



High site fidelity, slow growth, and compromised physiological condition in the Rapa Nui green turtle aggregation

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ABSTRACT: Despite the ecological and cultural importance of green turtles *Chelonia mydas* across Oceania, knowledge of their demography, population trends, physiological condition, and anthropogenic pressures at foraging habitats remains limited. Rapa Nui (Easter Island), located at the eastern edge of the Polynesian Triangle, represents a key biogeographical link connecting South American and Polynesian green turtle populations. Here, we evaluated the demographic structure, residency patterns, somatic growth, body condition, and physiological status of green turtles inhabiting Rapa Nui during surveys conducted in 2018, 2023, and 2024. Using photo-identification, morphometric measurements, and hematological and biochemical analyses, we provide an integrated assessment of this isolated neritic aggregation. The aggregation was dominated by juvenile yellow-morphotype turtles, which exhibited exceptionally high site fidelity, unusually slow somatic growth, and relatively high body condition compared with turtles from other foraging aggregations across Oceania. Significant interannual variation was detected in multiple hematological and biochemical parameters, yet recurrent physiological alterations, including disrupted erythropoiesis, leukocyte imbalance, and biochemical evidence of subclinical hepatic and renal dysfunction, persisted across sampling periods, indicating a persistent pattern of compromised physiological condition. Together with previous clinical and toxicological evidence, these findings suggest that resident turtles are exposed to persistent local environmental and anthropogenic stressors. Our results identify Rapa Nui as a biologically important foraging ground supporting a physiologically compromised green turtle aggregation and emphasize the need for integrated conservation strategies that combine physiological, demographic, and ecological information to safeguard a species of profound cultural and spiritual importance to many Pacific Island communities.

KEY WORDS: *Chelonia mydas* · Demographic structure · Health assessment · Morphotypes · Easter Island · Oceania

1. INTRODUCTION

Marine turtles in Oceania have been exploited for centuries and hold profound cultural, traditional, and spiritual significance for Indigenous Pacific communities (Maison et al. 2010, Álvarez-Varas et al. 2020). Their conservation is therefore essential not only for species persistence but also for safeguarding cultural practices and ancestral knowledge across the region.

Five marine turtle species occur in Oceania, including the green turtle *Chelonia mydas*, which is widely distributed across the Pacific, with nesting populations on numerous islands and atolls of the Western and Central Pacific (Maison et al. 2010, Becker et al. 2019). Although *C. mydas* was listed as Endangered for several decades (and only recently reclassified globally as Least Concern by the IUCN), the species has received uneven levels of protection under national legislation and international agreements across Oceania (Maison et al. 2010). Despite its broad regional distribution, information on stock structure, abundance, and long-term population trends remains limited, and research has largely focused on nesting sites, with comparatively little information available from foraging habitats, where individuals spend most of their lifespan (Maison et al. 2010, Sterling et al. 2013, Becker et al. 2019).

Rapa Nui (Easter Island), located at the eastern edge of the Polynesian Triangle, constitutes an important neritic foraging habitat for *C. mydas*, the most frequently observed marine turtle species around the island (Álvarez-Varas et al. 2015). By hosting both recognized Pacific genetic lineages or morphotypes (the black and yellow turtles), Rapa Nui acts as a key biogeographical link between South American and Polynesian populations across the South Pacific (Álvarez-Varas et al. 2022).

C. mydas has a complex life cycle and shows varying degrees of site fidelity to both nesting and foraging areas across its global range (Seminoff et al. 2021). Within Oceania, evidence from some locations reveals strong site fidelity to foraging grounds; for instance, individuals in the Northern Mariana Islands have remained associated with the same site for up to 17 yr (Summers et al. 2017). Across this region, demographic structure varies markedly among locations, with some foraging areas dominated by juveniles (Argument et al. 2009, McFadden et al. 2014, Summers et al. 2017, Read et al. 2020) and others by adults (Grant et al. 1997). Pelagic juveniles recruit to neritic habitats at approximately 25–45 cm straight carapace length (SCL) and display foraging-ground-specific growth rates, with growth trajectories varying among

sizes and ages (Balazs & Chaloupka 2004, Chaloupka et al. 2004, Prakash & Piovano 2020, Álvarez-Varas et al. 2025).

Most health studies of green turtles at foraging habitats in Oceania have focused on Australia and Hawaii, primarily addressing anthropogenic contaminants and fibropapillomatosis (Aguirre et al. 1995, Aguirre & Balazs 2000, Hamann et al. 2006, Flint et al. 2019, Kophamel et al. 2022). Elsewhere, evaluations of overall health are limited and reveal pronounced spatial heterogeneity. For example, green turtles at Palmyra Atoll appear markedly healthy based on body condition, hematological and plasma biochemistry profiles, and contaminant levels (Sterling et al. 2013, McFadden et al. 2014), whereas studies conducted in Rapa Nui have reported poor body condition and significant mercury–blood analyte associations, suggesting compromised health in this Polynesian aggregation (Álvarez-Varas et al. 2025).

Given its extreme geographic isolation and regional ecological context, Rapa Nui provides a unique natural setting to investigate the demography, growth, and temporal variation in the physiological condition of *C. mydas* at a neritic foraging ground. Here, we assessed demographic structure, residency, somatic growth, body condition, and physiological status of this aggregation across 3 study years (2018, 2023, and 2024) using photo-identification, morphometrics, and blood count and chemistry analyses. This study provides a baseline for long-term monitoring, supports locally and regionally informed conservation strategies, and contributes to the protection of the cultural and spiritual heritage associated with marine turtles in Pacific Island coastal communities.

2. MATERIALS AND METHODS

2.1. Study area and turtle capture

This study was conducted in the bays of Hanga Roa (27° 99' S, 109° 269' W) and Hanga Piko (27° 91' S, 109° 46' W), on the southwestern coast of Rapa Nui, located at the eastern corner of the Polynesian Triangle (Fig. 1). Manual turtle captures were conducted by trained local divers during 3 field campaigns (November 2018, August 2023, and August 2024). Individual identification was based on photo-identification, and biometric measurements, body mass, and blood samples were collected for each turtle. Fieldwork was authorized by the Chilean Undersecretariat for Fisheries and Aquaculture under

