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Differences in the morphological body condition index of sea turtles between species and size classes

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Abstract

The body condition of animals is an important indicator of their habitats and the effects of anthropogenic activities and pollution. Body condition indices calculated from morphometric measurements have been widely employed as they are easy to use and inexpensive. In sea turtles, Fulton's condition index, calculated as the bodyweight divided by the cube of straight carapace length (SCL), has been commonly used and it has been proposed that an index of ≥1.2 indicates a good body condition. However, comparing Fulton's condition index between different species and size classes is problematic as it does not consider the mass-length relationship. In this study, we conducted a meta-analysis to evaluate the differences between sea turtles. A literature review indicated that most studies reported the SCL-based Fulton's condition index for green turtles (*Chelonia mydas*), followed by loggerhead turtles (*Caretta caretta*) and hawksbill turtles (*Eretmochelys imbricata*). Therefore, we compared the values reported for healthy turtles of these three species. Meta-analysis supported the adequacy of 1.2 as a threshold in juvenile and adult green turtles and large juvenile and adult loggerhead turtles. High Fulton's condition index values were found for hatchlings and post-hatchlings of all three species and small loggerhead turtle juveniles. Low Fulton's condition index values were found for hawksbill turtles, particularly small juveniles. The differences in the Fulton's condition index between species and size classes indicated that it should be used carefully as a threshold for health condition evaluation.

Introduction

The health and body condition of endangered animals provide fundamental information in conservation biology. Body condition is an important indicator for evaluating habitats and the effects of anthropogenic activities and pollution (Johnson, 2007; Clukey *et al.*, 2017; Rodriguez & Heck, 2020). Body condition has been assessed using various techniques, including haematology and plasma biochemistry (Stevenson & Woods, 2006; Wang *et al.*, 2020; Kophamel *et al.*, 2022). The morphological body condition indices of endangered animals have been widely employed because they are easy to use and inexpensive. Various morphological condition indices have been suggested (Stevenson & Woods, 2006; Peig & Green, 2010; Sönmez, 2019); Fulton's condition index is one of the most common and is calculated as the bodyweight divided by the cube of body length (Ricker, 1975).

The body condition of sea turtles has recently become an important topic regarding their conservation as affected by marine debris (Clukey *et al.*, 2017) and fibropapillomatosis prevalence (Rossi *et al.*, 2019). Body condition indices based on morphometry have been widely used since Bjorndal *et al.* (2000*a*) calculated Fulton's condition index for juvenile green turtles (*Chelonia mydas*) as bodyweight/(straight carapace length [SCL])^3. In addition, the haematology and plasma biochemistry of sea turtles have also been investigated (Anderson *et al.*, 2011; Komoroske *et al.*, 2011). Morphological condition indices of sea turtles include not only the Fulton's index, but also simple mass and length ratios (Patino-Martinez *et al.*, 2012), relative factors incorporating mass-length relationships (Fukuoka *et al.*, 2015), and residuals from the mass-length relationship (Jessop *et al.*, 2004).

Fulton's condition index is a widely used simple metric, but it should be carefully interpreted. The index assumes isometric growth; therefore, comparing values between different size classes may be problematic (Peig & Green, 2010). Interspecific or interpopulation comparisons are also difficult when body dimensions or growth patterns differ. In sea turtles, Fulton's condition index has been widely used as a rough measure of nutritional status and health (Bjorndal *et al.*, 2000*a*; Diez & van Dam, 2002) and values exceeding 1.2 have conventionally been interpreted to indicate a good body condition (Norton & Wyneken, 2015; Maulida *et al.*, 2017; Adnyana *et al.*, 2020). However, the threshold value may change, considering that there are interspecific and/or intraspecific differences in the body shape and growth pattern of sea turtles (Wabnitz & Pauly, 2008; Álvarez-Varas *et al.*, 2019). Additionally, the carapace length, which has been used as a representative length for calculating the index, can be measured in several ways, such as by using the SCL *vs* curved carapace length (CCL) (Bolten, 1999). Evaluating these differences is important to establish a baseline condition index for sea turtles.

