen University, 361102 Xiamen, Fujian, China
[5] School of Business and Management, RMIT University, Vietnam, Handi Resco Building, 521 Kim Ma, Ba Dinh District, Hanoi, Vietnam
[6] Center of Fundamental and Continuing Education, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
[7] Faculty of Earth Science, Universiti Malaysia Kelantan, 17600, Jeli, Kelantan, Malaysia
[8] Skills Innovation and Academic Network Institute, Association for Biodiversity Conservation and Research, 756001, Odisha, India
[9] Institute of Tropical Biodiversity and Sustainable Development, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia
* Corresponding author's e-mail: bryan.nelson@umt.edu.my

ABSTRACT

Horseshoe crabs have survived until Holocene, but their persistence beyond the Anthropocene is challenged by drastic environment changes that entail impoverishments and the resultant unusual growth sizes. Previously, allometry via morphometric ratio was introduced to classify horseshoe crabs into normal-abnormal growth. However, the descriptive size and weight analysis indicated a considerable portion of *Tachypleus gigas* with normal allometry. This error was caused by the median sorting of values. Therefore, the same data was treated with correlation before generating a linear equation. By being sexual dimorphs, these arthropods actually have gender-specific morphology indicators which could generate a functional allometry. Since the assessed arthropods were mature, the 19 % yield of smaller female *T. gigas* was possibly due to degradation effects from poor diets or stress. Yet, for this population, an added risk was female-only harvest. Perhaps, close sizing to male counterparts could be perceived a survival strategy by the female *T. gigas*. More evidence is needed to strengthen this opinion but for now, this assessment method is novel for accurate allometry assessments in the species with sexual dimorphism. Overall, capture fisheries could have negative impacts and when made severe by sex-specific harvest, the unaccounted practices could collapse sustaining populations.

Keywords: *Tachypleus*; growth; ecology; morphology; fisheries; conservation.

INTRODUCTION

A rapidly growing human population is creating demands for food. However, sustainable practices in the wild stock supply chains are challenged by both climate and human activities [Pramanik et al. 2021]. Further challenges are caused by abrupt environmental changes due to human practices of the Anthropocene. Waste is a major concern for pollutant-introduction routes. Aside from being able to leach into water systems, pollutants have various retention periods and remain in the environment, unless it is metabolically detoxified or stabilized by free ions in the sediment. In the case of gravitational settling, waste or pollutants become bioavailable for uptake, from which, the internal metabolites of an organism become stimulated to manage the body burden (or stress). While not all aquatic organisms choose to evade stressful environments [Ariffin et al. 2022], the decisions to become a generalist could build up a body burden.

Hence, energy allocation is a metabolic strategy adopted by aquatic organisms, mainly fish, to survive under harsh conditions in polluted environments or during food scarcity. Energy compensation was theorized as practical for cryptic species until its grow-out (or filial) occupies the predator categories in food chains [Sastraprawira et al. 2020]. Yet, in some cases, energy-storing or energy conservativeness results in slower growth rates in juvenile fish, which then becomes detrimental to the persistence of the entire population [Post and Parkinson 2001]. In fact, energy conservation strategies are also responsible for exclusivity and vigor (or natural selection) in confined fish populations, especially in the temporary holding tanks [Jaffar et al. 2019].

Meanwhile, the ability to allocate energy is a strategy also discovered in *Tachypleus gigas*. Horseshoe crab embryos use energy allocation to manage stress from the external environment [Nelson et al. 2020]. When applied, energy allocation that manages stress compensates for the growth of the horseshoe crabs, which means the life stages related to molt cycles could either become delayed or collectively, the entire population would possess unique morphology measurements. Size-to-weight variations (or allometry) could indicate unhealthy growth in *T. gigas* [Vijayakumar et al. 2000]. Unfortunately, a similar approach was inconclusive to detect unhealthy sizing in small populations of *T. gigas* [Tan et al. 2012], which could be due to the samples originating from a single population. Descriptive analysis was introduced for size and weight variations, but for *T. gigas*, its telson length was an imperative inclusion [Sahu and Dey 2013].

However, for a population of *T. tridentatus*, its allometry was negatively skewed and indicated the population to be less healthy [Chatterji and Pati 2014]. The samples from the same area had a combination of both negative and positive allometry [Mohamad et al. 2016], which indicates that descriptive analysis is not reliable to assess the length-weight variations of horseshoe crabs (*T. gigas* or *T. tridentatus*). The major drawback in past assessments is the methodology, where the morphometrics of male and female crabs are compiled together, the pool of data is small (<40 crabs), or the comparison itself is biased towards the size range of earlier horseshoe crab populations. Thus, the allometry analysis is considered inaccurate and does not indicate the morphology sizing for the assessed horseshoe crab population.

A later examination on *T. tridentatus* was integrated with statistics and descriptive analysis and the use of Spearman's correlation to select suitable size indicators [Mohamed et al. 2021]. The findings were conclusive that male and female horseshoe crabs have unique size indicators aside from the agreement that telson length was part of the inclusion criteria. Now, with the objective to develop accurate gender-specific allometry for a large number of samples, the present work compared the differences between conventional (descriptive) and statistical outputs c.a. [Mohamed et al. 2021] and concluded on an accurate (traditional) allometry census c.f. [Vijayakumar et al. 2000] for a population of T. gigas in Sungai Merlimau Melaka. The findings for this study are imperative because only female T. gigas of Sungai Merlimau are target fishery for human consumption. There could be a survival strategy [Smith and Brockmann 2014; Hare and Simmons 2019] related to evolutionary morphism shifts in the populations that may suffer from operational sex ratio imbalances.