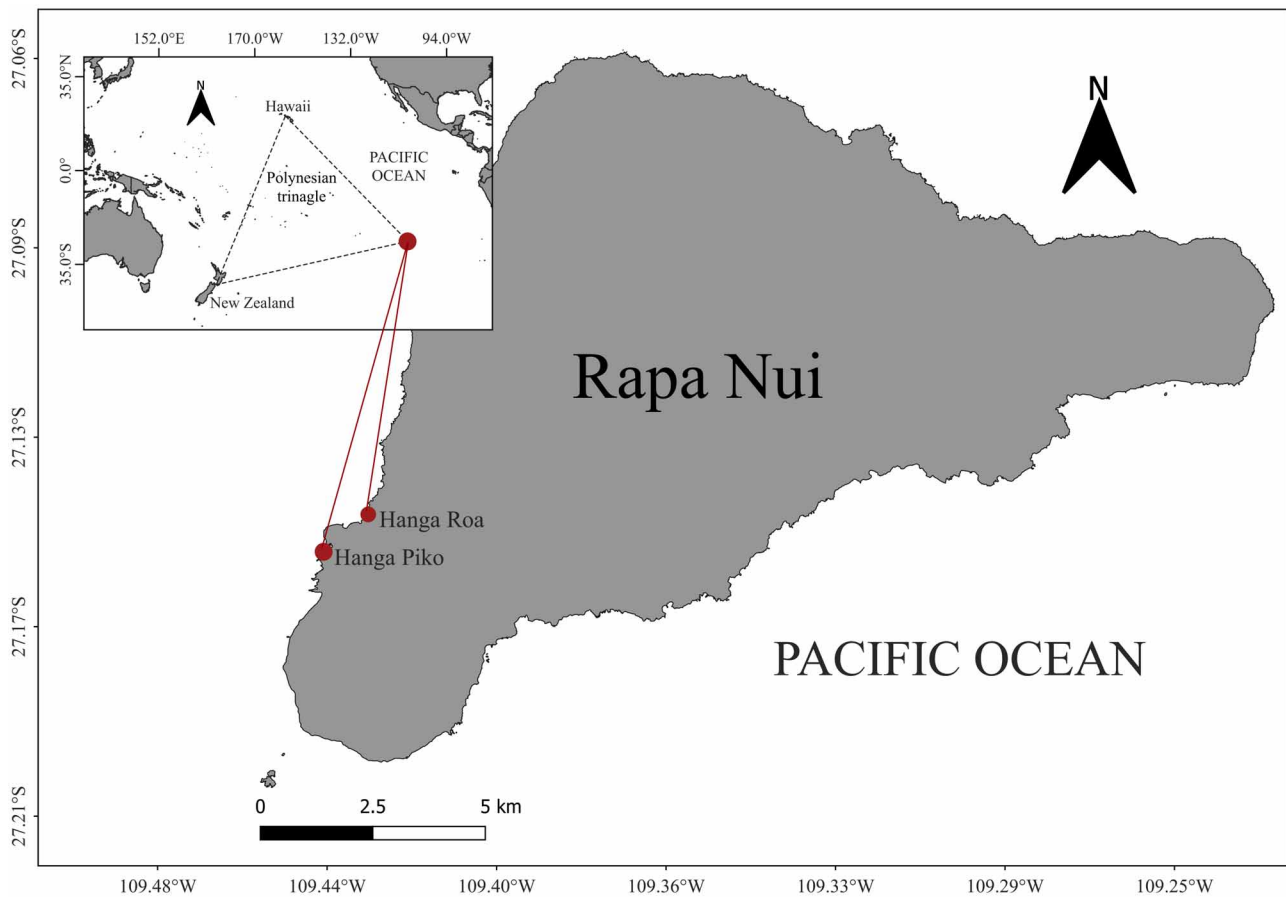


Fig. 1. Study area, showing Hanga Roa and Hanga Piko bays on the southwestern coast of Rapa Nui (Easter Island), Chile. Inset: location of Rapa Nui in the southeastern Pacific Ocean, at the eastern vertex of the Polynesian Triangle

Research Capture Permits (Exempt Resolution Nos. 3755 and E-2023-492), with additional approvals from the Koro Nui o Te Vaikava and the fishermen's unions of Hanga Roa and Hanga Piko. Ethical approval was granted by the Universidad Católica del Norte Scientific Ethics Committee (CEC UCN No. 15, 2021).

2.2. Photo-identification

Photographs from each sampled year (one photograph per turtle captured each year) of the left side of the head were analyzed in parallel using 2 software-assisted methods for individual identification: Wild-ID and I³S. Wild-ID (v.1.0) (Bolger et al. 2011) applies the scale-invariant feature transform (SIFT) algorithm to compare geometric features extracted from images, enabling robust matching despite differences in scale or rotation (Lowe 2004). The second, I³S (v.4.0.2) (den Hartog & Reijns 2014), uses an automatic key-point extraction algorithm to generate a mathematical fingerprint from natural body fea-

tures such as the eye, snout, and postocular scales (3 points). Both software programs produce paired comparisons of photographs and generate a ranked list of potential matches, which were then confirmed blindly and independently by 2 observers (E.A. for Wild-ID and C.B. for I³S). Confirmed matches obtained by both software programs were subsequently compared jointly by the observers, and the final list of recaptures was compiled as follows: if there was consensus between both software programs (i.e. both agreed that a pair of photographs was a match), the match was regarded as a recapture (i.e. the photographs belonged to the same individual). If there was disagreement between the software programs (i.e. one identified a pair of photographs as a match while the other did not), a final visual assessment was conducted to determine whether the photographs represented a recapture (Bardier et al. 2020). Recapture rate was calculated as the proportion of confirmed recaptures (n) relative to the total number of capture events (N), following Bardier et al. (2020) and (Buteler et al. 2022).

2.3. Morphotype, life stage, sexing, and BCI estimation

Rapa Nui harbors 2 distinct genetic lineages of *Che-*lonia mydas**: the north-central–eastern Pacific (black morphotype) and the south-central–western Pacific (yellow morphotype), which differ in morphology and evolutionary history (Álvarez-Varas et al. 2025). Morphotypes were identified based on external characteristics, including carapace shape and pigmentation of the carapace and plastron, following Álvarez-Varas et al. (2022).

For each individual, SCL, curved carapace length (CCL), and total tail length (TTL) were measured following Bolten (1999), using calipers or flexible tape as appropriate, and body mass was recorded with a digital scale (± 0.1 kg). Life stage was assigned using a threshold of 85 cm CCL, corresponding to the average size of nesting females at the natal rookeries of each morphotype (Galápagos for black turtles and French Polynesia for yellow turtles), with individuals < 85 cm classified as juveniles and ≥ 85 cm as adults (Zárate et al. 2013, Álvarez-Varas et al. 2022, 2025, Dolfo et al. 2023). Individuals with $TTL \geq 25$ cm were classified as males (McFadden et al. 2014, Álvarez-Varas et al. 2022, 2025). Body condition was assessed using the body condition index [$BCI = (\text{body mass} / \text{SCL}^3) \times 10\,000$], which provides an indirect proxy of nutritional status (Bjørndal et al. 2000, Álvarez-Varas et al. 2025).