In this study, we reviewed the literature on morphological condition indices in sea turtles and conducted a meta-analysis of Fulton's condition index in sea turtles. This study summarizes the prevalence of various morphological condition indices among sea turtle species to elucidate the knowledge gap regarding their health status. We then evaluated the differences in Fulton's condition index between species and size classes to establish baseline sea turtle body conditions. We also evaluated differences in the index values when different length metrics were used.

Materials and methods

Literature review

We searched for studies using Google Scholar and Web of Science with the queries 'sea turtle' and 'body condition index' or 'Fulton index' on 5–7 August 2020 and 12–13 April 2021. We additionally searched PubMed on 5–6 April 2022, but did not include references published after April 2021. We reviewed the references therein and retained literature on morphological condition indices.

Meta-analysis of Fulton's condition index

The average and standard deviation (SD) or standard error (SE) of Fulton's condition indices ($kg\,cm^{-3} \times 10^4$) calculated from the SCL in the literature were used. When the data appeared only in figures, they were extracted using Plot Digitizer 2.6.8 (Huwaldt, 2001). When the data were presented as median, maximum, minimum and/or quantile values, we estimated the average and SD using the method reported by Wan *et al.* (2014). The SCL can be measured as the length from the anterior point at the midline to the posterior notch at the midline (minimum SCL [SCLmin]) or the tip (standard SCL [SCLnt]) (Bolten, 1999). We could not differentiate these measurements in the following analysis as the literature sometimes did not clearly present which was used; however, we simulated the effects based on conversion equations (see below). We excluded studies that reported the body condition indices of unhealthy turtles to explore the standard baseline values for healthy turtles. Unhealthy turtles included dead and injured turtles, those noted as 'unhealthy' in the original texts, and those with tumours with scores (Work & Balazs, 1999) of 2–3 or labelled as 'developed', 'moderate' or 'severe'; however, we retained the data of turtles with 'mild' tumours or a tumour score of ~1. We also removed literature that may have contained data on the same individuals based on the authors, locations and study periods.

In addition to the dataset from the literature, we calculated Fulton's condition indices from the unstructurally searched literature that provided the bodyweights and SCLs of individuals. Furthermore, to complement the data of hawksbill turtle (*Eretmochelys imbricata*) hatchlings, we measured the bodyweight and SCL of 20 hawksbill turtle hatchlings each from 8 and 13 nests at Lankayan and Selingaan hatcheries, Sabah, Malaysia, respectively. We calculated the Fulton's condition index and its average ± SD at each rookery by randomly selecting one hatchling from one nest. A full list of literature compiled in this study is provided in Supplementary Table S1.

Fulton's condition index has mainly been reported for three species: green turtles, loggerhead turtles (*Caretta caretta*) and hawksbill turtles (see Results). Therefore, we focused on these three species in this study. Additionally, we categorized the data into one of three size classes: 'hatchling and post-hatchling', 'small juvenile' and 'large juvenile and adult'. The 'hatchling and post-hatchling' category included hatchlings measured just after emergence from the nests and post-hatchlings that were reared for several months (SCL of ~15 cm). The 'small juvenile' and 'large juvenile and adult' categories were separated at 50 cm SCL according to Bjorndal *et al.* (2000*b*), Gorham *et al.* (2014) and Hamabata *et al.* (2018). The 'small juvenile' category included juveniles recruited to their foraging grounds after oceanic dispersal, with SCLs ranging from 20–50 cm. The 'large juvenile and adult' category included nesting turtles, matured males and large juveniles with SCLs larger than 50 cm. When it was difficult to clearly assign these categories to the literature because average and SD or SE values were reported from individuals including both small juveniles and large juveniles or adults, categorization was based on whether or not the average SCL exceeded 50 cm. Regional information was also adopted and categorized into 'North Atlantic', 'South Atlantic', 'North-west Pacific', 'Central Pacific' and 'East Pacific' based on the regional management units (RMU) in Wallace *et al.* (2010) and distinct population segments (DPS) in Conant *et al.* (2009) and Seminoff *et al.* (2015).