MATERIAL AND METHODS

Data collection

The horseshoe crabs, *T. gigas* were retrieved from Sungai Merlimau (Jasin, West Peninsular

Malaysia), a river mouth where horseshoe crabs arrive for their monthly spawning activity. This arthropod arrives into the shallow river banks to deposit their eggs in burrows confined at the water edge, most likely medium to high shores. It is this lunar tide, regardless during the full or new moon where horseshoe crabs are seen as amplexus. Fishermen constantly use this opportunity to maximize the catch-per-unit effort. The 8-inch gill nets (300×1 m) were set during dawn (4.00–7.00 am) tide rise and retrieved 2.5–3 hours later. Removing each entangled horseshoe crab is tedious and would require roughly 5–10 mins/ crab. For each crab, the 9-point morphology (total length, interorbit distance, opisthosoma length, prosoma width and length, carapace length, telson length and weight) was measured by using a measuring tape (±0.1 cm; Figure 1) and portable scale (±0.01 g). All horseshoe crabs were returned to the water after the exercise.

Descriptive analysis

The conventional method of morphometrics involves allometry, a descriptive method that uses length-length and length-weight ratios. The standard values for morphology indicator were developed from available literature c.a. [Razak and Kassim 2018] for Malaysia, [Chatterji and Pati 2014] India and, [Mashar et al. 2017] Indonesia. The deviation from standard values gives rise to negative (small carapace size or small size-to-weight value), normal (balance growth, size-to-weight ratio = 0.0±0.1) and positive allometry (large carapace size or large size-to-weight value). These values are output from the distribution curve made on the x-axis with a random range of values or standard deviation in the y-axis of the linear equation. In addition, comparative size classifications from other horseshoe crab populations were also introduced to show the inconsistencies that arise from using the conventional allometry method.

The accurate analysis

Morphology, presented as body measurements for all male and female *T. gigas* were plotted in Microsoft Excel before being prepared for export into Primer v.7. The square root ($\sqrt{Xi}$) data was transformed before Bray-Curtis cluster analysis to generate the resemblance matrix. Then, Pearson's correlation is employed to reorganize the values into functional allometry for *T. gigas*. The indicators of morphology for each horseshoe crab gender group were identified with the highest correlation value. This morphometric group was then assessed for its mean ($\bar{x}$), standard deviation (σ), normal distribution ($y = mx + c$), and regression (r^2). Then, the x-axis and y-axis values were replaced with the new range of $\bar{x}$ and σ. This method omits methodological errors in classifying the horseshoe crab morphometrics because findings are specific for each gender and exclusive

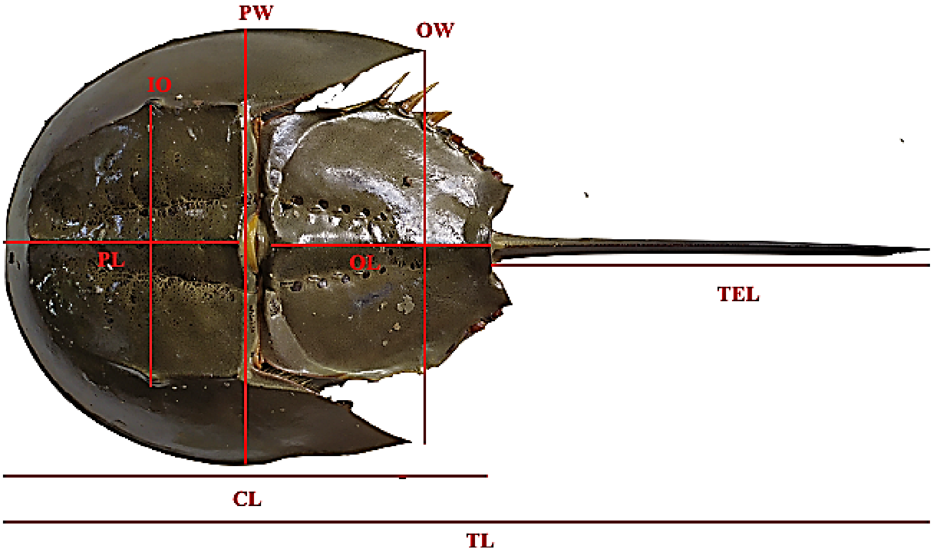

Figure 1. The morphometry of Tacypleus gigas. All morphometric points are indicated as PW/L – prosoma width/length, OW/L – opisthosoma width/length, TL – total length, CL – carapace length, TEL – telson length and IO – Interorbit distance

to the assessed horseshoe crab population. However, the final output retains the allometry reservation c.f. [Vijayakumar et al., 2000], which was proposed as negative, normal and positive.

