Dynamics of fibropapillomatosis in green turtles *Chelonia mydas* from Babitonga Bay, southern Brazil

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ABSTRACT: Green turtles *Chelonia mydas* are vital components of marine ecosystems and are recognized as indicators of environmental health. Fibropapillomatosis (FP), a debilitating disease associated with a chelonid herpesvirus, disproportionately affects juveniles in coastal foraging areas. This study presents the first analysis of FP dynamics in Babitonga Bay, southern Brazil, an important habitat for the species. Between 2019 and 2023, 171 juvenile green turtles were monitored using capture—mark—recapture and photo-identification techniques. FP prevalence in Babitonga Bay was among the highest reported in Brazil, reaching 53.2%. Tumors were predominantly located in the anterior region of the body, particularly around the flippers and axillary area, and were mostly small, consistent with mild FP. Disease severity was quantified using an FP index, and its association with body condition was examined, revealing no significant association. Data from recaptured individuals revealed both tumor progression and regression, underscoring individual variability and suggesting the influence of environmental and immunological factors. The predominance of FP in juveniles highlights their heightened vulnerability during early developmental stages. These findings enhance our understanding of FP dynamics in green turtles and support the need for continued health assessments and conservation measures. This research contributes to global efforts to safeguard marine biodiversity, aligning with the goals of the United Nations Decade of Ocean Science for Sustainable Development.

KEY WORDS: Sea turtle · Infectious disease · Fibropapilloma tumors · Epizootic · Atlantic Ocean

1. INTRODUCTION

Environmental degradation and pollution are major drivers of marine diseases, some of which have the potential to reach widespread epizootics (Herbst et al. 2004, Ene et al. 2005, Jones et al. 2016). Among these, fibropapillomatosis (FP) stands out as an epizootic neoplastic disease that predominantly affects green turtles *Chelonia mydas* (Linnaeus, 1758) (Testudines, Cheloniidae), especially juveniles in shallow coastal areas near human settlements (Herbst 1994, George 1996, Van Houtan et al. 2010, Jones et al. 2020, Kelley et al. 2022). By contrast, FP is rarely observed in adults and is virtually absent on remote nesting islands (Baptistotte 2016, Domiciano et al. 2017, Gattamorta et al. 2022).

Beyond its ecological role, the green turtle is considered an environmental sentinel, reflecting the health of marine ecosystems (Aguirre & Lutz 2004, Domiciano et al. 2017). This status supports the identification of critical areas and the implementation of measures to mitigate environmental impacts and improve animal health. The species is listed as Endangered by the IUCN Red List (Seminoff 2004), although the South Atlantic subpopulation is categorized as Least Concern (Broderick & Patricio 2019). In Brazil, it was recently removed from the Official National List of Threatened Fauna, where it had previously been listed as vulnerable (IBAMA 2014, 2022).

FP causes cutaneous tumors of varying size and location, affecting both external tissues and internal organs (Herbst & Klein 1995, Wyneken et al. 2013,

Jones et al. 2016, Domiciano et al. 2017). These tumors can impair essential functions such as movement, feeding, and vision, and may be fatal in severe cases (Herbst 1994, Ene et al. 2005, Flint 2013). The global variability in FP presentation underscores the importance of region-specific studies (Balazs 1991, Adnyana et al. 1997, Lackovich et al. 1999, Aguirre et al. 2000, Espinoza-Rodríguez & Barrios-Garrido 2021, Monteiro et al. 2021, Roost et al. 2022). In Brazil, FP was first reported in 1986, and current prevalence rates range from 18.6 to 58 % (Santos et al. 2010, Tagliolatto et al. 2016, Domiciano et al. 2019, Rossi et al. 2019, Silva-Júnior et al. 2019, Bastos et al. 2022, Miguel et al. 2022). Given its potential to compromise individual survival and population health, FP is a key concern for sea turtle conservation and remains a global research priority (Hamann et al. 2010, Rees et al. 2016).

Tumor development is associated with infection by scutavirus chelonidalpha5 (ChHV5) and is influenced by both environmental and immunological cofactors (Herbst et al. 2004, Ene et al. 2005, Jones et al. 2016, Zamana et al. 2021, Vanstreels et al. 2023). Despite advances in research, the mechanisms underlying tumor progression and regression remain poorly understood (Tagliolatto et al. 2016). This complexity is reflected in the wide range of clinical outcomes, from spontaneous tumor regression to severe and potentially fatal cases (Herbst 1994, Patrício et al. 2016, Kelley et al. 2022). Disease susceptibility is further modulated by host-related factors such as immunosuppression, genetic predisposition, and overall physiological condition (Aguirre 1991, Herbst 1994, George 1996, Farrell et al. 2021, Kelley et al. 2022).