The differences in Fulton's condition index between species and size classes were tested by random-effects modelling using the metafor package (Viechtbauer, 2010) in R ver 4.0.0 (R Core Team, 2020). First, we assumed a multilevel model that included regions as the upper level and studies as the lower level. We confirmed that the variance attributable to regions was small by the likelihood ratio test and variance distribution calculation using the dmetar package (Harrer *et al.*, 2019) (see Results); thus, we estimated a single-level model that included studies as random effects. Overall averages and 95% confidence intervals (CIs) were estimated for each species and size class.

Effects of different carapace length measurement

For the simulation, we randomly generated SCLnt values (N = 100) from a uniform distribution ranging from 30–100 cm. We then estimated the ratios of $SCLnt^3/CCLnt^3$ or $SCLnt^3/SCLmin^3$ using the relationship between SCLnt and CCLnt (i.e. the CCL measured from notch to tip) and SCLnt and SCLmin based on regression analyses (Limpus, 1992; Teas, 1993; Iwase & Kuroyanagi, 1999; Seminoff *et al.*, 2003; Peckham *et al.*, 2008; Okamoto *et al.*, 2012; Bjorndal *et al.*, 2013, 2016, 2017; Table 1). These ratios indicate the ratios of SCLnt-based *vs* CCLnt-based (or SCLnt-based *vs* SCLmin-based) Fulton's condition indices as follows:

$$\frac{\text{Bodyweight }/\text{CCLnt}^3}{\text{Bodyweight }/\text{SCLnt}^3} = \frac{\text{SCLnt}^3}{\text{CCLnt}^3}$$

We used three equations to convert SCLnt to CCLnt for green, loggerhead and hawksbill turtles estimated from Atlantic and Pacific data. To convert SCLmin to SCLnt, we used equations estimated from Atlantic turtles because we could not find conversion equations for Pacific turtles.

Results

We identified 77 articles that reported morphological condition indices. Most studies focused on green (N = 51), followed by loggerhead (N = 16) and hawksbill turtles (N = 6) (Table 2, Supplementary Table S2). Fulton's condition index was calculated based on the SCL in most studies (N = 54); however, some studies reported CCL-based indices (N = 7) (Table 2, Supplementary Table S2). Two studies calculated the modified Fulton's index considering carapace length × carapace width × carapace depth, instead of $(\text{carapace length})^3$ (Barco *et al.*, 2016; Cammilleri *et al.*, 2017). The mass-to-length ratio (mass/SCL) has been

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Table 1. Equations for converting the curved carapace length of sea turtles measured from notch to tip (CCLnt) or notch to notch straight carapace length (SCLmin) to the notch to tip straight carapace length (SCLnt)

Conversion	Species	Location	Equation	References
CCLnt to SCLnt	Green	West Atlantic	SCLnt (cm) = 0.294 + (0.937 × CCLnt)	Teas (1993)
		West Atlantic	SCLnt (cm) = −0.5385 + (0.9698 × CCLnt)	Bjorndal *et al.* (2017)
		Japan, Pacific	SCLnt (mm) = 4.584 + (0.946 × CCLnt)	Okamoto *et al.* (2012)
		East Pacific	SCLnt (cm) = −2.168 + (0.965 × CCLnt)	Seminoff *et al.* (2003)
	Loggerhead	West Atlantic	SCLnt (cm) = −1.442 + (0.948 × CCLnt)	Teas (1993)
		West Atlantic	SCLnt (cm) = −0.899 + (0.939 × CCLnt)	Bjorndal *et al.* (2013)
		Japan, Pacific	SCLnt (mm) = 8.621 + (0.940 × CCLnt)	Okamoto *et al.* (2012)
		East Pacific	SCLnt (cm) = 0.369 + (0.932 × CCLnt)	Peckham *et al.* (2008)
	Hawksbill	West Atlantic	SCLnt (cm) = −0.212 + (0.955 × CCLnt)	Teas (1993)
		West Atlantic	SCLnt (cm) = 0.4496 + (0.9326 × CCLnt)	Bjorndal *et al.* (2016)
		Japan, Pacific	SCLnt (cm) = 1.91 + (0.920 × CCLnt)	Iwase & Kuroyanagi (1999)
		Australia	SCLnt (cm) = 0.449 + (0.935 × CCLnt)	Limpus (1992)
SCLmin to SCLnt	Green	West Atlantic	SCLnt (cm) = 0.238 + (1.0138 × SCLmin)	Bjorndal *et al.* (2017)
	Loggerhead	West Atlantic	SCLnt (cm) = 0.999 + (1.003 × SCLmin)	Bjorndal *et al.* (2013)
	Hawksbill	West Atlantic	SCLnt (cm) = 0.1424 + (1.0409 × SCLmin)	Bjorndal *et al.* (2016)