2.4. Growth rates

Turtle growth was assessed from changes in SCL between capture events. Absolute growth rate (GR) was calculated as: $(LR - LC) / t$, where LR is SCL at recapture, LC at initial capture, and t is the time elapsed between events (van Dam 1999). Growth estimates were grouped into 10 cm size classes based on midlength $([LC + LR] / 2)$; Limpus & Chaloupka 1997). For individuals with multiple recaptures, only the first and last measurements were used (Summers et al. 2017).

2.5. Blood count and chemistry analyses

Blood samples were obtained from the dorsal cervical sinus. For hematological analyses, 4 ml of blood was collected into sodium heparinized tubes and maintained at 4°C. Complete blood counts were performed manually. Packed cell volume (PCV%) was deter-

mined by microhematocrit centrifugation (5000 rpm, ca. $1390 \times g$; 5 min), hemoglobin concentration [HB] was measured using an automated hematology analyzer (Mindray BC-2800 VET), and red and white blood cell counts [RBC, WBC] were conducted using a modified Neubauer hemocytometer with Natt and Herrick diluent. Erythrocyte indices (mean corpuscular volume [MCV], mean corpuscular hemoglobin [MCH], and mean corpuscular hemoglobin concentration [MCHC]) were calculated following Latimer (2011). Differential leukocyte counts (heterophils, lymphocytes, eosinophils, basophils, monocytes, and azurophils) and thrombocyte counts were determined from blood smears based on 100-cell counts (Álvarez-Varas et al. 2025).

For serum biochemistry, 4 ml of blood was collected into tubes without anticoagulant. Within 12 h of collection, 2 ml was centrifuged (5000 rpm, ca. $1390 \times g$; 5 min), and serum was stored at -20°C until analysis. Biochemical parameters (alanine aminotransferase [ALT], alkaline phosphatase [ALP], aspartate aminotransferase [AST], calcium [CA], cholesterol [CHOL], creatine phosphokinase [CPK], creatinine [CREA], gamma-glutamyl transferase [GGT], phosphorus [PHOS], total protein [TP], blood urea nitrogen [BUN], uric acid [URIC AC], albumin [ALB], globulin [GLOB], and UREA) were quantified using a wet chemistry analyzer (Mindray BS-200) according to manufacturer protocols and quality control standards. All analyses were conducted at the Laboratorio Clínico Veterinario of the Universidad de O'Higgins, Chile.

2.6. Statistical analysis

Means, SD, and ranges were calculated for morphological variables, BCI, growth rates, and hematological parameters. Normality was evaluated using the Shapiro-Wilk test, and homogeneity of variances was determined with Levene's test. Differences in SCL between morphotypes were assessed using Mann-Whitney U -tests due to non-normal distributions. Variation in BCI across morphotypes and life stages was analyzed using two-way ANOVA, followed by Tukey's HSD post hoc comparisons. Model assumptions were verified through inspection of residual distributions and variance homogeneity. Differences in BCI and SCL between sexes were not examined due to limited sample sizes (females, $n = 5$; males, $n = 2$). Results were visualized using boxplots produced with 'ggplot2' in R (v.4.3.1) (R Core Team 2023).

Differences in growth rates among 10 cm SCL size classes were evaluated using Kruskal-Wallis tests be-

cause assumptions of normality were not met. When significant, pairwise comparisons were conducted using Dunn's tests with Bonferroni correction.

Hematological data were collected only in 2023 and 2024. Interannual differences were initially evaluated across 27 parameters, including morphometric (SCL and BCI), hematological, and biochemical variables. Depending on the distribution of each variable, differences between years were evaluated using either Welch's *t*-tests or Mann-Whitney *U*-tests. Given that substantial collinearity was expected among blood parameters, a subsequent variable-reduction procedure was implemented prior to association analyses. Multicollinearity was assessed using the variance inflation factor (VIF), following Zuur et al. (2010). Variables with VIF > 10 were first excluded. A linear model was then fitted with the remaining predictors, VIF values recalculated, and variables with VIF > 5 subsequently removed (Liu et al. 2025). This process yielded a subset of 14 biologically interpretable and non-redundant predictors (HB, MCHC, leukocytes, lymphocytes, eosinophils, monocytes, AST, ALT, ALP, CHOL, CA, PHOS, CPK, and SCL). Interpretation of interannual differences focused on this reduced set. Finally, to explore relationships among physiological variables and body condition, Spearman's rank correlation coefficients (ρ) and associated *p*-values were calculated using 'cor.test' in R (v.4.3.1) (R Core Team 2023), given that most variables deviated from normality. Results were visualized using heatmaps produced with 'ggplot2'. All analyses were conducted in R (v.4.3.1) (R Core Team 2023). Given the substantial imbalance in sample sizes among categories, comparisons of hematological variables among morphotypes, life stages, and sexes were not performed. Similarly, growth-rate differences among these categories were not evaluated.

3. RESULTS

3.1. Morphotype, life stage, sexing and BCI

From 80 capture events, photo-identification identified 51 unique green turtles *Chelonia mydas*, of which 84.31% ($n = 43$) were the yellow morphotype and 15.69% ($n = 8$) were the black morphotype (Fig. 2). Most individuals were juveniles (86.27%, $n = 44$), while adults accounted for 13.73% ($n = 7$), of which 71.43% ($n = 5$) were females and 28.57% ($n = 2$) males. Annual distributions by morphotype, life stage, and sex are summarized in Table 1.