Regional differences in FP expression may also be driven by the genetic diversity of the ChHV5. Phylogeographic analyses have identified 4 major viral genetic groups associated with distinct oceanic regions: central Pacific, eastern Pacific, western Atlantic—eastern Caribbean, and Atlantic (Herbst et al. 2004, Ene et al. 2005, Patrício et al. 2012). In Brazil, molecular studies in northern São Paulo detected 2 ChHV5 variants: one from the Atlantic group and another genetically similar to strains from Hawai'i and Taiwan, suggesting potential viral gene flow between geographically distant populations (Zamana et al. 2021). Such genetic variability may influence viral pathogenicity and contribute to the heterogeneous clinical presentation of FP across different regions.

In Babitonga Bay, an important developmental habitat for juvenile green turtles in southern Brazil, FP has been recorded since at least 2001 (Cremer & Sartori 2009, Cremer et al. 2020). The bay is also a strategic economic hub, supporting large-scale port opera-

tions and surrounded by municipalities with significant industrial activity (Cremer 2006). Understanding how FP manifests in this population and which biological parameters influence its prevalence and severity is essential for evaluating viral spread and population health. This study investigates FP in green turtles from Babitonga Bay by analyzing temporal prevalence, variation across size classes, associations between disease severity and body condition, and tumor progression in affected individuals.

2. MATERIALS AND METHODS

2.1. Study site

Babitonga Bay is located on the northern coast of Santa Catarina state, southern Brazil (26° 13′ 51″ S, 48° 38′ 5″ W) (Fig. 1). The estuary is characterized by an extensive mangrove area (approximately 160 km^2) and an average depth of 6 m. It is connected to the Atlantic Ocean by a single channel approximately 1850 m wide. The bay is heavily impacted by domestic and industrial effluents resulting from nearby urban expansion and industrial development, and it also supports intense port activity (Cremer 2006, Gerhardinger et al. 2021). Despite these anthropogenic pressures, Babitonga Bay plays a key role in regional biodiversity and is recognized as a priority area for conservation (MMA/SBio/DCME 2023).

Sampling was carried out at 3 sites along the southern margin of Babitonga Bay, within the urban area of São Francisco do Sul municipality. All sites are affected by untreated domestic sewage, feature alternating sandy and rocky shores, and are exposed to low to moderate small-boat traffic. The sampling locations include Bela Vista (Point A), Figueira Beach (Point B), and Calixto Beach (Point C) (Fig. 1). Bela Vista is adjacent to the São Francisco do Sul Port, while the other 2 sites are progressively more distant from this area.