used for hatchlings (van de Merwe *et al.*, 2005, 2010; Patino-Martinez *et al.*, 2012) or post-hatchlings (Mansfield *et al.*, 2012); however, Fulton's condition index has recently been applied to hatchlings (Banerjee *et al.*, 2020; Fleming *et al.*, 2020).

We included studies that reported the SCL-based Fulton's index for green, loggerhead and hawksbill turtles in further meta-analyses. After removing potential duplicate data and adding the data calculated in the present study, data from 68 studies were used to evaluate the differences between species and size classes (Supplementary Table S3). The multilevel model showed that regions and studies explained 25.7 and 34.3% of the variation, respectively, and the effects of regions were not significant (likelihood ratio test: $\chi^2 = 0.27$, $P = 0.603$). The single-level model attributed 53.3% of the total variance to between-study heterogeneity but showed a significant effect of moderators ($Q = 186.4$, $df = 8$, $P < 0.0001$). A high Fulton's condition index was observed in 'hatchling and post-hatchling' turtles (averages for green, loggerhead and hawksbill turtles: 2.24 [95% CI: 1.87–2.61], 2.13 [1.97–2.28], 2.06 [1.82–2.30], respectively) (Figure 1). The CIs overlapped between 'small juveniles' and 'large juveniles and adults' for each species (green turtle: 1.31 [1.25–1.36] and 1.41 [1.34–1.47], loggerhead turtle: 1.59 [1.45–1.73] and 1.40 [1.33–1.48], hawksbill turtle: 1.09 [0.98–1.20] and 1.26 [1.07–1.45], respectively); however, the value of small juvenile hawksbill turtles was smaller than that of green and loggerhead turtles (Figure 1).

The averages and ranges of estimated $SCLnt^3/CCLnt^3$ ratios of green turtles based on equations from Teas (1993), Bjorndal *et al.* (2017), Okamoto *et al.* (2012) and Seminoff *et al.* (2003) were 0.835 (range: 0.830–0.847), 0.887 (range: 0.865–0.897), 0.867 (range: 0.858–0.887) and 0.805 (range: 0.729–0.842), respectively. The ratios for loggerhead turtles based on equations from Teas (1993), Bjorndal *et al.* (2013), Okamoto *et al.* (2012) and Peckham *et al.* (2008) were 0.791 (range: 0.740–0.816), 0.790 (range: 0.758–0.806), 0.869 (range: 0.853–0.906), and 0.825 (range: 0.819–0.840), respectively. The ratios for hawksbill turtles based on equations from Teas (1993), Bjorndal *et al.* (2016), Iwase and Kuroyanagi (1999), and Limpus (1992) were 0.861 (range: 0.853–0.865), 0.831 (range: 0.822–0.849), 0.863 (range: 0.825–0.948) and 0.837 (range: 0.829–0.855), respectively. The estimated $SCLnt^3/SCLmin^3$ ratios for green, loggerhead and hawksbill turtles were 1.055 (range: 1.049–1.067), 1.061 (range: 1.040–1.114) and 1.016 (range: 1.013–1.023), respectively.