Of the 51 identified individuals, 28 were captured once, 17 were captured in 2 different years, and 6

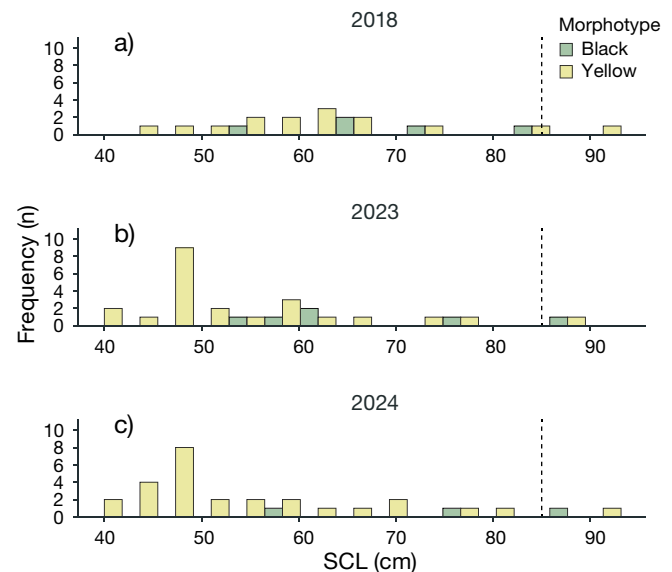


Fig. 2. Straight carapace length (SCL) in *Chelonia mydas* from Rapa Nui by morphotype in (a) 2018 ($n = 20$), (b) 2023 ($n = 30$), and (c) 2024 ($n = 30$). Dashed line: estimated size at sexual maturity (85 cm SCL; Álvarez-Varas et al. 2022)

were captured across all 3 study years. Based on the 23 recaptures (individuals captured 2 and 3 times), the overall recapture rate was 45.1% (0.451). Most recaptured turtles were yellow turtles ($n = 21$) and juveniles ($n = 18$). Five adults were recaptured, including 3 females (2 yellow and 1 black morphotype) and 2 males (one of each morphotype).

Across study years (2018, 2023, and 2024), SCL ranged from 40.0 to 91.5 cm, with small juveniles (40–60 cm SCL) comprising most individuals (63%). Mean SCL was 56.29 ± 12.81 cm for the yellow morphotype and 68.55 ± 11.88 cm for the black morphotype. The Mann-Whitney *U*-test revealed a significant difference between the morphotypes ($p = 0.001$), with larger sizes in black turtles (Fig. 2).

BCI ranged from 1.11 to 2.37 (mean: 1.60 ± 0.23 ; $n = 51$). Although higher BCI values were observed in black turtles and adults (Fig. 3), two-way ANOVA showed no significant effects of morphotype ($F_{1,52} = 3.221$, $p = 0.079$), life stage ($F_{1,52} = 0.363$, $p = 0.549$), or their interaction ($F_{1,52} = 3.714$, $p = 0.059$). Tukey's HSD tests confirmed no significant pairwise differences (all $p > 0.05$).

3.2. Growth rates

Growth rates of recaptured turtles ranged from 0.63 to 1.86 cm yr^{-1} (mean: 1.08 cm). Growth differed significantly among 10 cm SCL size classes (Kruskal-Wallis:

Table 1. Morphological variables (SCL: straight carapace length; CCL: curved carapace length), body mass, and body condition index (BCI) of *Chelonia mydas* from Rapa Nui by life stage, sex, and morphotype. Values are presented as mean $\pm$ SD

Life stage, sex	Morphotype	n	SCL (cm)	CCL (cm)	Mass (kg)	BCI
Adult, female	Black	1	86.28	93.07	102.05	1.59
	Yellow	4	83.88 $\pm$ 9.21	94.80 $\pm$ 6.99	93.00 $\pm$ 63.64	1.93 $\pm$ 0.18
	All	5	84.36 $\pm$ 8.05	94.45 $\pm$ 6.10	96.02 $\pm$ 45.30	1.81 $\pm$ 0.23
Adult, male	Black	1	74.90	83.10	73.85	1.83
	Yellow	1	74.50	80.20	83.50	1.91
	All	2	74.70 $\pm$ 0.28	81.65 $\pm$ 2.05	78.68 $\pm$ 6.82	1.87 $\pm$ 0.06
Juvenile, indeterminate	Black	7	59.78 $\pm$ 4.02	69.17 $\pm$ 5.89	40.75 $\pm$ 13.52	1.7 $\pm$ 0.23
	Yellow	37	52.13 $\pm$ 8.24	56.21 $\pm$ 9.46	23.90 $\pm$ 13.83	1.55 $\pm$ 0.23
	All	44	53.20 $\pm$ 8.20	58.06 $\pm$ 10.08	26.12 $\pm$ 14.78	1.57 $\pm$ 0.23
All individuals		51	70.42 $\pm$ 12.84	66.27 $\pm$ 26.77	78.05 $\pm$ 15.13	1.75 $\pm$ 0.24

$\chi^2 = 18$, $df = 3$, $p = 0.0004$), with post hoc tests showing higher growth in the 60–70 cm ($p = 0.047$) and 70–80 cm ($p = 0.001$) classes compared with the 40–50 cm class. The 80–90 cm class was excluded from the analyses due to small sample size ($n = 2$) (Fig. 4).

3.3. Blood count and chemistry analyses

Given that we evaluated wild aggregations of *C. mydas*, blood count and blood chemistry values were compared with those previously reported for the species in Oceania, which were used as reference values. Table S1 in the Supplement at www.int-res.com/articles/suppl/esr01544_suppl.pdf summarizes the hematological parameters obtained from green tur-

tles in Rapa Nui and those reported in published studies from Oceania.

Blood count analyses of green turtles from Rapa Nui ($n = 39$) showed mean PCV values within the reference range reported for the species (Table S1). For RBC, HB, MCHC, MCV, and MCH, comparisons were only possible with values reported for green turtles from Hawaii, the only location in Oceania where these parameters have been described for the species (Aguirre et al. 1995). Compared with Hawaiian turtles, individuals from Rapa Nui exhibited higher RBC, HB, and MCHC values, whereas MCV and MCH values were approximately 2- to 3-fold lower (Table S1). Furthermore, several individuals from Rapa Nui exhibited polychromatophilic erythrocytes, anisocytosis, and poikilocytosis. Circulating azuro-