2.2. Intentional capture procedures

Intentional capture campaigns of green turtles were conducted between 2019 and 2023 using a 70 m long, 3 m high gillnet with a 25—30 cm mesh size, made of 0.60 mm monofilament nylon, set parallel to the rocky shore (Ehrhart & Ogren 1999). Continuous monitoring by 2 teams, one in the water and another in a small boat, ensured that entangled animals were promptly released to prevent drowning. Some individuals were
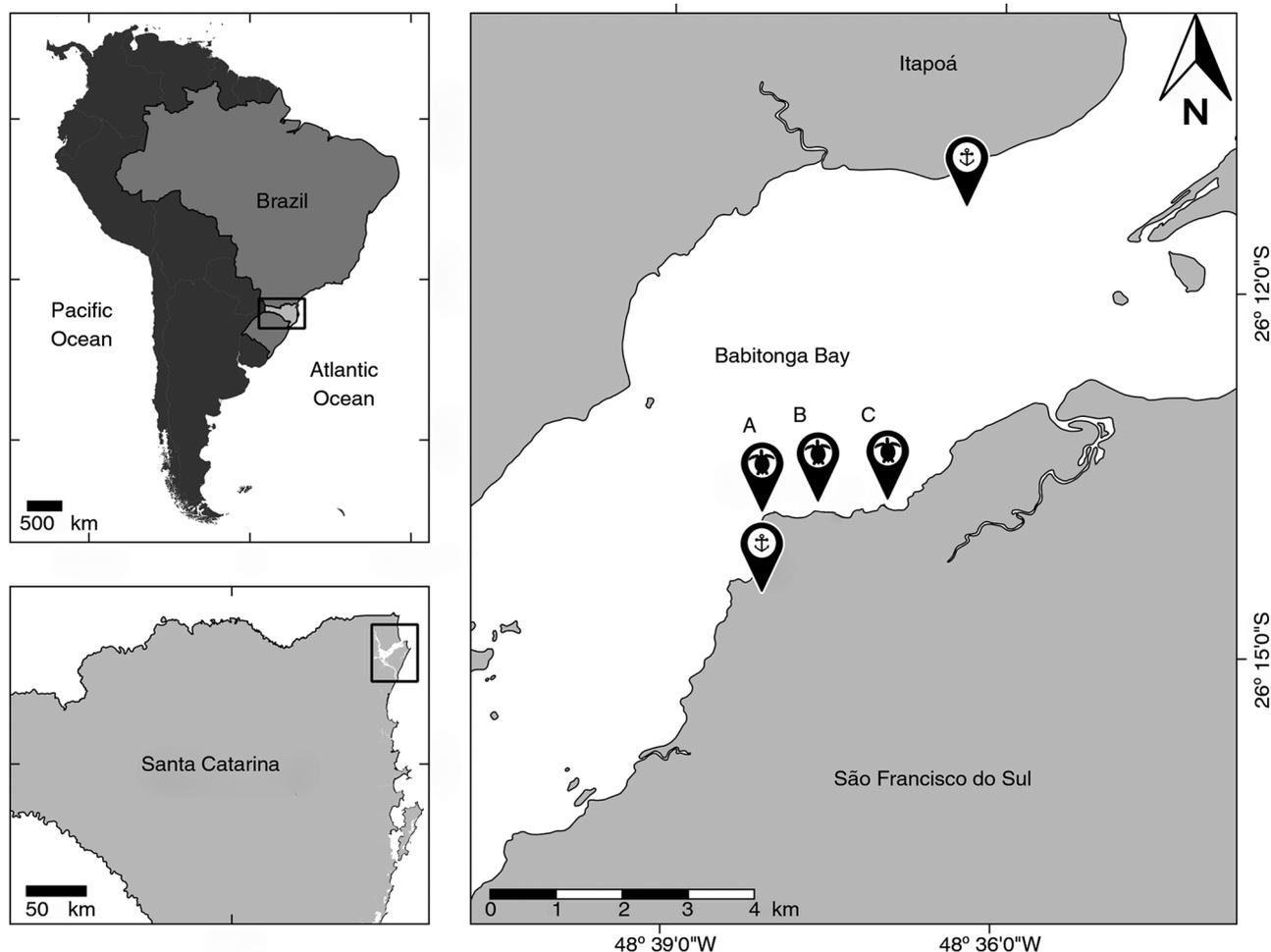
Fig. 1. Sampling locations of green turtles in Babitonga Bay, southern Brazil. Circles: capture sites (A, B, and C); anchor symbol: the port area

also captured manually. Turtles were restrained and transported to a land-based facility for data collection. Animals with FP were handled separately from FP-free animals. Gloves were changed between each animal, and 2 sets of sampling kits were used: one dedicated to FP turtles and another to turtles without FP. Disposable materials (e.g. scalpel blades, needles) were replaced for each animal, while reusable instruments (e.g. scissors, forceps, scalpel handles, calipers, and measuring tapes) were disinfected or sterilized between animals to avoid cross-contamination.

This research was conducted under federal authorization from the Biodiversity Authorization and Information System (SISBIO, permit no. 63333).

2.3. Data collection

For each green turtle, curved carapace length (CCL, cm) and body mass (in kg) were recorded using a flex-ible measuring tape and a suspended mechanical scale, respectively (Bolten 1999). External tumors were measured with calipers and classified by their maximum diameter into 4 categories: A (<1 cm), B (1−4 cm), C (>4−10 cm), and D (>10 cm) (Work & Balazs 1999).

