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Short Communication

Morphometry and allometry of free-living olive ridley sea turtles (*Lepidochelys olivacea*) from the Mexican Central Pacific

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ABSTRACT. Research on olive ridley sea turtle (*Lepidochelys olivacea*) has emphasized egg-laying females and neonates, using data collected on nesting beaches, but no systematic studies on morphological characteristics by size and sex have been published. This research describes the morphometry of free-living olive ridley sea turtles from coastal and oceanic waters of the Mexican Central Pacific captured and released from 2011 through 2013. A total of 3469 km was surveyed, and 142 sea turtles were evaluated by sex, size class, marine area, and geographic region for nine corporal measurements and their allometric relationships. The average curved carapace length (CCL) was 62.12 cm, range 42-94 cm. Significant differences were found by sex and size class with total tail length (TTL) (♂ = 26.33 cm, ♀ = 12.4 cm); similarly with vent to tail tip length (VTTL) (♂ = 6.38 cm, ♀ = 3.86 cm); and for rear flipper length (RFL) (♂ = 28.17 cm, ♀ = 38.62 cm, immatures = 23.80 cm). Turtles from the coastal region of Colima-Michoacán showed longer CCL = 62.46 cm and wider CW = 66.58 cm. Adult female RFLs showed positive allometry, $b = 1.098$, suggesting an accelerated growth of the posterior extremities, probably favoring reproductive behaviors, e.g. nest digging and egg-covering. Morphological differences were likely due to ontogenetic sexual distinctions rather than marine area or geographic differences.

Keywords: *Lepidochelys olivacea*; sexual dimorphism; allometry; ontogeny; size class; geographic distribution

The olive ridley turtle (*Lepidochelys olivacea*) is the most abundant sea turtle and one of the smaller species within the Cheloniidae family (Márquez et al. 1976, Abreu-Grobois 1999). It is listed as vulnerable in the Red List of the International Union for Conservation of Nature (IUCN, Abreu-Grobois & Plotkin 2008), and it is listed as endangered by the NOM-059-2010 (DOF 1990), a listing of protected species in Mexico. The olive ridley turtle studies are scanter than other turtles found in the Mexican Pacific (Briseño 1998, Abreu-Grobois & Plotkin 2008). Due to logistic and economic reasons, ecological studies have focused mainly on organisms found on beaches, i.e. nesting females and neonates (García et al. 2003, Hart et al. 2018, Girard et al. 2021), or on dead individuals caught during fisheries interactions (Vera & Rosales 2012), and only one published study is available that estimates the abundance of free-living olive ridleys (Eguchi et al. 2007).

Morphology is a scarcely studied ecological indicator in free-living sea turtles; it is the first step for taxonomic differentiation, especially when genetic analyses are unlikely to occur due to budget and logistics

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reasons. Morphological studies could help distinguish the sexes; however, this is difficult in sea turtles, given the low number of male individuals, as most of the available data come from nesting adult females (Michel-Morfin et al. 2001, Torres 2002, Vega & Robles 2005, Girard et al. 2021).

Morphological differences between the sexes have been shown in females with larger plastron and carapace and in males with a larger tail (Frazier 1983); while recent research found an unusual sexual dimorphism, including males being larger than females in olive ridleys from the Republic of the Congo (Girard et al. 2021). Michel-Morfin et al. (2001) found significant differences in the number of vertebral and costal scutes, straight carapace length, and carapace width of male and female neonates; however, it is uncertain whether this morphological pattern applies to free-living juveniles and adults. Studies focusing on the body growth of olive ridley turtles are scarce; there is only a study on the relationship between the size of the head and flipper, which is more evident in juveniles than adults (Torres 2002). There is even less knowledge on the relationship between body shape, growth patterns, and the surrounding environment.

We hypothesized a differential morphology by sex, given by an allometric growth of the body regions related to an ecological indicator (e.g. feeding or breeding) in olive ridley turtles distributed in the Mexican Central Pacific (MCP). Thus, this research describes nine morphometric measurements and their allometric relationships for olive ridley individuals of both sexes and different size classes captured in coastal and oceanic MCP waters to identify differences in the marine area and geographic region.