RESULTS

Descriptive allometry

There were 37 male and 168 female *T. gigas* sampled from Sungai Merlimau for the allometry assessment (Table 1). All horseshoe crabs were classified as sexually mature (or adult) from which, all the male crabs were discovered in an amplexus, whereas the female crabs were gravid. Denoted with average ($\bar{x}$; mm) values, the morphometrics for the male crab was described with prosomal width of 162 (or 149–186; σ = ±8), opisthosoma width of 88 (or 78–98; σ = ±5), total length of 328 (or 155–434; σ = ±41), carapace length of 165 (or 115–195; σ = ±15), prosoma length of 87 (or 75–97; σ = ±6), opisthosoma length of 68 (or 54–86; σ = ±8), telson length of 168 (or 140–189; σ = ±12), and interorbit distance

Table 1. The 9-point morphometry used to indicate the size of Tachypleus gigas from Sungai Merlimau (Melaka), West Peninsular Malaysia

Code	PW (mm)	OW* (mm)	TL (mm)	CL (mm)	PL* (mm)	OL (mm)	TEL* (mm)	BW* (g)	IO* (mm)
Female *Tachypleus gigas*									
F1	191	178	326	191	107	100	185	653	131
F2	208	182	423	213	119	82	194	721	130
F3	200	184	410	201	120	80	191	658	133
F4	209	173	425	232	131	101	184	805	136
F5	200	174	408	210	129	81	181	707	127
F6	211	182	421	218	121	94	190	722	131
F7	189	178	371	195	110	75	185	708	130
F8	198	176	320	205	112	83	185	779	121
F9	209	182	409	210	110	100	191	655	127
F10	198	184	411	202	110	83	195	668	130
F11	191	173	391	193	124	92	193	616	124
F12	202	187	397	228	125	85	206	739	137
F13	205	186	445	224	130	101	211	785	134
F14	194	190	380	217	122	78	199	631	131
F15	208	176	436	210	125	90	204	674	126
F16	206	166	432	206	113	98	217	702	131
F17	210	178	428	225	122	95	205	727	134
F18	212	179	440	214	110	87	225	695	134
F19	202	178	430	212	111	93	213	697	127
F20	213	195	440	214	126	95	221	823	134
F21	170	154	350	181	104	80	165	677	104
F22	198	184	397	213	126	87	195	713	122
F23	215	198	460	225	125	125	211	745	136
F24	201	181	386	210	116	84	186	694	132
F25	210	184	414	206	118	89	192	777	130
F26	217	192	411	225	135	87	204	830	140
F27	223	189	296	218	121	90	195	772	124
F28	213	189	432	225	121	106	207	716	125
F29	205	178	413	216	116	98	202	694	130
F30	195	170	388	203	123	81	185	638	128
F31	212	190	428	214	135	78	223	773	139
F32	208	178	434	216	113	83	222	681	130

Table 1. Cont. 1. The 9-point morphometry used to indicate the size of Tachypleus gigas from Sungai Merlimau (Melaka), West Peninsular Malaysia

F33	204	173	400	213	111	93	203	669	124
F34	202	181	422	211	109	99	216	650	132
F35	196	179	403	212	121	93	202	766	128
F36	200	166	408	208	116	76	210	781	126
F37	211	178	348	214	129	92	178	686	128
F38	191	165	384	191	91	86	194	752	118
F39	194	179	392	297	112	89	193	670	130
F40	197	173	394	211	115	85	192	770	121
F41	210	192	437	216	111	86	213	790	134
F42	199	186	404	229	124	94	186	694	130
F43	196	170	402	202	109	82	203	709	122
F44	185	165	368	168	99	82	176	679	119
F45	201	171	424	210	110	101	212	650	125
F46	220	186	412	211	117	88	183	868	131
F47	200	163	420	208	108	97	208	665	130
F48	210	202	410	215	114	95	202	731	137
F49	202	186	432	225	120	95	207	827	138
F50	210	178	420	221	124	97	203	706	124
F51	199	176	389	207	110	88	164	625	126
F52	176	157	357	183	104	73	185	698	113
F53	199	166	437	201	111	85	222	755	120
F54	250	198	403	220	122	92	192	638	127
F55	220	186	420	215	122	83	205	695	132
F56	200	179	420	207	112	95	202	660	133
F57	196	173	393	201	105	81	196	742	126
F58	191	187	300	191	98	81	188	731	119
F59	200	189	348	208	111	92	189	668	128
F60	208	179	372	205	122	85	193	629	126
F61	197	173	305	207	120	92	192	665	121
F62	208	178	398	212	107	88	188	684	128
F63	187	170	346	199	115	75	183	639	120
F64	218	162	374	211	118	86	186	663	131
F65	177	169	290	185	107	73	185	668	127
F66	202	176	430	247	149	100	187	708	120
F67	207	176	473	252	149	105	232	697	131
F68	223	193	454	262	157	115	202	805	131
F69	210	191	429	250	150	105	191	688	132
F70	205	191	453	273	162	115	194	807	139
F71	200	177	449	246	145	109	207	644	123
F72	210	176	465	264	152	110	213	766	132
F73	190	167	454	234	140	102	234	584	118
F74	195	175	479	246	145	95	240	652	122
F75	196	184	430	230	140	98	205	579	119
F76	190	176	406	232	139	99	179	510	119
F77	198	187	420	246	146	109	183	605	121
F78	200	186	437	244	144	102	200	672	126
F79	195	171	453	241	142	106	215	598	120
F80	214	180	446	250	155	106	195	759	126

Table 1. Cont. 2. The 9-point morphometry used to indicate the size of Tachypleus gigas from Sungai Merlimau (Melaka), West Peninsular Malaysia