Tumor location was recorded as either ventral or dorsal, and each tumor was also classified by specific anatomical region: anterior (head, neck, front flippers), posterior (rear flippers, tail, inguinal), ocular (eyelid, periocular, cornea), carapace, and plastron (Rossi et al. 2016, Tagliolatto et al. 2016). Each turtle was identified with 2 Inconel metal tags provided by the Sea Turtle Center of the Chico Mendes Institute for Biodiversity Conservation (Centro TAMAR/ICMBio), following standard tagging protocols (Centro TAMAR/ICMBio 2017). Individuals were photographed dorsally and ventrally to document marks and deformities on the body, and laterally on the head to record the head scale configuration, which is unique to each turtle and is used as a supplementary identification

method, a widely recognized non-invasive technique in sea turtle research (Bennett et al. 2000, Carpentier et al. 2016, Hancock et al. 2023, Neves-Ferreira et al. 2023).

2.4. Data analysis

Analyses were conducted using different data sets depending on the purpose: tumor macroscopic assessment used all available tumor records without repeating individuals; FP prevalence, severity analyses, and body condition used only the last capture of each individual; and annual prevalence and size-class analyses used the last capture per individual per year. Progression and regression of tumors, as well as the transition matrix, used all capture events for turtles with multiple recaptures.

Total FP prevalence for the study period was calculated by dividing the number of turtles with tumors by the total number of individuals captured. Annual variation in FP prevalence was assessed using Pearson's chi-squared test, and variation in prevalence across size classes (defined in 5 cm CCL intervals) was assessed using Fisher's exact test with simulated p-values (based on 10 000 replicates).

To examine temporal changes in turtle size, variation in mean CCL across years was analyzed using the non-parametric Kruskal-Wallis test, followed by Dunn's post hoc test. This was done to explore whether years with differences in turtle size coincided with variations in FP prevalence, without directly testing FP as a function of size. Differences in mean CCL between turtles with and without FP were assessed using the Mann-Whitney-Wilcoxon test to determine whether disease occurrence was related to body size. The relationship between CCL and average tumor size score was assessed using Spearman's rank correlation and linear regression to evaluate whether tumor size was related to body size.

To examine the relationship between FP occurrence (presence−absence) and turtle body size, binomial generalized linear mixed models (GLMMs) were fitted. Candidate models included CCL (cm) as a linear and quadratic predictor. Individual turtle ID was included as a random intercept to account for repeated captures of the same animal. Model selection was based on Akaike's information criterion (AIC), and the improvement of the quadratic term was assessed by a likelihood ratio test. Model fit was further quantified by marginal and conditional R^2 values. Predicted probabilities and 95% confidence intervals were generated from the final model and plotted against CCL.

Disease severity was assessed using the Fibropapillomatosis Index (FPI), calculated as $FPI = 0.1 \times nA + 1 \times nB + 20 \times nC + 40 \times nD$, where nA, nB, nC, and nD represent the number of tumors in size classes A, B, C, and D, respectively, found on each individual turtle. This index incorporates both the number and size of tumors to provide a weighted severity score. FPI values were classified according to the Southwestern Atlantic Fibropapillomatosis Severity Score (FPS_{SWA}) as follows: no FP ($FPI = 0$), mild ($0 < FPI < 40$), moderate ($40 \leq FPI < 120$), and severe ($FPI \geq 120$) (Rossi et al. 2016). Differences in mean turtle size among FPS_{SWA} categories were analyzed using the Kruskal-Wallis test.

The body condition index (BCI) was calculated for each turtle as $BCI = body\ mass \div SCL^3 \times 10\,000$ (Bjorndal et al. 2000), where SCL is the straight carapace length estimated by the formula $SCL = 0.93 \times CCL − 0.28$ (Rossi et al. 2019). Differences in BCI between turtles affected and unaffected by FP were tested using a Student's t-test. Relationships between BCI and FP severity were assessed by comparing BCI across FPS_{SWA} categories using 1-way ANOVA and by evaluating the association between BCI and FPI scores through linear regression.

Photographic comparisons were used to assess tumor progression and regression in recaptured turtles with a history of FP. Only capture pairs with high-quality photographs, enabling reliable evaluation, were included. Progression was defined as the appearance of new tumors or an increase in size, and regression as their reduction or disappearance. To visualize disease dynamics, a transition matrix was constructed for all recaptured turtles, using consecutive FPS_{SWA} to track progression, regression, or stability across captures.