Two main geographic areas, Jalisco and Colima-Michoacán, were used as the separation criterion to compare turtles morphologically between geographic regions. The MCP is located within the Mexican Transitional Pacific ecoregion; its northern limit is Cabo Corrientes, in the south of Banderas Bay, Jalisco (20°21'22.24"N, 105°21'35.67"W), and its southern limit was Maruata, a fishing village from Michoacán (18°16'23.60"N, 103°20'41.15"W). Coastal and oceanic areas were differentiated with a parallel line ~75 km from the coast where the 4000 m isobath is found; the oceanic area extends ~186 km towards the open ocean (Fig. 1).

Fieldwork: boat surveys were conducted in coastal and oceanic waters of the MCP from December 2011 to December 2013. Coastal surveys were conducted aboard FACIMAR II, a small (7.9 m) fiberglass boat with an outboard motor (Yamaha 75 hp). Sampling was done twice a month, with a total research effort of 1755 km. Three observers were located at the bow, using Fujinon 7×50 binoculars to locate sea turtles resting on the water surface. When turtles were sighted, the date, time, and the number of organisms were recorded, and the geographic position was obtained using a geolocating device (Garmin GPSmap 76cs).

Whenever a sea turtle was sighted, we approached it to identify the species considering its color pattern, relative size, and morphological features of the head using the Pritchard & Mortimer (2000) guidelines. In addition, by being close to the turtle, it was possible to check if its carapace was dry (by appreciating a light brown opaque coloration), which would make it easier to capture the turtle because it could not be submerged quickly. One crew member leaned overboard, captured the turtle by the front flipper joints, and brought it onboard. The head was immediately covered with a wet cloth to minimize stress. Immediately after capture, nine biometric measurements were obtained using a 3 m (± 0.5 cm) flexible measuring tape. After obtaining the biometrics, a digital photograph was taken with a Canon EOS 60D camera to confirm the species (Fig. 2; Pritchard & Mortimer 2000) and then carefully released into the water.

Three oceanic surveys were conducted aboard the research ship BIP XII (24.3 m length and 6.3 m draft) and the MaryChuy III private yacht (10.6 m length and 4.3 m draft), from 1) February 27 to March 7, 2012, 2) June 25 to July 3, 2012, and 3) June 17-23, 2013, a period that totalized a research effort of 1714 km. During these trips, three main observers and one independent searched for sea turtles on the water surface using Fujinon 7×50 binoculars. When an important aggregation was observed, i.e. over 15 individuals recorded in less than 15 min, CEUNIVO I, a smaller (4.8 m) boat with an outboard motor (Mercury 30 hp), was used to approach the turtles and proceed as described above to measure the individuals. The biometric measurements considered in this study were described by Bolten (1999) and are summarized in Table 1. According to Vega & Robles (2005) and Del Campo-Flores (2014), the size of adults' female olive ridleys is 60 cm of curved carapace length (CCL); thus, for our study, individuals with a CCL equal to or greater than 60 cm were considered adults, and individuals of less than 60 cm were considered immature (juveniles and subadults). The tail length was used to help identify the sex externally; males show a longer tail, which exceeds the posterior fin size (Márquez 1996, Eckert et al. 1999, Chacon et al. 2008, Pérez & Alegría 2009).

Desk work: the maximum, minimum, average, and biometric measurements standard deviation were calculated. The distribution and variation of biometric data were analyzed using Kolmogorov-Smirnov's (Z) and Kruskal-Wallis (H) tests (D) (Steel & Torrie 1980)