F81	196	169	443	242	143	106	207	620	124
F82	213	191	484	257	155	106	235	780	128
F83	213	195	444	250	149	106	202	714	124
F84	195	171	431	232	139	102	203	581	120
F85	195	178	443	240	144	101	206	604	116
F86	211	190	461	253	152	109	217	634	130
F87	210	180	456	251	151	100	207	684	129
F88	216	182	518	274	161	116	249	683	140
F89	205	182	428	241	140	104	192	634	126
F90	185	156	408	221	132	91	109	497	109
F91	208	187	431	252	147	110	187	668	126
F92	205	191	461	251	150	104	215	736	124
F93	183	176	437	234	138	90	209	543	118
F94	198	175	436	245	146	102	195	644	128
F95	189	169	459	240	148	99	221	634	111
F96	216	178	428	238	142	105	201	560	120
F97	200	191	500	270	159	116	234	829	130
F98	206	202	461	250	149	108	218	731	129
F99	228	182	448	246	147	104	221	687	130
F100	211	195	487	271	166	114	227	802	135
F101	210	191	466	257	153	104	212	666	135
F102	208	190	509	274	163	118	240	883	135
F103	193	192	474	257	152	109	221	709	129
F104	200	175	470	253	149	109	226	713	128
F105	189	190	478	249	146	108	237	673	125
F106	189	181	354	231	135	99	130	539	116
F107	205	176	437	234	143	98	204	615	123
F108	199	165	450	248	149	104	211	668	124
F109	211	202	467	263	156	113	214	806	125
F110	188	170	430	236	138	103	201	601	119
F111	208	178	487	254	153	106	238	732	129
F112	203	186	423	250	146	110	180	669	127
F113	204	187	478	250	147	108	237	588	126
F114	200	172	464	240	144	106	233	608	125
F115	200	189	385	248	141	110	143	682	127
F116	214	195	490	272	165	114	218	979	135
F117	199	167	436	224	130	100	218	547	112
F118	203	183	430	235	139	102	204	622	120
F119	201	164	394	250	149	105	150	538	130
F120	200	189	464	250	147	111	215	772	125
F121	198	184	461	245	147	105	218	725	122
F122	200	174	463	260	155	110	205	755	136
F123	210	204	440	254	151	106	202	739	130
F124	198	179	419	225	137	95	195	561	115
F125	218	202	466	253	153	107	219	709	128
F126	208	198	441	245	145	104	199	680	124
F127	196	175	460	253	148	110	216	709	126
F128	203	162	473	248	147	108	222	675	123

Table 1. Cont. 3. The 9-point morphometry used to indicate the size of Tachypleus gigas from Sungai Merlimau (Melaka), West Peninsular Malaysia

F129	209	186	482	259	153	108	226	767	130
F130	190	166	433	238	141	102	205	588	115
F131	206	190	476	244	148	110	230	731	129
F132	207	191	479	258	154	111	230	758	133
F133	204	180	445	250	148	107	206	738	127
F134	209	185	446	240	142	105	215	664	125
F135	195	177	428	244	147	100	195	625	117
F136	210	196	485	252	150	105	232	713	131
F137	201	170	386	250	149	106	140	768	124
F138	190	169	441	230	135	102	213	522	115
F139	221	190	498	270	163	111	222	872	133
F140	202	175	471	249	149	105	225	715	127
F141	214	195	436	246	150	95	194	664	127
F142	199	168	444	246	150	101	202	683	125
F143	208	192	473	248	148	105	222	659	124
F144	216	200	482	265	160	110	216	812	136
F145	210	181	468	255	150	105	215	761	132
F146	200	179	446	236	139	104	212	601	111
F147	211	179	490	260	155	105	235	756	125
F148	208	190	447	240	144	98	206	705	125
F149	191	174	428	233	138	96	196	624	122
F150	193	155	440	241	147	94	202	627	124
F151	196	167	431	234	138	101	196	598	120
F152	201	182	439	238	140	103	201	550	124
F153	209	193	452	255	155	101	204	761	128
F154	200	167	444	245	145	101	206	615	122
F155	205	184	442	234	135	105	211	646	120
F156	194	160	420	235	142	92	186	594	113
F157	198	186	441	241	142	103	199	620	122
F158	210	182	455	246	147	100	211	698	125
F159	197	175	450	243	147	102	215	650	122
F160	194	169	440	239	142	104	205	605	117
F161	209	194	498	273	164	110	230	799	135
F162	204	174	468	262	157	108	208	760	125
F163	223	175	489	270	160	116	220	864	135
F164	198	173	435	242	145	103	195	574	122
F165	204	180	359	226	132	101	134	611	117
F166	192	174	404	225	133	95	185	516	118
F167	218	180	465	258	185	105	203	774	129
F168	213	192	463	259	152	110	206	707	127
Male *Tachypleus gigas*									
M1	168	94	339	164	88	69	168	289	83
M2	165	90	337	167	97	71	170	292	83
M3	157	86	324	158	84	70	178	262	80
M4	176	94	319	170	92	60	140	333	86
M5	149	78	295	148	80	57	147	284	70
M6	160	85	310	155	81	65	163	232	72
M7	166	91	340	161	91	68	171	262	82

Table 1. Cont. 4. The 9-point morphometry used to indicate the size of Tachypleus gigas from Sungai Merlimau (Melaka), West Peninsular Malaysia