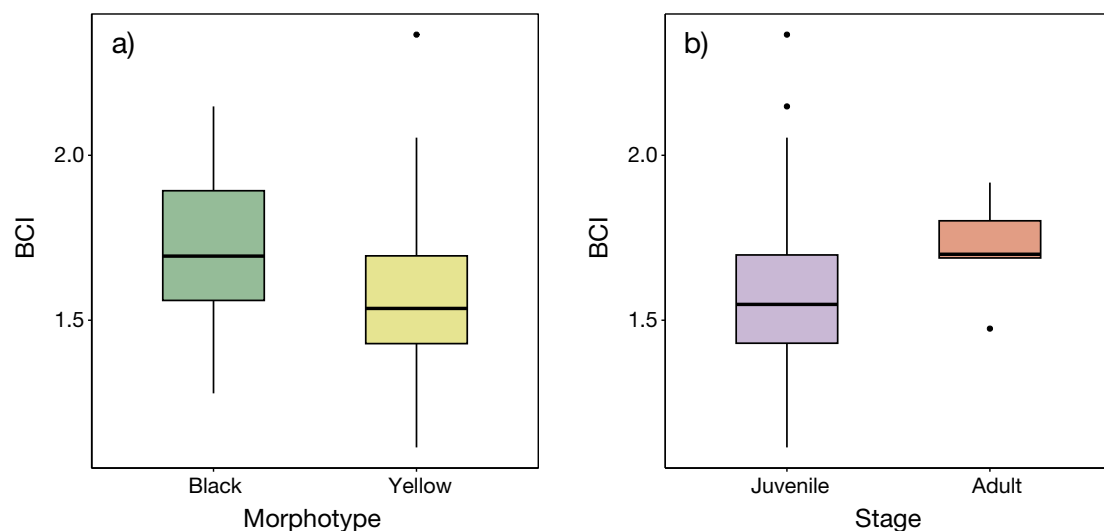


Fig. 3. Body condition index (BCI) in *Chelonia mydas* from Rapa Nui, pooled across the 3 study years (2018, 2023, and 2024) and presented by (a) morphotype and (b) life stage. The y-axis is scaled to the minimum and maximum BCI values observed in the data set. Boxes: interquartile range; horizontal lines: medians; whiskers: extend to the most extreme values within 1.5 $\times$ the interquartile range; black dots: outliers

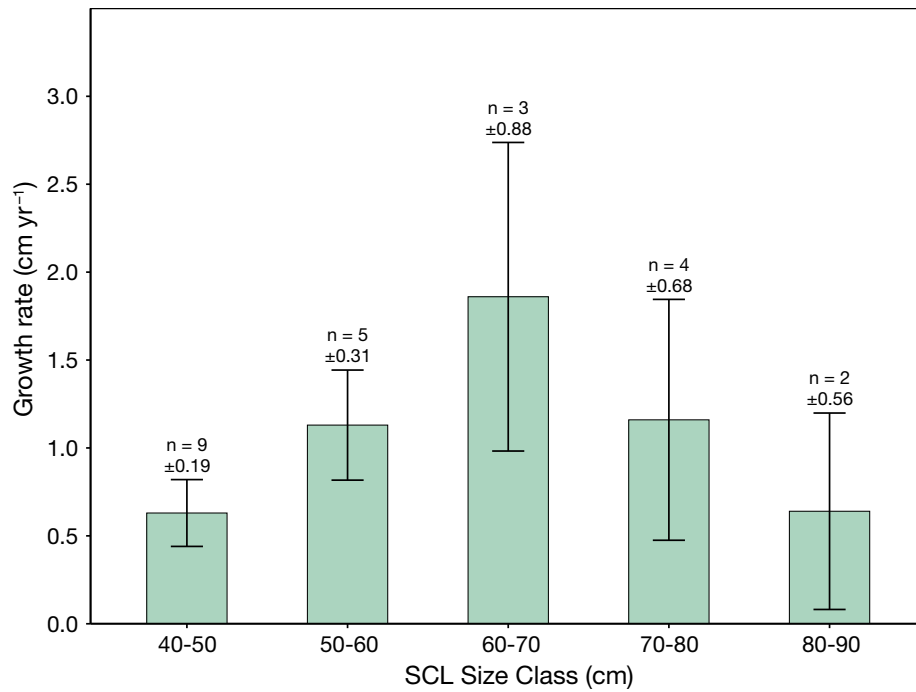


Fig. 4. Mean ($\pm$ SE) somatic growth rates of *Chelonia mydas* from Rapa Nui by 10 cm straight carapace length (SCL) size classes, pooled across the 3 study years (2018, 2023, and 2024). Sample sizes for each size class are indicated above the bars

phils were observed in one individual, whereas toxic heterophils were present in all turtles examined.

Lymphocyte counts were lower than those reported for both healthy and unhealthy green turtles across Oceania (Table S1). Similarly, eosinophil, basophil, and monocyte counts were markedly lower than previously published values, whereas heterophil counts were substantially higher, reaching values up to 5-fold greater than those previously reported for the species (Table S1; Aguirre et al. 1995).

Blood chemistry analyses ($n = 45$) revealed elevated ALT activity and markedly higher BUN and UREA concentrations compared with most published values for *C. mydas* in Oceania (Table S1). By contrast, all other biochemical parameters fell within the ranges previously reported for the species (Table S1).

Welch's *t*-tests detected significant interannual differences (2023–2024) in ALT, PHOS, monocytes, ALB, TP, and PCV% (all $p < 0.05$), whereas Mann-Whitney *U*-tests identified differences in ALP, URIC AC, MCHC, CPK, CA, MCH, BUN, UREA, GGT, basophils, and erythrocytes (all $p < 0.05$). Using variables with low collinearity, Spearman's correlation analyses revealed significant positive associations among multiple biochemical and hematological parameters, including CA–ALT ($r^2 = 0.425$), CA–ALP ($r^2 = 0.541$), CA–HB ($r^2 = 0.322$), ALT–ALP ($r^2 = 0.766$), ALT–PHOS ($r^2 = 0.356$), ALT–

CHOL ($r^2 = 0.357$), ALT–AST ($r^2 = 0.454$), ALP–PHOS ($r^2 = 0.372$), ALP–CHOL ($r^2 = 0.395$), ALP–HB ($r^2 = 0.348$), eosinophils–PHOS ($r^2 = 0.368$), PHOS–CHOL ($r^2 = 0.479$), lymphocytes–leukocytes ($r^2 = 0.549$), lymphocytes–monocytes ($r^2 = 0.407$), lymphocytes–CHOL ($r^2 = 0.319$), leukocytes–monocytes ($r^2 = 0.708$), SCL–CHOL ($r^2 = 0.494$), HB–AST ($r^2 = 0.316$), and MCHC–CPK ($r^2 = 0.361$) (Fig. 5).

Significant negative correlations were detected between CA–leukocytes ($r^2 = -0.373$), ALT–MCHC ($r^2 = -0.355$), ALP–MCHC ($r^2 = -0.346$), PHOS–MCHC ($r^2 = -0.391$), and PHOS–CPK ($r^2 = -0.365$) (Fig. 5).