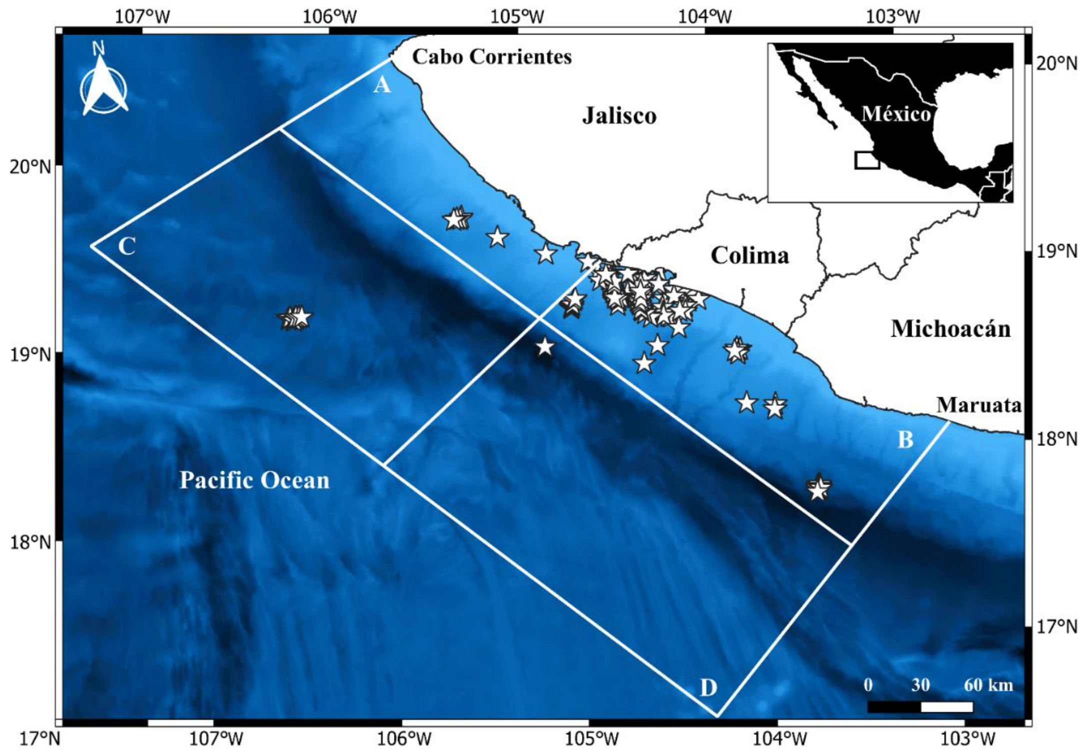

Figure 1. The geographic location of olive ridley sea turtles (*Lepidochelys olivacea*) (white stars) captured in the Mexican Central Pacific. Quadrants: A: Jalisco-coastal, B: Colima/Michoacán-coastal, C: Jalisco-oceanic, D: Colima/Michoacán-oceanic. The 4000 m isobath was considered a division between coastal and oceanic areas.

to compare between sexes, size classes, marine areas (coastal and oceanic), and geographic regions (Jalisco and Colima-Michoacan). All statistical evaluations were performed at a 0.05 significance level using Statistica v.8.0. Allometric measurements respond to Huxley's (1924) general equation: $y = b\,x^{\alpha}$, where y is the magnitude of the studied variable whose growth is considered concerning variable x, usually body total length, and b and ∞ are parametric constants. We obtained logarithms for both sides of the equation: log y = log b + α log x. With this linear equation, when $b = 1$ growth is isometric; when $b > 1$ growth is positive allometric; and when $b < 1$ growth is negative allometric (e.g. a study on blue whale morphometry, Ortega-Ortiz et al. 2018). Allometric relationships were compared by grouping data by sex, size class, marine area, and geographic region.

A total of 142 olive ridley individuals were captured and measured. The total of 3469 km surveyed came from oceanic surveys (1714 km) and coastal surveys (1755 km). Most olive ridley turtles were captured in the coastal area (89.44%) in the Colima-Michoacán region (87.94%) (Fig. 1).

The 142 sampled turtles had a mean CCL of 62.12 cm (range: 42-94 cm, Table 1, Fig. 3). Of these turtles, 36.62% were males, 33.10% were females, 30.28% were immatures (juveniles and subadults) of unknown sex. Male size (64.99 cm CCL, range: 60-90 cm) was similar to that of females (64.66 cm CCL, range: 60-94 cm) (D = 0.0749, $P > 0.05$; Fig. 3). However, the biometric measurements total tail length (TTL), vent to tail tip length (VTTL), curved plastron length (CPL) and rear flipper length (RFL) were significantly different between males and females. Males and females were significantly larger than immatures (56.28 cm CCL, range: 42-59 cm) ($H_{2,142} = 89.74862$, $P < 0.001$; Fig. 3); and biometric measurements of curved carapace width (CCW), front flipper length (FFL), and circumference (CIRCUM) were also significantly different between adults of known sex and immatures (Table 1). The RFL biometric measurement differed significantly between the three groups, being larger in females (38.62 cm) ($H_{2,141} = 42.17908$, $P < 0.001$, and D = 0.2962).