M8	164	90	345	169	90	66	179	285	81
M9	158	91	329	160	88	55	165	235	79
M10	172	91	351	174	95	70	171	301	86
M11	155	85	324	161	90	63	163	253	76
M12	155	85	310	162	91	71	160	212	75
M13	167	89	335	168	90	66	173	301	81
M14	164	91	349	173	96	67	180	309	82
M15	159	92	324	164	88	70	161	300	79
M16	156	83	299	146	82	54	141	286	76
M17	164	92	354	169	96	65	181	271	81
M18	149	88	312	159	86	66	147	243	77
M19	165	88	335	162	92	71	172	289	78
M20	153	83	316	150	82	56	163	230	73
M21	166	92	341	170	93	62	177	290	81
M22	165	98	155	170	93	69	189	315	85
M23	159	89	322	165	89	62	166	287	84
M24	165	90	341	165	90	66	178	288	81
M25	166	92	356	115	90	64	189	285	86
M26	160	90	310	160	90	65	149	261	80
M27	158	84	434	150	82	68	177	253	77
M28	158	98	322	158	86	65	163	242	76
M29	186	84	319	145	75	65	163	213	74
M30	174	87	353	183	79	72	175	313	88
M31	170	91	373	195	84	84	173	302	100
M32	171	80	338	193	80	86	174	283	98
M33	173	85	356	187	78	83	176	279	103
M34	151	82	326	172	79	80	160	275	91
M35	160	93	251	189	81	84	167	278	100
M36	153	80	354	178	83	80	170	205	90
M37	151	86	355	169	79	76	176	286	85

Note: Abbreviations follow the order PW/L – prosoma width/length, OW/L – opisthosoma width/length, TL – total length, CL – carapace length, TEL – telson length, BW – body weight, IO – interorbit distance. The asterisk (*) indicates associations with the highest Pearson correlation values for female (ρ = 0.979; OW, TEL, BW & IOL) and male (ρ = 0.971; OW, PL, TEL, BW) *Tachypleus gigas* morphometric values.

of 83 (or 70–103; σ = ±8) while for weight (g), it was 274 (or 205–333; σ = ±31).

Meanwhile, the similar treatment was also employed on the female *T. gigas*. On average ($\bar{x}$; cm), the prosomal width measured 203 (or 170–250; σ = ±10), opisthosoma width was 180 (or 154–204; σ = ±10), total length was 429 (or 290–518; σ = ±42), carapace length was 233 (or 168–297; σ = ±23), prosoma length was 136 (or 91–185; σ = ±18), opisthosoma length was 99 (or 73–125; σ = ±11), telson length was 203 (or 109–203; σ = ±21) and interorbit distance was 126 (or 104–140; σ = ±6) while for weight (g), it was 690 (or 497–979; σ = ±81). From this, 24–28 (65–76%) of male crabs were indicated with normal allometry and it was seconded by 5–7 (14–19%) crabs with negative allometry. Meanwhile, 109–134 female crab individuals (59–72%) recorded normal allometry and a higher number (21–30; 11–16%) was indicated with positive allometry.

Revised allometry

The 9-point morphometry was used to classify horseshoe crabs into size-size indicators for their growth. The male *T. gigas* achieved *p* =

0.791 for the correlation values that involve opisthosoma width, prosoma length, telson length, and body weight values. It was $p = 0.620$ for prosoma width and the total length and $p = 0.469$ for carapace length, opisthosoma length and interorbit distance. The morphology of the female crab was indicated with better correlation values where $p = 0.973$ was achieved for opisthosoma width, telson length, and body weight and $p = 0.971$ for interorbit distance. For other morphology aspects, correlation values were reduced to $p = 0.839$ for prosoma width, total length, and carapace length and $p = 0.812$ was indicated for prosoma length and opisthosoma length.

Alongside regression ($r^2 = 0.726–0.769$), the opisthosoma width, telson length, and body weight were identified as relevant to both genders. However, the prosoma length and interorbit distance were unique indicators for the allometry of the male and female *T. gigas* (Table 2).

By reprocessing the descriptive allometry into the linear equation, there were marked differences for all 5-morphometric points (Table 3). The large proportion of male *T. gigas* recorded with normal allometry (24–28 crabs) for opisthosoma width, prosoma length, telson length, and body weight were actually reclassified with

Table 2. Selected morphometric indicators for Tachypleus gigas and its range of values before and after insertion into linear equation

Criteria	Gender	OW (cm)	PL (cm)	TEL (cm)	IO (cm)	BW (g)
Mean ($\bar{x}$)	M	83.5-93.0	80.9-92.6	156.1-179.8	-	243.0-304.3
	F	169.9-190.6	-	182.3-223.7	119.7-132.6	609.3-770.4
Linear equation	M	y=-0.007+8.974	y=-0.028+9.204	y=0.023+16.340	-	y=-0.312+279.55
	F	y=0.001+17.94	-	y=0.071+19.701	y=0.003+12.902	y=0.264+712.17
r^2	M	0.750	0.728	0.769	-	0.741
	F	0.752	-	0.759	0.726	0.739
Revision ($\bar{x}$)	M	83.0-89.4	67.9-90.4	166.3-203.2	-	194.2-270.2
	F	179.5-181.2	-	198.5-211.4	129.2-133.3	733.5-894.6

Note: Abbreviations follow the order M – male, F – female, PL – Prosoma length, OW – opisthosoma width, TEL – Telson length, BW – Body weight, IO – interorbit distance. The r^2 represents a goodness-of-fit measure for linear regression.