Discussion

Fulton's condition index has been widely applied in sea turtle studies, excluding flatback turtles (*Natator depressus*). Values of Fulton's condition index based on SCLs ≥1.2 have been interpreted to indicate a relatively good body condition for sea turtles (Norton & Wyneken, 2015; Maulida *et al.*, 2017; Adnyana *et al.*, 2020). Although index values ≥1.3 were generally observed in large green and loggerhead turtles, the meta-analysis in this study supported the adequacy of this threshold for juvenile and adult green turtles and large juvenile and adult loggerhead turtles. This study also indicated further differences in Fulton's condition index between species and size classes; thus, it should be carefully applied on body condition evaluation.

The meta-analysis indicated high Fulton's condition index values for hatchlings and post-hatchlings of all three species. This is to be expected because the bodyweight of sea turtles is not proportional to SCL^3, but $SCL^{2.7}$–$SCL^{2.9}$ (Wabnitz & Pauly, 2008), resulting in a decrease in Fulton's condition index as bodyweight increases (Figure 2). The relationship between bodyweight and SCL also supports the finding that Fulton's condition index of small loggerhead juveniles was lower than that of hatchlings and post-hatchlings, but slightly higher than that of large juveniles and adults. This tendency was not observed in green and hawksbill turtles, which may be because the index values from foraging grounds included both small juveniles and large juveniles or adults, and the categorization was based on the average SCL. Evaluating hatchling and post-hatchling sea turtles using Fulton's condition index requires caution. Additionally, a threshold higher than 1.2 is more suitable to indicate the good body condition of small juvenile loggerhead turtles.

A lower Fulton's condition index was observed for hawksbill turtles, particularly small juveniles. The relationships between the bodyweight and SCL (Wabnitz & Pauly, 2008) indicated that the bodyweight of hawksbill turtles in relation to SCL (i.e. Fulton's condition index) is lower than that of green and

Table 2. Number of studies that have reported the morphometric body condition index for each sea turtle species

Index	*N*	Green	Loggerhead	Hawksbill	Olive Ridley	Kemp's Ridley	Leatherback
Fulton (SCL-based)	54	34	14	5	4	3	2
Fulton (CCL-based)	7	6				1	
Modified Fulton	2		2				
Relative	4	4					
Residual	6	4		1			1
Mass/Length	4	2	1				1
log(Mass)/log(Length)	3	3					
Scaled mass index	1	1					
Total[a]	77	51	16	6	4	4	4

[a]Some studies have reported indices of multiple species or multiple indices; therefore, the total numbers are different from the summation of the columns. See Supplementary Table S2 for further details.

loggerhead turtles (Figure 2). This difference is likely due to the relatively depressed plastron of hawksbill turtles, which is supported by the relationship between body depth and SCL (van Dam & Diez, 1998), when compared with loggerhead turtles (Marn *et al*., 2015). In addition, carapace widening is observed in juvenile green and loggerhead turtles (Salmon & Scholl, 2014), but not in juvenile hawksbill turtles (Salmon *et al*., 2018), possibly resulting in lower bodyweights of juvenile hawksbill turtles in relation to SCL. Considering the differences in body proportion and the results of the meta-analysis, Fulton's condition index of values of ~1.0 rather than 1.2 could be a threshold for indicating good body condition in juvenile and adult hawksbill turtles.