The 127 olive ridley turtles captured in the coastal area were significantly larger (CCL = 62.62 cm, CCW = 66.67 cm) than the 15 turtles sampled from the oceanic area (CCL = 58.69 cm, CCW = 58.63 cm) (D = 0.40, $P < 0.05$; $H_{1,142} = 5.61$, $P = 0.02$, and D = 0.71, $P < 0.05$; $H_{1,142} = 23.44$, $P < 0.001$). The remaining

Table 1. Biometric measurements (average ± standard deviation, and range all in cm) of olive ridley sea turtles (*Lepidochelys olivacea*) captured in the Mexican Central Pacific, by sex and size class (immatures = CCL < 60 cm, Vega & Robles 2005, Del Campo-Flores 2014). CCL: total curved carapace length, CCW: curved carapace width, HW: head width, FFL: front flipper length, RFL: rear flipper length, TTL: total tail length, VTTL: vent to tail tip length, CPL: curved plastron length, CIRCUM: circumference.

	CCL	CCW	HW	FFL	RFL	TTL	VTTL	CPL	CIRCUM
Males	64.99 ± 4.47 60-90 n = 52	67.79 ± 3.12 59.8-76.5 n = 52	12.98 ± 2.36 10-20.3 n = 52	40.16 ± 3.07 35-47.5 n = 52	28.17 ± 3.45 22-38 n = 52	26.33 ± 4.78 15.4-34 n = 52	6.38 ± 1.16 4-9.5 n = 52	45.72 ± 1.72 42-50 n = 52	124.27 ± 5.66 107.5-142.5 n = 52
Females	64.66 ± 5.01 60-94 n = 47	67.95 ± 4.63 53.5-76 n = 47	12.32 ± 2.41 8-22 n = 47	38.62 ± 3.20 29-47 n = 47	29.63 ± 3.42 23-39.2 n = 47	12.40 ± 3.44 5.5-20.5 n = 47	3.86 ± 0.88 1.8-6 n = 47	47.63 ± 2.27 42-52.5 n = 47	125.13 ± 18.89 101-134.5 n = 46
Immatures	56.28 ± 3.24 42-59.5 n = 43	61.11 ± 4.46 48-72.4 n = 43	11.50 ± 2.48 8.5-23.6 n = 41	35.16 ± 3.77) 27-48.5 n = 42	23.80 ± 3.95 13.8-33.7 n = 42	12.51 ± 4.59 6-25.5 n = 42	3.62 ± 1.15 1.5-6 n = 41	41.63 ± 2.99 32.5-49.5 n = 43	114.89 ± 9.32 86.5-147 n = 41

biometric measurements did not differ between turtles captured in the two areas (Table 2). Turtles sampled in Jalisco (n = 18) measured on average 60.47 cm for CCL, 60.56 cm for CCW and 11.38 cm for TTL, whereas the ones sampled at Colima-Michoacán (n = 124) were larger, measuring on average 62.46 cm for CCL, 66.58 cm for CCW and 18.48 cm for TTL ($D = 0.55$, $P < 0.05$; $H_{1,142} = 19.16$, $P < 0.001$ and $D = 0.52$, $P < 0.05$; $H_{1,142} = 16.24$, $P < 0.001$) (Table 2).

The relationship between five biometric measurements and CCL showed negative allometric growth, whereas the relationship between the remaining three biometric measurements and CCL showed positive allometric growth, i.e. a development rate faster than CCL. These measurements were RFL ($b = 1.0978$, $r^2 = 0.3548$), TTL ($b = 2.1026$, $r^2 = 0.1645$), and VTTL ($b = 1.7248$, $r^2 = 0.1876$) (Fig. 4). When data were grouped by sex, size class, marine area, and region, similar results were found.

For this study, random surveys were conducted in different marine areas and geographic regions, providing a wide and diverse sample that included males, females, and immature in similar proportions. Therefore, these morphological comparisons are considered more representative of the species than those obtained using only nesting beaches as sampling areas, the most common means of sea turtle studies (Bjorndal 1999).