Data normality was assessed using the Shapiro-Wilk test, and homogeneity of variances was verified using Levene's test where applicable. Non-parametric alternatives were applied when assumptions for parametric tests were violated. All statistical analyses were performed at a significance level of $\alpha = 0.05$ in R (v.4.3.1) (R Core Team 2023), using the packages 'readxl', 'ggplot2', 'rstatix', 'RcmdrMisc', and their dependencies (Wickham 2016, Fox & Marquez 2023, Kassambara 2023, Wickham & Bryan 2023). To account for multiple comparisons and reduce the likelihood of false positives, p-values were adjusted using the Benjamini-Hochberg method to control the false discovery rate (FDR; Glickman et al. 2014) within biologically meaningful families of hypotheses (e.g. temporal comparisons, morphometric measurements, body condition indices). Both raw p-values and FDR-

adjusted p-values (q-values) are reported, with q < 0.05 considered significant.

3. RESULTS

3.1. FP prevalence

A total of 331 capture events resulted in the capture of 171 individual green turtles, with CCLs ranging from 29.5 to 71.2 cm (mean: 43.5 ± 9.2 cm). Turtles affected by FP ranged from 32.5 to 66.4 cm (42.5 ± 6.8 cm; n = 80), while unaffected individuals ranged from 29.5 to 71.2 cm (44.7 ± 11.3 cm; n = 91). Overall FP prevalence was 53.2% (91 out of 171). No significant difference in mean size was found between FP-affected and unaffected turtles (Mann-Whitney U-test: W = 3580.5, p = 0.855, q = 0.855). FP prevalence varied significantly across size classes (Fisher's exact test: p = 0.001, q = 0.005), peaking in the 40—45 cm CCL class, decreasing in larger classes, with a slight increase in the 65—70 cm class (Fig. 2).

The quadratic GLMM provided the best fit to the data (AIC = 383.0) compared to the linear model (AIC = 409.5), with a significant improvement in fit (likelihood ratio test: χ^2 = 28.5, df = 1, p < 0.001). The probability of FP exhibited a non-linear relationship with CCL, increasing with body size up to a certain point and declining thereafter (Fig. 3). Both the linear (estimate = 1.33 ± 0.37, p < 0.001) and quadratic terms (estimate = −0.015 ± 0.004, p < 0.001) were strongly significant. The vertex of the quadratic curve occurred at approximately 45 cm CCL, indicating that FP prevalence peaked around this size class. The marginal R^2 indicated that fixed effects (CCL and CCL^2) explained 26% of the variation in FP occurrence, while the conditional R^2 (including the random effect of turtle ID) reached 73%, reflecting substantial individual heterogeneity.

FP prevalence also varied significantly over the study period (χ^2 = 15.291, df = 4, p = 0.004, q = 0.008), with the highest values observed in 2019. Although mean turtle size showed significant variation across years (Kruskal-Wallis: χ^2 = 10.259, df = 4, p = 0.036, q =
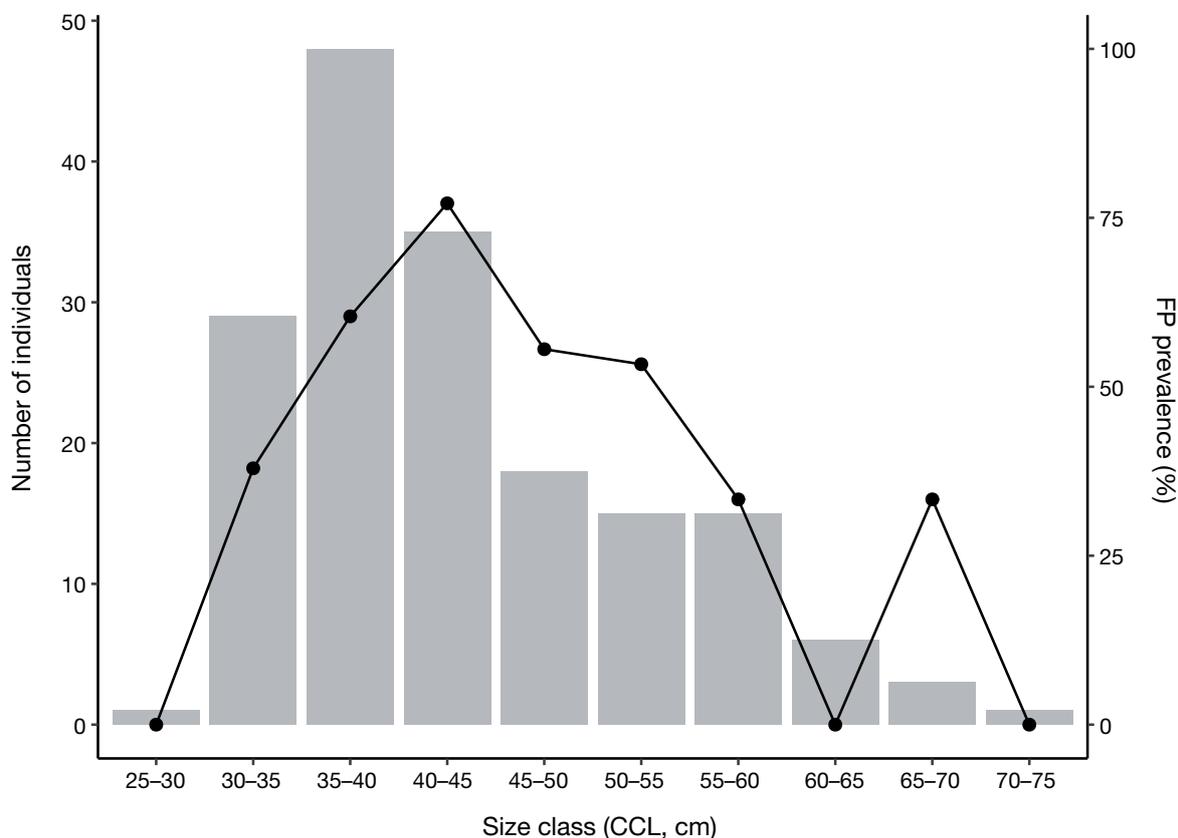