Table 3. Comparison before and after the statistical revision to the morphometric indicators of Tachypleus gigas from Sungai Merlimau (Melaka), West Peninsular Malaysia

Criteria	Allometry	OW (n)	PL (n)	TEL (n)	IO (n)	BW (n)
Direct estimation from morphometric indicators						
Male	Negative	6	7	5	-	7
	Normal	27	24	28	-	26
	Positive	4	6	4	-	4
Female	Negative	29	-	13	24	26
	Normal	109	-	134	118	116
	Positive	30	-	21	26	26
Revision to statistical-selected morphometric indicators						
Male	Negative	6	0	15	-	0
	Normal	13	27	22	-	13
	Positive	18	10	0	-	24
Female	Negative	85	-	60	112	122
	Normal	9	-	52	34	45
	Positive	74	-	56	22	1

Note: Abbreviations follow the order PL – prosoma length, OW – opisthosoma width, TEL – telson length, BW – body weight, IO – interorbit distance. The denominator (n) represents the number of *Tachypleus gigas* associated to the census for each of the statistical-selected (Pearson correlation, ρ) morphometric indicators. Denominators for the allometry census (negative, normal and positive) were used to arrange the *Tachypleus gigas* size into a classification limit for the adult body condition.

Table 4. Compilation of Tachypleus gigas morphology indicators around Peninsular Malaysia and the actual projection of the same indicators for populations in Merlimau

State	Site	Gender	PW (cm)	OW (cm)	TL (cm)	CL (cm)	PL (cm)	OL (cm)	TEL (cm)	BW (g)	IO (cm)	Source
Pahang	Balok	M	19.1	-	-	20.3	11.9	-	17.8	332.9	-	Tan et al., 2012
		F	24.7	-	-	26.0	15.4	-	21.9	824.4	-	
		M	17.3±0.8	-	-	17.5±1.0	-	-	17.5±1.4	351.3±54.1	-	Razak & Kassim, 2018
		F	23.3±1.0	-	-	23.8±1.0	-	-	21.0±2.1	928.5±123.1	-	
	Chendor	M	16.5±1.2	-	34.4± 2.9	-	-	-	-	340.2±21.0	-	Ismail et al., 2012
		F	21.9±1.4	-	45.8± 2.8	-	-	-	-	958.7±97.9	-	
	Cherating	M	16.5±1.5	-	35.5± 1.8	-	-	-	-	294.0±29.6	-	
		F	21.9±1.4	-	46.2± 2.7	-	-	-	-	879.3±115.1	-	
	Cherok Paloh	M	18.1±1.0	-	-	18.4±0.8	-	-	17.0±1.4	348.6±42.7	-	Razak & Kassim, 2018
		F	25.1±1.6	-	-	25.4±1.5	-	-	19.3±3.0	939.8±125.7	-	
Sarawak	Pasir Putih	M	17.2±1.0	-	33.6±4.2	-	-	-	17.5±2.8	295.4±29.2	-	Jawahir et al., 2017
		F	21.7±2.0	-	41.8±5.2	-	-	-	20.3±4.5	726.3±172.6	-	
	Pantai Gerigat	M	17.7±0.7	-	34.4±2.9	-	-	-	17.7±2.7	299.4±46.0	-	
		F	22.1±1.0	-	41.9±6.0	-	-	-	20.0±6.0	864.1±247.5	-	
Melaka	Merlimau	M	18.9±1.2	-	-	19.2±1.2	-	-	15.5±2.7	374.4±42.6	-	Razak & Kassim, 2018
		F	19.6±0.9	-	-	21.1±1.1	-	-	16.2±2.3	519.7±66.3	-	
		M	16.2±0.8	8.8±0.5	32.9±4.1	16.5±1.5	8.7±0.6	6.8±0.8	16.8±1.2	273.6±30.7	8.3±0.8	Present study
		F	20.3±1.0	18.0±1.0	43.0±4.2	23.3±2.3	13.6±1.8	9.9±1.1	20.3±2.1	689.8±80.6	12.6±0.7	
		M	-	8.3-8.9	-	-	6.8-9.0	-	16.6-20.3	194.2-270.0	-	Revision*
		F	-	17.9-18.1	-	-	-	-	19.9-21.1	733.5-894.6	12.9-13.3	

Note: abbreviations follow the order M – male, F – female, PW/L – prosoma width/length, OW – opisthosoma width, OL – opisthosoma length, TL – total length, CL – carapace length, TEL – telson length, BW – body weight, IO – interorbit distance. The revision* refers to the statistical-projection for wild *Tachypleus gigas* morphology in Merlimau.

positive allometry (10–24 crabs), and concerning telson length measurements, 15 crabs were indicated with negative allometry. Similarly, the large proportion of female crabs described with normal allometry (109–134 crabs) was actually vastly having negative (60–122 crabs) and, if not, substantially having normal (9–52 crabs) or positive allometry (1–74 crabs).

The findings are conclusive towards better allometry assessments, because the samples from Pahang, Sarawak, and Melaka were previously missing some morphometric points (Table 4). In fact, the descriptive analysis that used mean and standard deviation as median values did not produce a conclusive range that supports the actual condition (or health) of the *T. gigas*. Comparatively, the revised range was constructed with a linear equation. Through this equation, the range of 83–93 mm for male opisthosoma width classified the *T. gigas* with a narrow body layout (Table 4). This example adds support for the need of data transformation before statistics is used to indicate the most-associated morphology for a population. Only then should a linear equation be produced to generate an accurate version of allometry.