Whereas the CCL reported in this study represented adults of both sexes and immatures, providing a better representativity of the size classes making up the population. The average CCL of olive ridley turtles in the MCP (62.12 cm) was lower than those reported in studies carried out on adult females at nesting beaches of the Mexican Pacific (64.3 cm, Márquez et al. 1976; 67.6 cm, Torres 2002). The range of CCL reported in this study was wider than expected (Fig. 3), with the lower limit given by an immature individual (42 cm) and the upper limit by a mature female (94 cm; Fig. 2) being the largest reported for this species. However, previous studies on different olive ridley populations worldwide also reported large CCLs of up to 65-82 cm (Arciniegas 1988, Whiting et al. 2007, Rosales et al. 2010, Vera & Rosales 2012, Karam-Martínez et al. 2017). Future genetic analysis could elucidate whether these individuals with unusually large CCL were hybrids.

TTL is the body portion generally used to differentiate visually between sexes in sea turtles (Márquez 1996, Eckert et al. 1999, Chacon et al. 2008, PNLC 2008, Pérez & Alegría 2009). Morphological differences were reported between males and females for TTL and VTTL measurements, as the adult male tail

Table 2. Biometric measurements (average ± standard deviation, and range all in cm) of olive ridley sea turtles (*Lepidochelys olivacea*) captured in coastal and oceanic areas in Jalisco and Colima-Michoacán. CCL: total curved carapace length, CCW: curved carapace width, HW: head width, FFL: front flipper length, RFL: rear flipper length, TTL: total tail length, VTTL: vent to tail tip length, CPL: curved plastron length, CIRCUM: circumference.

	CCL	CCW	HW	FFL	RFL	TTL	VTTL	CPL	CIRCUM
Coastal	62.27 ± 5.70 50.3-94 n = 127	66.67 ± 4.41 53.5-76.5 n = 126	12.40 ± 2.55 8-23.6 n = 125	38.32 ± 3.88 27-48.5 n = 126	27.64 ± 4.07 17-39.2 n = 126	18.43 ± 7.90 5.5-34 n = 126	4.87 ± 1.69 1.5-9.5 n = 125	45.30 ± 3.25 37-52.5 n = 127	122.22 ± 7.62 100.1-147 n = 125
Oceanic	58.69 ± 5.70 42-66.5 n = 15	58.63 ± 5.17 48-67 n = 15	11.67 ± 1.75 9-16 n = 15	36.77 ± 3.95 29-44 n = 15	24.94 ± 5.45) 13.8-36 n = 15	10.33 ± 3.62 6-19 n = 15	3.56 ± 0.63 2.5-4.5 n = 14	43.58 ± 3.94 32.5-48.5 n = 15	117.91 ± 31.57 86.5-134.5 n = 14
Jalisco	60.47 ± 4.24 53-68 n = 18	60.56 ± 4.99 52.3-72 n = 18	11.35 ± 1.30 9.5-14 n = 17	39.04 ± 3.72 32.7-48.5 n = 18	27.58 ± 4.98 13.8-38 n = 18	11.38 ± 6.05 6-33 n = 18	4.07 ± 1.66 2.5-9.5 n = 17	44.18 ± 3.02 37-49 n = 18	121.34 ± 28.78 109-134.5 n = 17
Colima-Michoacán	62.46 ± 5.98 42-94 n = 124	66.58 ± 4.68 48-76.5 n = 124	12.46 ± 2.58 8-23.6 n = 123	38.03 ± 3.93 27-47.5 n = 123	27.32 ± 4.21 17-39.2 n = 123	18.48 ± 7.80 5.5-34 n = 123	4.82 ± 1.64 1.5-9 n = 123	45.25 ± 3.40 32.5-52.5 n = 124	121.85 ± 8.32 86.5-147 n = 122

Figure 2. A female olive ridley sea turtle (*Lepidochelys olivacea*), whose curved carapace length was 94 cm, was sampled on the coast of Colima on January 19, 2012.