Fig. 2. Distribution of green turtle captures (left axis) and fibropapillomatosis (FP) prevalence (right axis) by curved carapace length (CCL) class in Babitonga Bay, southern Brazil. Prevalence values were scaled to match the range of the primary axis for visualization
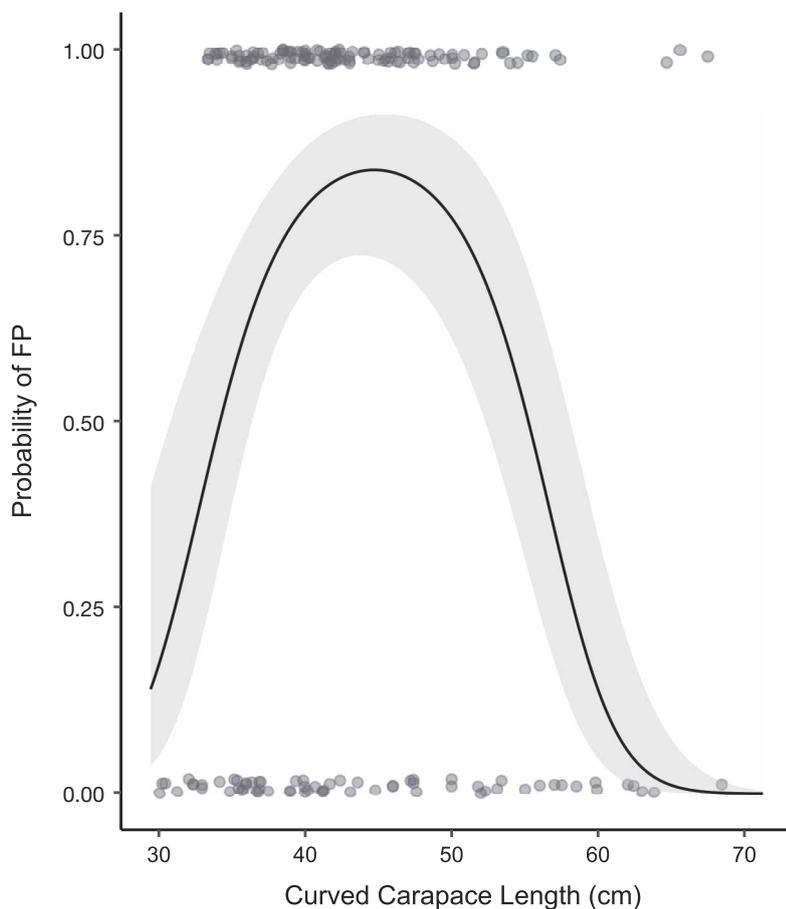
Fig. 3. Probability of fibropapillomatosis (FP) in green turtles from Babitonga Bay, southern Brazil, as a function of curved carapace length. Points: individual capture events (jittered for clarity); solid line: fitted quadratic generalized linear mixed model (with turtle ID as a random intercept); shaded area: 95% CI

the posterior. Carapace or plastron and ocular tumors accounted for 4.9 and 2.5%, respectively (Table 1).