4. DISCUSSION

This study provides the first integrated assessment of demographic structure, residency patterns, somatic growth, body condition, and physiological status in the Rapa Nui green turtle *Chelonia mydas* aggregation. Our findings reveal a juvenile-dominated aggregation characterized by exceptionally high site fidelity, unusually slow somatic growth despite relatively high body condition, and recurrent hematological and biochemical alterations. Although physiological biomarkers exhibited significant interannual

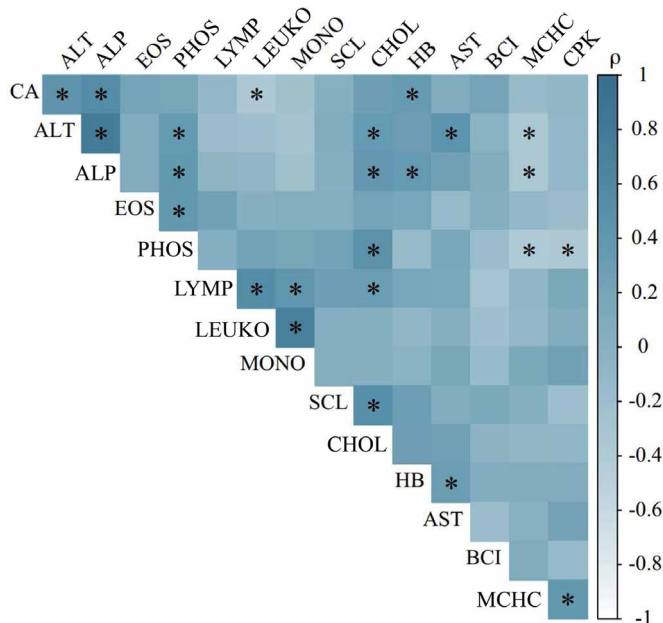


Fig. 5. Heatmap of Spearman's correlation coefficients (ρ) among hematological, blood chemistry, morphometric, and body condition parameters of *Chelonia mydas* from Rapa Nui, based on samples collected in 2023 and 2024. Color intensity ranges from white to blue (darker shades: increasingly positive correlation coefficients). Asterisks indicate significant correlations ($*p < 0.05$)

variability, the integration of these findings with previous clinical and toxicological evidence indicates a persistent pattern of compromised physiological condition. The following sections discuss the ecological and environmental processes that may underlie these demographic, physiological, and health patterns, together with their implications for the conservation of this isolated South Pacific foraging aggregation.

4.1. Environmental and ecological drivers of juvenile dominance in Rapa Nui

Juvenile-dominated aggregations of green turtles are common in shallow coastal foraging habitats throughout Oceania and the Pacific, having been reported in Fiji, New Caledonia, Australia, New Zealand, Hawaii, and other Central Pacific systems (Godoy et al. 2016, Becker et al. 2019, Piovano et al. 2019, Kophamel et al. 2022, Read et al. 2024). Consistent with this broader regional pattern, the Rapa Nui aggregation was strongly dominated by small juveniles, most of which measured 40–60 cm SCL. This demographic structure is likely driven by a combination of ecological and environmental factors.

Ontogenetic shifts in habitat use are among the primary mechanisms underlying juvenile-dominated

coastal aggregations. Following recruitment from oceanic habitats, juveniles typically settle in neritic foraging areas, where they may remain for several years, whereas larger juveniles and adults often expand their movements and use a broader range of coastal and offshore environments (Bolten et al. 2003, Arthur et al. 2008, Bresette et al. 2010, López-Castro et al. 2010, Welsh & Mansfield 2022). These shifts are thought to reflect changes in energetic requirements, resource use, and mechanisms that reduce intraspecific competition among life stages (Arthur et al. 2008, Velez-Zuazo et al. 2014, Godoy et al. 2016, Madeira et al. 2022, Quiñones et al. 2022).

Habitat characteristics may further reinforce this pattern. Juvenile green turtles frequently occupy shallow, sheltered habitats that provide foraging opportunities while reducing energetic expenditure and exposure to predators, whereas larger individuals often use deeper or more exposed environments (Koch et al. 2007, Bresette et al. 2010, López-Castro et al. 2010, Madeira et al. 2022, Pillans et al. 2022, Welsh & Mansfield 2022). Ecological studies have documented clear spatial segregation among life stages within shared foraging grounds, with juveniles concentrated in nearshore environments and adults using deeper lagoonal, reef-associated, or offshore areas (Pillans et al. 2022, Welsh & Mansfield 2022). Shallow habitats can function as refuges from large predators such as sharks, potentially increasing their suitability for younger turtles (Heithaus et al. 2005, 2007, Kubis et al. 2010). Although predation pressure was not evaluated in this study, the refuge value of shallow habitats may further contribute to the life-stage distribution observed within the Rapa Nui aggregation.

Importantly, all surveys were conducted within sheltered bays. Consequently, the demographic structure described here likely reflects the segment of the population using these environments and may underrepresent individuals occupying deeper or more exposed areas around the island. Although variation in resource availability and habitat quality may also influence habitat use and demographic structure (Velez-Zuazo et al. 2014, Quiñones et al. 2022), these factors were not evaluated directly in this study. Nevertheless, the slow growth rates and physiological alterations reported for this aggregation (see discussion below) suggest that trophic resources may play an important role and warrant further investigation. Future studies integrating stable isotope analyses, satellite telemetry, and habitat characterization could help clarify habitat use, trophic ecology, and movement patterns across life stages, as well as determine whether larger individuals occupy habitats not represented in our surveys.

4.2. High site fidelity and unique composition of the Rapa Nui turtle aggregation

Although several studies have reported high foraging-site fidelity in green turtles across Oceania using satellite telemetry and stable isotope analyses (Brill et al. 1995, Shimada et al. 2014, Pillans et al. 2022, Read et al. 2024), relatively few have quantified residency through mark–recapture approaches in regional foraging grounds. Available studies consistently report moderate recapture rates, ranging from 11.9% in Grand Lagon Sud, New Caledonia (Read et al. 2015) and 12.1% in Palmyra Atoll (Naro-Maciel et al. 2018), to a maximum of 32% in the southern Great Barrier Reef, Australia (Chaloupka et al. 2004). By contrast, the recapture rate documented in Rapa Nui reached 45.1%, substantially exceeding values reported for other green turtle foraging aggregations in Oceania.

Several non-mutually exclusive mechanisms may contribute to this pattern. High fidelity to foraging grounds in marine megavertebrates has frequently been linked to the spatial predictability of food resources and the energetic and opportunity costs associated with relocating to alternative habitats (Enstipp et al. 2016, Shimada et al. 2020). For benthic-feeding life stages of green turtles, relatively stable algal resources may allow specific foraging areas to remain suitable over long periods of time, reducing the potential benefits of dispersal (Shimada et al. 2020). In addition, long-term occupancy may provide individuals with detailed knowledge of local environmental conditions, potentially increasing foraging efficiency and reducing the risks associated with exploring unfamiliar habitats (Shimada et al. 2020).