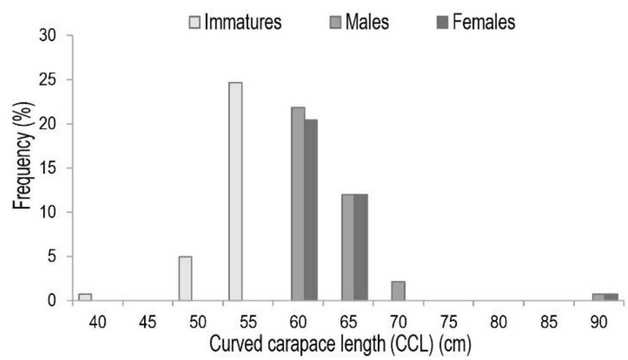

Figure 3. Curved carapace length of 142 olive ridley sea turtles (*Lepidochelys olivacea*), separated by sex and age class, captured in the Mexican Central Pacific during the period of study.

was considerably longer than those for females. No differences in CCL were observed between sexes, a result that is contrasting with smaller females probably associated with egg production because when females are larger, egg production decreases, probably due to restricted three-dimensional volume (Girard et al. 2021).

Significant morphological differences between size classes were detected based on three biometric measurements: CCW, CIRCUM, and FFL. Adults presented longer FFL, considered their main propulsion system. Their size could be related to swimming efficiency in the adult stages, as water mass displaced and swim speed are directly proportional to flipper size (Blake 1983). The RFL biometric measurement pointed out significant differences between size class categories; females had larger rear flippers compared with adult males and immatures; this could be associated