While smaller tumors (Groups A and B) predominated and affected the majority of turtles, larger tumors (Group D) were rare and usually restricted to a single lesion per individual (Fig. 5). No correlation was found between CCL and tumor size score (Spearman's ρ = 0.028, p = 0.610, q = 0.813). Similarly, linear regression showed no significant relationship ($F_{1,329}$ = 1.324, r^2 = 0.004, p = 0.251, q = 0.502).

3.3. FP severity and BCI

Of the 91 turtles that presented FP in their last capture, FPS_{SWA} were mild in 78%, moderate in 16.5%, and severe in 5.5%. FPI values ranged from 0.1 to 138.1 (mean: 26.1 ± 38.3). Mean CCL was 42.8 ± 7.27 cm in mild cases, 40.5 ± 4.00 cm in moderate, and 44.1 ± 6.59 cm in severe cases, with no significant differences among the severity levels (Kruskal-Wallis: χ^2 = 1.081, df = 3, p = 0.782, q = 0.855).

BCI ranged from 1.14 to 2.06 in turtles without FP (1.56 ± 0.17) and from 1.14 to 1.96 in those with FP (1.58 ± 0.16), with no significant difference between groups (Student's t-test: t = 1.2948, df = 154.77, p = 0.197, q = 0.592) (Fig. 6A).

Similarly, BCI did not differ among turtles classified according to FPS_{SWA}: mild (1.58 ± 0.15; n = 71), moderate (1.58 ± 0.21; n = 15), and severe (1.50 ± 0.12; n = 5) (ANOVA: $F_{2,88}$ = 0.554, p = 0.577, q = 0.850) (Fig. 6B). No significant correlation was observed between BCI and FPI (linear regression: $F_{1,82}$ = 0.03603, r^2 < 0.001, p = 0.850, q = 0.850).

0.036), post hoc pairwise comparisons using Dunn's test with Benjamini-Hochberg correction did not detect any statistically significant differences between individual years (all adjusted p-values > 0.05) (Fig. 4).

3.2. Macroscopic assessment of tumors

Tumors were assessed macroscopically using 98 available tumor records, each corresponding to a unique individual, regardless of recaptures. Lesions were observed in 95.9% of turtles in the ventral region and 52% in the dorsal region. The anterior region was affected in 84.7% of turtles, and the posterior region in 83.7%. Additionally, tumors were recorded on the carapace and/or plastron in 30.6% of individuals and in the ocular region in 23.5% (Table 1).

Of the 1459 tumors measured, 85.5% were located ventrally, 53.8% in the anterior region, and 38.7% in

3.4. Progression and regression of FP

Tumor changes were assessed in 38 recaptured turtles with confirmed FP and suitable photographic records, yielding a total of 75 tumor comparison events. Based on individual turtles, tumor progression was observed in 17 individuals (44.7%), including 5 that developed tumors after initially showing no
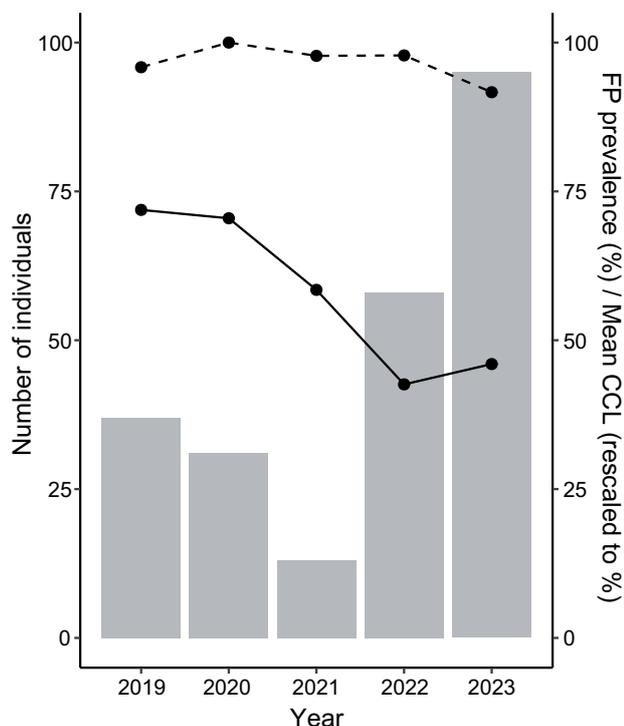
Fig. 4. Annual variation in FP prevalence (black line), mean curved carapace length (CCL; dashed line), and number of green turtles captured (bars) in Babitonga Bay, southern Brazil, from 2019 to 2023. Prevalence values were scaled to match the range of the primary axis, and mean CCL values were rescaled to a 0—100% range relative to the maximum observed mean CCL across all years (i.e. 100% corresponds to the year with the largest mean CCL). This rescaling allows visualization of trends in mean CCL alongside prevalence and capture numbers on a single plot