These mechanisms may be particularly important in geographically isolated systems such as Rapa Nui. Given that the nearest location known to support green turtles, the Pitcairn Islands (Maison et al. 2010), lies nearly 2000 km away, the costs and uncertainty associated with dispersal are likely amplified, potentially promoting prolonged residency once individuals successfully recruit to the island (Enstipp et al. 2016, Shimada et al. 2020).

Beyond the high site fidelity displayed by individuals within this aggregation, its ecological significance is further underscored by its unusual demographic structure. The co-occurrence of both Pacific green turtle morphotypes (yellow and black) is rare in Oceania and has previously been reported only in Palmyra Atoll and New Caledonia (Sterling et al. 2013, Read et al. 2024). Although the Rapa Nui turtle aggregation is dominated by the yellow morphotype,

approximately 15.7% of individuals correspond to the black morphotype, likely originating from Galápagos and Mexican rookeries (Álvarez-Varas et al. 2022). This proportion is substantially higher than that reported for Palmyra Atoll and New Caledonia, where black morphotype turtles appear to occur only sporadically (Sterling et al. 2013, Read et al. 2024). Adult males were also recorded, despite this life stage being relatively uncommon in coastal foraging habitats and more frequently associated with offshore environments (Hatase et al. 2002, Plotkin 2003, Schofield et al. 2017). Collectively, the coexistence of both morphotypes, the occurrence of adult males, and the high site fidelity exhibited by resident green turtles underscore the ecological significance of Rapa Nui as a unique and isolated foraging ground in the South Pacific.

4.3. Slow somatic growth and its ecological determinants

Rapa Nui turtles grow at an average rate of 1.08 cm SCL yr⁻¹, substantially lower than those reported for most green turtle foraging grounds across Oceania, with the exception of Hawaii (Balazs & Chaloupka 2004, R. Coelho unpubl. data). For example, an average growth rate of 4.68 cm yr⁻¹ has been reported for the Solomon Islands (Argument et al. 2009), while neritic aggregations in the Northern Mariana Islands exhibit mean growth rates of 3.11 cm yr⁻¹ (Summers et al. 2017). By contrast, Hawaiian green turtles exhibit similarly low growth rates to those observed in Rapa Nui, averaging 1.07 cm yr⁻¹ at Punalu'u Beach (R. Coelho unpubl. data), with estimates ranging from approximately 0 to 2.5 cm SCL yr⁻¹ across 5 foraging grounds within the Hawaiian Archipelago (Balazs & Chaloupka 2004). These patterns have been largely attributed to local foraging-ground conditions, particularly food availability and the nutritional quality of available resources (Balazs & Chaloupka 2004, R. Coelho unpubl. data).

Consistent with patterns reported from other Pacific foraging aggregations, green turtles in Rapa Nui exhibited the characteristic dome-shaped, size-specific growth function previously described for the Great Barrier Reef, the Galápagos Islands, and Hawaii (Green 1993, Limpus & Chaloupka 1997, Balazs & Chaloupka 2004, Chaloupka et al. 2004). This pattern is characterized by slow growth following recruitment, followed by a period of accelerated growth, and subsequently a decline in growth rates as individuals approach sexual maturity (Balazs & Chaloupka 2004).

Variation in the magnitude and timing of this growth pattern has likewise been associated with local foraging-ground conditions, particularly food quality and resource availability (Balazs & Chaloupka 2004). In addition, density-dependent processes have also been proposed as potential drivers of somatic growth in green turtles (Balazs & Chaloupka 2004). Continued long-term, systematic monitoring of green turtles and their habitat at Rapa Nui will therefore be essential to determine whether growth rates are associated with turtle abundance, trophic resource availability and quality, or other local biological and environmental factors. Likewise, future studies incorporating larger sample sizes will help disentangle potential differences in growth patterns between morphotypes, as previously reported for green turtles at foraging grounds in the Galápagos and the Colombian Pacific (Sampson et al. 2015, Zárate et al. 2015), while strengthening inferences across the size classes examined here.

4.4. Body condition patterns and the potential role of anthropogenic food subsidies

The BCI of green turtles from Rapa Nui ranged from 1.11 to 2.37, with a mean value of 1.60, exceeding those reported for several other foraging grounds across Oceania. For instance, McFadden et al. (2014) reported a mean BCI of 1.42 for a healthy green turtle population inhabiting a remote Central Pacific atoll, similar to the mean value of 1.40 reported for Hawaiian green turtles at Punalu'u Beach (R. Coelho unpubl. data). By contrast, Kophamel et al. (2022) reported a substantially lower mean BCI of 1.16 for green turtles from 2 foraging aggregations in North Queensland, Australia.

Although BCI did not differ significantly between morphotypes, black turtles and adult individuals consistently exhibited higher mean values. This pattern may reflect differences in trophic resource use among morphotypes and life stages. While green turtles become predominantly herbivorous after recruiting to neritic habitats, increasing evidence indicates that black morphotype individuals maintain a more omnivorous diet, incorporating a greater proportion of animal prey than the yellow morphotype (Amorochio & Reina 2007, Seminoff et al. 2012, 2021). These dietary differences may partly explain the relatively higher BCI observed in black turtles at Rapa Nui.

Interestingly, the relatively high BCI observed in Rapa Nui contrasts with the slow somatic growth and the physiological alterations reported for this aggre-

gation (see discussion below). As BCI is generally considered an indicator of body energy reserves rather than a comprehensive measure of physiological condition (Labrada-Martagón et al. 2010a), this apparent mismatch suggests that body condition, growth, and physiological status may respond differently to local ecological conditions. One possible explanation is that predictable access to energy-rich anthropogenic food subsidies, such as fishery discards associated with artisanal fisheries in the bays of Hanga Roa and Hanga Piko, may allow turtles to maintain relatively high body condition while reducing foraging effort, without necessarily translating into faster somatic growth or improved physiological condition. Likewise, the relatively higher BCI observed in adult turtles may be consistent with the cumulative effects of prolonged access to these food subsidies during extended residency at this foraging ground. This interpretation is also consistent with previous observations indicating that fishery discards constitute an important food resource for this aggregation (Álvarez-Varas et al. 2022, 2025).

Future studies integrating trophic ecology, physiological biomarkers, systematic growth monitoring, and larger sample sizes across morphotypes and life stages will help disentangle the ecological and biological processes shaping body condition in this population.

4.5. Interannual physiological variability within a persistent pattern of compromised physiological condition

In Oceania, assessments of green turtle health at foraging grounds have largely focused on populations from Australia and Hawaii, with only a few studies from isolated oceanic aggregations such as Palmyra Atoll and Rapa Nui, where contrasting health patterns have been reported (Aguirre et al. 1995, Aguirre & Balazs 2000, McFadden et al. 2014, Flint et al. 2019, Álvarez-Varas et al. 2025). While turtles inhabiting the highly protected Palmyra Atoll exhibit hematological profiles consistent with good health (McFadden et al. 2014), previous studies from Rapa Nui have consistently suggested compromised health condition in this aggregation (Álvarez-Varas et al. 2022, 2025).