DISCUSSION

The present assessment provided the largest sample size involving 37 male and 168 female *T. gigas*. It is to be noted that the 20–30 crabs [Tan et al. 2012; Sahu and Dey 2013] and then a larger sample size <50 crabs [Chatterji and Pati 2014; Razak and Kassim 2018] mentioned in previous studies were a combined value of both genders. On the other hand, all horseshoe crabs that arrive at Sungai Merlimau are amplexus, but due to fishing gear, the 8-inch gill nets were thought to be specifically successful for trapping the female crab. In fact, the 4.0–4.5-inch mesh size effectively brought more male than female crabs [Fairuz-Fozi et al. 2018; Zauki et al. 2019]. Despite an imbalance in sample yield for this population, the findings are conclusive that prosomal length and interorbit distance are useful to develop accurate allometry for the male and female *T. gigas*, respectively. In contrast, the first attempt was made on *T. tridentatus* from three localities with sample sizes <40 per population [Mohamed et al. 2021]. Still, it should not be misunderstood that statistically-validated allometry has neglected the application of descriptive analysis.

The highlight is the extensive range of minimum-maximum values for all morphology indicators. Researchers, such as Vijayakumar et al. [2000] and Tan et al. [2012], decided to include small-sized horseshoe crabs in the data pool, but Sahu and Dey [2013] recommended the exclusion of small-sized crabs. Then, Chatterji and Pati [2014] suggested observing molt cycles, which means the samples having carapace dorsal spines are juvenile crabs. Instead, another consortium of researchers was persistent that size is the best criterion to identify juvenile crabs and this criterion is useful to separate adults from juveniles in a sample pool [Mohamad et al. 2016; Razak and Kassim 2018]. Hence, the developments concerning sample size and size classification itself were rather insufficiently justified. Conversely, the examination of molt cycles is efficient but, a second inclusion criterion is needed. The first is the visibility of eggs in the thin prosoma sheet of the female crab, and the second is the swelling of the genital pore of the male crab. This method of examination adopted from Mohamed et al. [2021] allowed smaller horseshoe crabs that were sexually mature to be part of the allometry assessment.

The samples from Sungai Merlimau recorded 6 female *T. gigas* of smaller size (c.a. opisthosoma width, interorbit distance and telson length) class. In contrast, another 26 crabs were slightly larger but below the normal range for these indicators. Cross-referencing with bodyweight suggests that mass increase exceeds the body size simply because eggs (white-yellow) that are visible in their prosoma were the baggage that added to their body weight. These 32 female *T. gigas* were gravid with eggs ready for fertilization, which indicated them to be sexually mature. Thus, it is clear that 19 % of the female *T. gigas* in this captured population resort to survival strategies that reduce the risk of them being captured. Comparatively, 6 % of *T. tridentatus* captured in Sabah were similarly recorded with this strategy [Mohamed et al., 2021]. Though an indication, more assessments would be better to denote the connections between the 8-inch fishing gear and the chances of capturing both male and female *T. gigas*. The chances of capturing the entire amplexus increase when both male and female crabs have almost relative sizes. Yet, it is unclear if the smaller female-only opts to form an amplexus with large male crabs. However, the authors are certain that imbalances in operational sex ratio are forcing a survival strategy that was theorized to exist with the *Limulus polyphemus* [Smith and Brockmann 2014; Hare and Simmons 2019]. This is the first record where *T. gigas*, similar to the *T. tridentatus* of Sabah, were reported to practice survival strategies to sustain their population. It was assumed that male mimicry was the strategy utilized where the female grew to appear monomorphic to the male crab.

The classic method of size classification would use median values and then re-class the size and weight of horseshoe crabs in the order of (positive and negative) binomial bulges. However, this method produces inconsistent results (Table 4), which means a definite morphometric indicator could not be established. For instance, ichthyologists used baseline fish measurements and successfully developed length-weight mathematical assessments [Jisr et al. 2018]. Moreover, the carapace width of porcelain crab could indicate age and readiness to reproduce [Hamasaki et al. 2020]. However, horseshoe crabs are neither crustaceans nor fin-fish and have 16–17 molt stages before maturing into the adult [John et al. 2018]. With this, the accurate allometry assessment introduced for *T. tridentatus* [Mohamed et al. 2021] also indicated opisthosoma width, telson length and body weight as inclusive morphometric-indicators for the *T. gigas*. Nevertheless, by using a larger sample size, it was found that prosoma length and interorbit distance are additional morphometric indicators for the allometry of *T. gigas*. Overall, baseline or benchmark measurements are no longer required in any processes that evaluate the growth or health of horseshoe crabs. In addition, the accurate size class projection for a population also reduces the baseline errors that arise from using random sampling.

CONCLUSIONS

The novelty of this work arises from using a larger sample size because the prosoma length and interorbit distance were exclusive for the male and female *T. gigas,* respectively. By using statistical-validated allometry, this work discovered the presence of female *T. gigas* that were diminished in size which not only suggested that male mimicry is taking place in populations with weak operational sex ratio but, depending on fishing gear, the chances of capturing both, male and female horseshoe crab also increases. Thus, the strategy adopted by the female crabs by appearing monomorphic to the male could be a new research exploration by the scientific community to realize the impacts of sex-based capture in marine species.

Acknowledgments

The sampling of this work was supported by Ocean Park Conservation Foundation Hong Kong (OT-01 2020). The facilities provided by Universiti Malaysia Terengganu enabled the execution of the work and the graduation of the first author L.Y.C.