SCL has been used as the representative body length for calculating Fulton's condition index in sea turtles, as used by Bjorndal *et al*. (2000*a*). Some studies measured the CCL but converted it to SCL to calculate the SCL-based Fulton's condition factor (López-Mendilaharsu *et al*., 2016; Rossi *et al*., 2019; Lamont & Johnson, 2021). We found seven studies that calculated Fulton's condition factor directly using CCL. Fulton's condition index values calculated from the CCL were ~0.81–0.89 times lower than those calculated using the SCL in green and hawksbill turtles. Therefore, an SCL-based index value of 1.2 is equivalent to a CCL-based index value of 1.0. Moreover, CCL-based values were lower in Atlantic loggerhead turtles (0.79 × SCL-based values). There may be a regional difference in the relationship between SCL and CCL for Atlantic and Pacific loggerhead turtles that results in differences in the CCLnt-based index/SCLnt-based index ratio among conversion equations (~0.79 based on Teas, 1993 and Bjorndal *et al*., 2013 *vs* 0.82–0.87 based on Okamoto *et al*., 2012 and Peckham *et al*., 2008).

We only evaluated three species of sea turtles, i.e. green, loggerhead and hawksbill turtles, because data are scarce for the other species. Further studies are required to evaluate other sea turtle species. Kemp's Ridley turtle (*Lepidochelys kempii*) may have a higher Fulton's condition index than green turtles due to

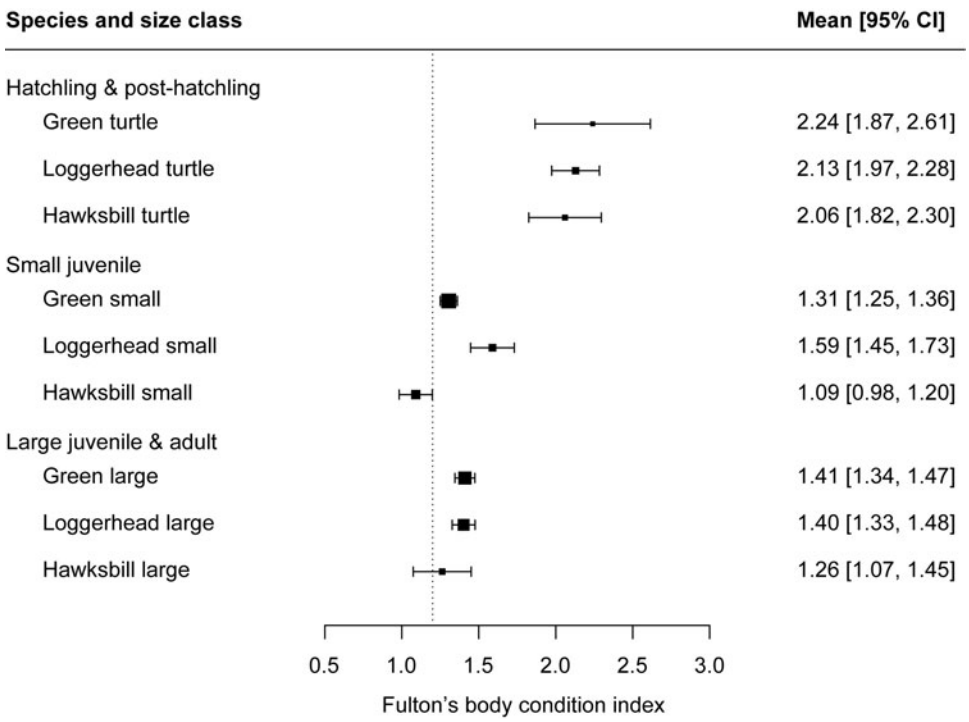

Fig. 1. Forest plot of Fulton's body condition index values estimated using meta-analysis. The mean and 95% confidence interval (CI) values are shown in the right column, and the dashed line shows the value of 1.2.