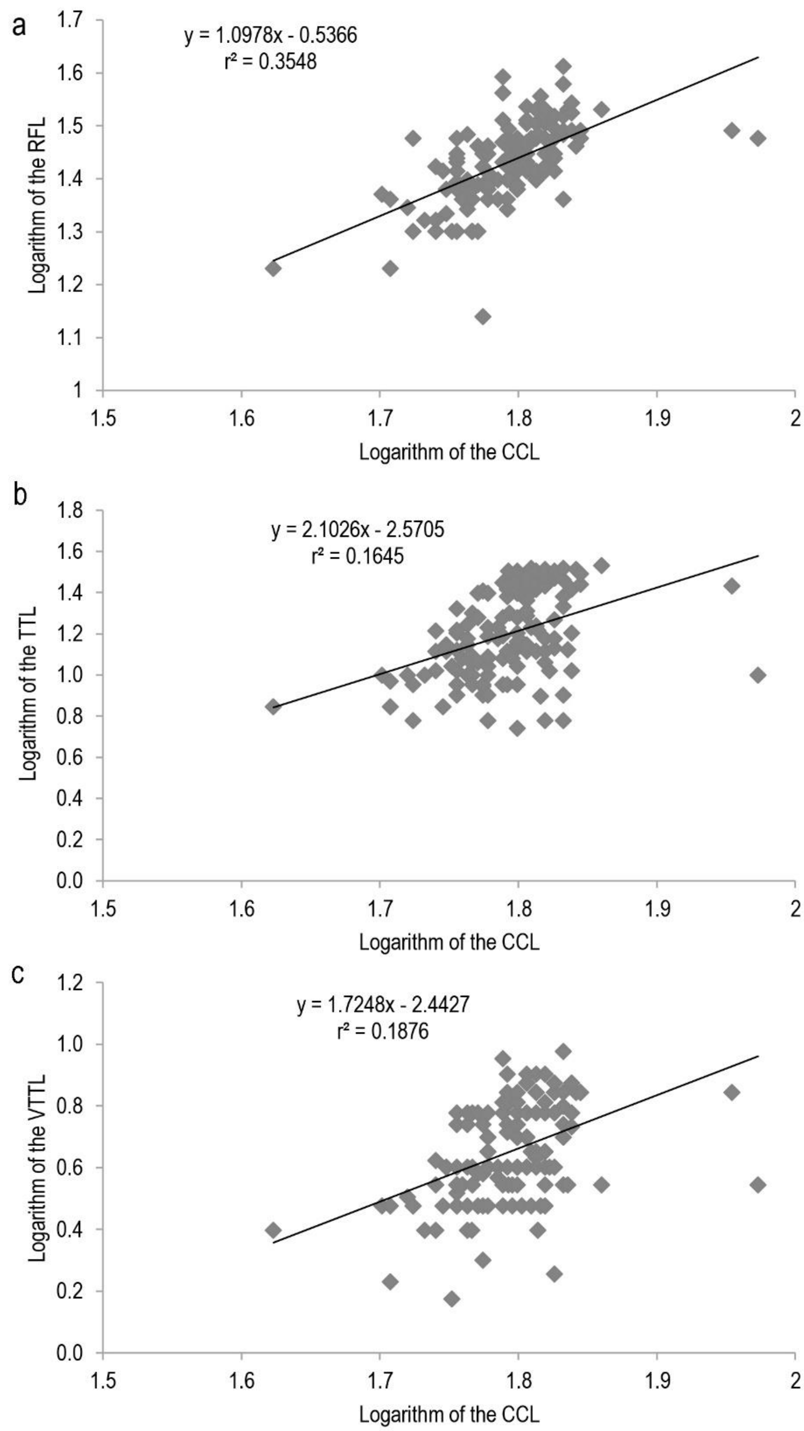

Figure 4. Allometric relationships of the a) rear flipper length (RFL), b) total tail length (TTL), and c) vent to tail tip length (VTTL) relative to the curved carapace length (CCL) of 142 olive ridley sea turtles (*Lepidochelys olivacea*) captured in the Mexican Central Pacific.

with the physical requirements of this sex for digging and covering the nest during egg-laying (Chacon et al. 2008).

More olive ridley turtles were captured in the coastal area and Colima-Michoacán than in the oceanic area and Jalisco, which could be related to differences in sampling effort conducted among areas because a slightly greater effort was made in the coastal zone of Colima since the port of departure and arrival was located there; in addition, to a major abundance of mature individuals in Colima-Michoacán coasts due to their reproductive habits during summer and fall seasons (Márquez 1996, CONANP 2008). Individuals in the coastal area had larger and wider carapaces than those from the oceanic region (Table 2), suggesting that the large individuals are likely mature (including CCL and whether it was both sexes or not), and their presence near the coast is associated with reproductive activities, that is, for mating and egg-laying purposes (Márquez 1996). Furthermore, probably a greater number of individuals may be more marked towards the south of the study region, where the nesting beach of Ixtapilla, Michoacán, is located and where "arribada" events occur (massive arrival of females to nest in a synchronized manner) (CONANP 2008). In contrast, immature individuals are probably distributed in oceanic areas associated with oceanographic events of the MCP that could provide optimal conditions to access food resources (Zepeda-Borja et al. 2017).

Of the eight biometric measurements used to describe the growth of body parts compared with CCL growth in olive ridley turtles captured in MCP waters, three measurements, TTL, VTTL, and RFL, had a positive allometric relationship with the CCL, i.e. the tail and rear flippers grew at a faster rate than the carapace (Fig. 4).

The allometric analyses showed that TTL and VTTL had an accelerated growth rate in males, resulting in a long tail, which has been used as a visual identification tool to discriminate adult males (Márquez 1996, Eckert et al. 1999, Chacon et al. 2008, Pérez & Alegría 2009). However, the RFL measure also showed accelerated growth in adult females, confirming the previously described result of larger rear flipper size in females compared to males or immatures (Chacon et al. 2008). The accelerated growth of the RFL in olive ridley turtles described in this study contrasts with the accelerated growth of the head in the black caiman (*Melanosuchus niger*), which was explained as a process that makes predation more efficient in this reptile (Monteiro 1997). Several morphological studies on fish, birds, and reptiles have shown a significant relationship between morphology and some aspects of the ecology of organisms, such as diet, foraging behavior, and locomotion (Ricklefs & Miles 1994). However, olive ridley turtles are potentially related to reproduction, particularly in the digging and nest-covering process (Godínez-Domínguez 1988, Chacon et al. 2008).

Our study assessed the morphological differences in the olive ridley turtles sampled in the MCP waters possibly related to ontogenic differences and habitats, among other factors. Future studies should be carried out to investigate possible correlations between morphometric-allometric aspects concerning other biological information (e.g. genetic tracers) to increase ecological knowledge about the species and its populations.

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