REFERENCES

1. Ariffin M.S.A., Ramlee M.N.A., Pati S., Edinur H.A. Nelson B.R. 2022. Fish Distribution in Tropical Bidong Island, South China Sea Under Influence from Nearshore Sea Acidification. Springer Cham, Switzerland.
2. Chatterji A., Pati S. 2014. Allometric relationship in the adult population of the Malaysian horseshoe crab (*Tachypleus tridentatus*; Leach). International Journal of Research, 1, 1378–1385.
3. Fairuz-Fozi N., Satyanarayana B., Zauki N.A.M., Muslim A.M., Husain M.L., Ibrahim S., Nelson B.R. 2018. *Carcinoscorpius rotundicauda* (Latreille, 1802) population status and spawning behaviour at Pendas coast, Peninsular Malaysia. Global Ecology and Conservation, 15, e00422.
4. Jaffar M., Yunus N.M., Nelson B.R. 2019. Regional tinfoil barb imports can alter its native species genetic makeup. Journal of Sustainability Science and Management, 14, 51–65.
5. 5. Jisr N., Younes G., Sukhn C., El-Dakdouki M.H. 2018. Length-weight relationships and relative condition factor of fish inhabiting the marine area of the Eastern Mediterranean city, Tripoli-Lebanon. Egyptian Journal of Aquatic Research, 44, 299–305.
6. 6. John B.A., Nelson B.R., Sheikh H.I., Cheung S.G., Wardiatno Y., Dash B.P., Tsuchiya K., Iwasaki Y., Pati S. 2018. A review on fisheries and conservation status of Asian horseshoe crabs. Biodiversity and Conservation, 27, 3573–3598.
7. Hamasaki K., Ishii M., Dan S. 2020. Reproductive traits and population structure of the porcellanid crab *Petrolisthes japonicus* (Decapoda: Anomura: Porcellanidae). Crustacean Research, 49, 121–132.
8. Hare R.M., Simmons L.W. 2019. Sexual selection and its evolutionary consequences in female animals. Biological Reviews, 94(3), 929–956.
9. Mashar A., Butet N.A., Juliandi B., Qonita Y., Hakim A.A., Wardiatno Y. 2017. Biodiversity and distribution of horseshoe crabs in northern coast of Java and southern coast of Madura. Environmental Earth Sciences, 54, 012076.
10. Mohamad F., Manca A., Ahmad A., Fawwaz M. 2016. Width-weight and length-weight relationships of the tri-spine horseshoe crab, *Tachypleus tridentatus* (Leach 1819) from two populations in Sabah, Malaysia: implications for population management. Journal of Sustainability Science and Management, 11, 1–13.
11. Mohamed R., Paul N.A., Isa N.S., Damanhuri J.H., Shahimi S., Pati S., John A., Nelson B.R. 2021. Using applied statistics for accurate size classification of the endangered *Tachypleus tridentatus* horseshoe crab. Journal of Ecological Engineering, 22, 273–282.
12. Nelson B.R., John A., Zhong J.H., Jalal K.C.A. 2020. Membrane retention potential of *Tachypleus gigas* during early embryogenesis. Desalination and Water Treatment, 187, 17–23.
13. Post J.R., Parkinson E.A. 2001. Energy allocation strategy in young fish: allometry and survival. Ecology, 82, 1040–1051.
14. Pramanik A., Rajesh A.S., Tudu S., Beata M.M., Shahimi S., Nelson B.R., Sarkar T., Satyanarayana B., Pati S., Dash B.P. 2021. Review on biology, distribution and conservation challenges for horseshoe crabs in India. Journal of Sustainability Science and Management, 16, 332–346.
15. Razak M.R., Kassim Z. 2018. Comparison of horseshoe crabs (*Tachypleus gigas*) morphometry between different populations using allometric analysis. Aquaculture, Aquarium, Conservation & Legislation, 11, 143–157.
16. Sahu A.C., Dey L. 2013. Spawning density and morphometric characteristics of the horseshoe crab *Tachypleus gigas* (Müller) on the Balasore coast of Bay of Bengal, India. Science Vision, 13, 76–84.
17. Sastraprawira S.M., Razak I.H.A., Shahimi S., Pati S., Edinur H.A., John A.B., Ahmad A., Kumaran J.V., Martin M.B., Chong J.L., Nelson B.R. 2020. A review on introduced *Cichla* spp. and emerging concerns. Heliyon, 6, e05370.
18. Smith M.D., Brockmann H.J. 2014. The evolution and maintenance of sexual size dimorphism in horseshoe crabs: an evaluation of six functional hypotheses. Animal Behaviour, 96, 127–139.
19. 19. Tan A.N., Christianus A., Shakibazadeh S., Hajeb P. 2012. Horseshoe crab, *Tachypleus gigas* (Müller, 1785) spawning population at Balok Beach, Kuantan, Pahang, Malaysia. Pakistan Journal of Biological Sciences, 15, 610–620.
20. Vijayakumar R., Das S., Chatterji A., Parulekar A.H. 2000. Morphometric characteristics in the horseshoe crab *Tachypleus gigas* (Arthropoda: Merostomata). Indian Journal of Marine Sciences, 29, 333–335.
21. Zauki N.A.M., Satyanarayana B., Fairuz-Fozi N., Nelson B.R., Martin M.B., Akbar-John B., Chowdhury A.J.K. 2019. Citizen science frontiers horseshoe crab population regain at their spawning beach in East Peninsular Malaysia. Journal of Environmental Science and Management, 232, 1012–1020.