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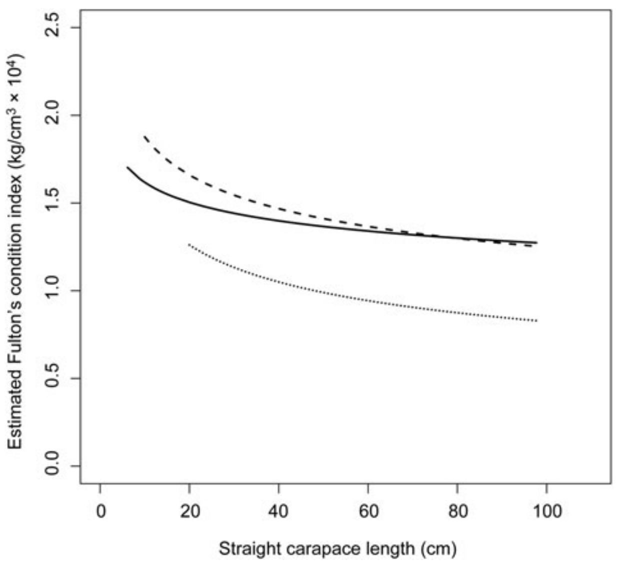

Fig. 2. The relationship between Fulton's body condition index and straight carapace length (SCL) estimated from the relationships between bodyweight and SCL in green (Bodyweight = 0.000206 $SCL^{2.895}$), loggerhead (Bodyweight = 0.000282 $SCL^{2.823}$) and hawksbill turtles (Bodyweight = 0.000278 $SCL^{2.736}$) (Wabnitz & Pauly, 2008). Green, loggerhead and hawksbill turtles are illustrated by solid, dashed and dotted lines, respectively.

interspecific morphological differences (Lamont & Johnson, 2021). Additionally, we did not evaluate the eastern Pacific green turtle subspecies, the black turtle (*Chelonia mydas agassizii*) because foraging grounds may contain both black turtle-like and ordinal green turtle-like morphotypes, and values have not been reported separately (Sielfeld *et al.*, 2019). However, a smaller Fulton's condition index has been reported in small juveniles of black turtle-like morphotypes than in ordinary green turtles (Sampson *et al.*, 2014).

In the present study, the effect of region was not significant; however, regional differences were possible sources of between-study heterogeneity. Fulton's condition index has not been reported equally from all regions and was tested as a random effect in this study. Further studies are necessary to explore regional differences. In addition, foraging aggregations sometimes contain turtles from various rookeries (Amorocho *et al.*, 2012; Nishizawa *et al.*, 2013, 2018), which may result in high individual differences and within-study heterogeneity in the condition index. Another factor for heterogeneity is the difference in carapace length measurement. SCL can be measured as notch-to-notch (SCLmin) or notch-to-tip (SCLnt) (Bolten, 1999). Calculating the index using SCLmin slightly increases the index from that based on SCLnt by 1.01–1.06 times. Defining which length is used clearly will be important for further establishing baseline body condition index values in sea turtles.

In conclusion, caution should be applied when using Fulton's condition index as a body condition indicator for sea turtles. Using Fulton's condition index for different species and size classes is problematic, as it does not consider the mass-length relationship (Peig & Green, 2010). Different threshold values for good body condition must be implemented for species and size classes. Morphometric body condition indices that incorporate mass-length relationships have been calculated for sea turtles (relative condition index: Labrada-Martagón *et al.*, 2010, 2011, 2013; Fukuoka *et al.*, 2015; scaled mass index: Bell *et al.*, 2019). Fulton's condition index is a simple metric that can be used to assess sea turtle body conditions. Because accidental errors can always occur when measuring bodyweight and length, the proposed threshold values for good body condition in this study must be carefully applied for individual body condition evaluation. Nonetheless, this study proposed baseline Fulton's condition index values for adequate sea turtle habitats and body conditions, which will be compared in future studies.

Data. The data that support the findings of this study are available from the online supplementary materials.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0025315422000765.

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Author contributions. HN: formulating the research questions, designing the study, carrying out the study, analysing the data, interpreting the findings and writing the article. JJ: formulating the research questions, providing financial support, carrying out the study, revising the article.

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Conflict of interest. The authors declare no conflict of interests.

Ethical standards. Fieldwork in Sabah, Malaysia followed the guidelines and permitted under the Sabah Biodiversity Centre (SaBC) Access Licence: JKM/MBS.1000-2/2 JLD.12(23) and Sabah Parks: TTS/IP/100-6/2 JLD.11(119).

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