Our results show that the physiological condition of the Rapa Nui green turtle aggregation varied throughout the study period. Significant interannual differences in multiple hematological and biochemical parameters were detected between 2023 and 2024, indicating that blood-based health indicators respond

to year-to-year changes in environmental, ecological, and population-level conditions (Labrada-Martagón et al. 2010b, Kophamel et al. 2022, Fernández-Sanz et al. 2025). Such variation may reflect fluctuations in demographic structure, including differences in life-stage composition, recruitment, and morphotype representation (Kophamel et al. 2022, Álvarez-Varas et al. 2025), as well as changes in oceanographic conditions, resource availability, and seasonal productivity (Becker et al. 2019, Seminoff et al. 2021, Kophamel et al. 2022). As dynamic indicators of physiological status, blood biomarkers should therefore be interpreted within their ecological context rather than as fixed descriptors of population health (Stacy et al. 2011, Kophamel et al. 2022, Fernández-Sanz et al. 2025).

Despite the observed interannual variation, the overall hematological profile remained consistent with physiological dysfunction. Although population-level anemia was not detected, reduced MCV and MCH values, together with polychromasia, anisocytosis, and poikilocytosis, suggest altered erythropoiesis and an impaired regenerative response, potentially associated with prolonged metabolic stress, nutritional constraints, contaminant exposure, or chronic inflammation (Aguirre et al. 1995, Stacy et al. 2011, Steinberg & Divers 2022). Likewise, marked lymphopenia, pronounced heterophilia, and the presence of azurophils and toxic heterophils are consistent with stress-associated immunological imbalance and systemic inflammation (Stacy et al. 2011, Kophamel et al. 2022).

The biochemical profile further supported the presence of subclinical organ dysfunction. Elevated ALT activity, together with positive correlations among hepatic-associated enzymes (ALT–ALP and ALT–AST) and metabolic variables (ALT–CHOL, ALP–CHOL, and ALP–PHOS), suggests coordinated alterations in hepatic function consistent with hepatocellular stress. These alterations may reflect the combined effects of persistent contaminant exposure, including mercury previously documented in this aggregation (Álvarez-Varas et al. 2025), together with metabolic adjustments associated with the mobilization of endogenous energy reserves during brumation or the consumption of atypical diets, including fisheries-derived food subsidies (Delgado et al. 2011, Mader & Divers 2013, Álvarez-Varas et al. 2015, 2025, Discalfani et al. 2024).

Markedly elevated BUN and UREA concentrations support the presence of renal stress (Anderson et al. 2011, Delgado et al. 2011, Álvarez-Varas et al. 2025). In addition, the observed relationships between mineral-associated variables and hematological param-

eters, including negative correlations between PHOS and MCHC and CPK, a positive correlation between PHOS and CHOL, and a negative correlation between CA and leukocyte counts, suggest alterations in mineral metabolism accompanying these physiological changes. Together, these findings are consistent with renal dysfunction likely resulting from a combination of contaminant exposure, dehydration-related hemoconcentration, increased protein catabolism, and disrupted immune-mineral homeostasis (Delgado et al. 2011, Smith et al. 2025).

Importantly, blood biomarkers provide a snapshot of an individual's physiological status at the time of sampling (Stacy et al. 2011, Mader & Divers 2013). However, the findings of the present study gain broader significance when interpreted in the context of previous independent surveys conducted in 2022 and 2025 (Álvarez-Varas et al. 2022, 2025). In addition to revealing significant interannual physiological variability, recurrent hematological and biochemical alterations, and unusually slow somatic growth despite apparently favorable body condition, our results complement previous clinical and toxicological evidence of traumatic injuries associated with boat strikes and fishing gear, lesions consistent with infectious processes, and elevated mercury concentrations correlated with multiple blood analytes (Sellanes et al. 2021, Álvarez-Varas et al. 2022, 2025). Together, these complementary lines of evidence indicate that the physiological alterations documented here are unlikely to represent isolated events but instead reflect a persistent pattern of compromised physiological condition.

Given the high site fidelity exhibited by green turtles in Rapa Nui, repeated exposure to local environmental and anthropogenic stressors (including mercury contamination, eutrophication-related coastal pollution, intense artisanal boat traffic, and anthropogenic food subsidies) likely contributes to the compromised physiological condition documented in this aggregation (Álvarez-Varas et al. 2015, 2022, 2025). Future long-term, integrative monitoring will be essential to disentangle natural physiological variability from the cumulative effects of these stressors. Increasing the number of recaptured individuals across size classes will also help determine whether the physiological alterations documented here are associated with the unusually slow somatic growth observed in this aggregation.

While continued long-term monitoring remains essential, it should be accompanied by management actions targeting local anthropogenic stressors. Given the accumulating evidence that these pressures are

compromising the health condition of green turtles, mitigating their impacts should become a conservation priority for this isolated resident aggregation.

5. CONCLUSIONS

Green turtles are of profound ecological and cultural importance across Oceania, yet information from isolated foraging grounds remains scarce despite these habitats supporting individuals through most of their lives. This study provides the first integrated assessment of demographic structure, residency, somatic growth, body condition, and physiological status in the Rapa Nui green turtle aggregation. Our findings reveal a juvenile-dominated aggregation characterized by exceptionally high site fidelity, unusually slow somatic growth despite relatively high body condition, and significant interannual physiological variability occurring within a persistent pattern of compromised physiological condition.

Conducted at an isolated foraging ground that represents a key biogeographical link between South American and Polynesian green turtle populations, this study provides a comprehensive perspective on the biological, ecological, and health aspects of a green turtle foraging aggregation in the South Pacific. The recurrence of physiological alterations across independent sampling periods, together with previous clinical and toxicological evidence, suggests that resident turtles are exposed to persistent local environmental and anthropogenic stressors. These findings highlight the importance of integrating individual-level physiological biomarkers with population-level demographic and ecological assessments to better understand population health and the factors underlying it.

Beyond continued monitoring, our results emphasize the need for management actions aimed at reducing or mitigating local anthropogenic stressors, including coastal pollution, intense artisanal boat traffic, and anthropogenic food subsidies. Addressing these pressures should become a conservation priority, not only to improve the long-term health and resilience of this resident green turtle aggregation, but also to protect the unique coastal marine biodiversity and cultural heritage of Rapa Nui.

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