signs of FP (Fig. 7A). Tumor regression occurred in 14 individuals (36.8%) (Fig. 7B), with 7 individuals (18.4%) exhibiting both progression and regression between recaptures. An individual monitored over 4.5 yr (Fig. 8) showed tumor progression followed by partial regression.

At the event level, progression occurred in 41 events (54.7%), including 9 events with new tumor development, 14 with tumor growth, and 18 with both. Tumors appeared at an average (±SD) of 338 ± 285 d (range: 34—1116 d). Regression occurred in 34 events (45.3%), comprising 6 events of complete regression, 13 of partial regression, and 15 showing both. Tumors regressed at an average of 468 ± 392 d (range: 63—1242 d), whereas complete remission was observed after 793 ± 494 d (range: 188—1242 d).

A transition matrix based on FPS_{SWA} scores for all recaptured turtles (Table 2) revealed that most turtles initially classified as absent remained tumor-free (75%), with a few progressing to mild or moderate stages. Mild cases mostly remained stable (69%), while moderate cases either progressed to severe or regressed to mild, and severe cases were split between remaining severe or regressing to moderate.

4. DISCUSSION

The FP prevalence in Babitonga Bay (53.2%) ranks as the second highest value among Brazilian foraging grounds, only surpassed by Espírito Santo Bay (58.3%; Santos et al. 2010). Most other studies report lower prevalence values, generally between 18.6 and 43.1% (Tagliolatto et al. 2016, Rossi et al. 2019, Silva-Júnior et al. 2019, Bastos et al. 2022, Miguel et al. 2022, Vanstreels et al. 2023). Earlier records suggest that FP was historically rare or sporadic in the region: a study documented no FP cases among 30 stranded green turtles between 2004 and 2009, though 2 tumor-bearing turtles were reported in 2001 and 2002 (Cremer & Sartori 2009). The current high prevalence indicates a marked increase over the past 2 decades, although it remains below global FP hotspots such as Florida (72.5%; Lackovich et al. 1999), Australia (70%; Aguirre et al. 2000), Puerto Rico (up to 75%; Patrício et al. 2016), and Hawai'i (up to 92%; Balazs 1991), which has since declined to around 9% (Chaloupka et al. 2009).

As noted by Herbst (1994), FP prevalence is often positively correlated with proximity to agricultural, industrial, and urbanized areas. However, Monteiro et al. (2021) documented moderate prevalence in

Table 1. Anatomical distribution of tumors and number of affected green turtles in Babitonga Bay, southern Brazil. Regions: anterior (head excluding eyes, neck, and fore flippers); posterior (hind flippers, tail, and inguinal area); ocular (eyelid, periocular surfaces, and cornea)

| | \multicolumn{4}{c}{Tumors} | \multicolumn{2}{c}{Individuals} |
	n	%	Min.—max.	Mean ± SD	n	%
Body part						
Ventral	1247	85.5	1—49	13.3 ± 12.49	94	95.9
Dorsal	212	14.5	1—18	4.2 ± 3.43	51	52.0
Location on body						
Anterior region	784	53.8	1—39	8.0 ± 9.26	83	84.7
Posterior region	564	38.7	1—26	5.8 ± 6.25	82	83.7
Carapace and/or plastron	72	4.9	1—9	0.7 ± 1.65	30	30.6
Ocular region	37	2.5	1—3	0.4 ± 0.74	23	23.5
Total	1457[a]	—	1—67	14.9 ± 14.68	98	—
[a]Two tumors had no recorded body location
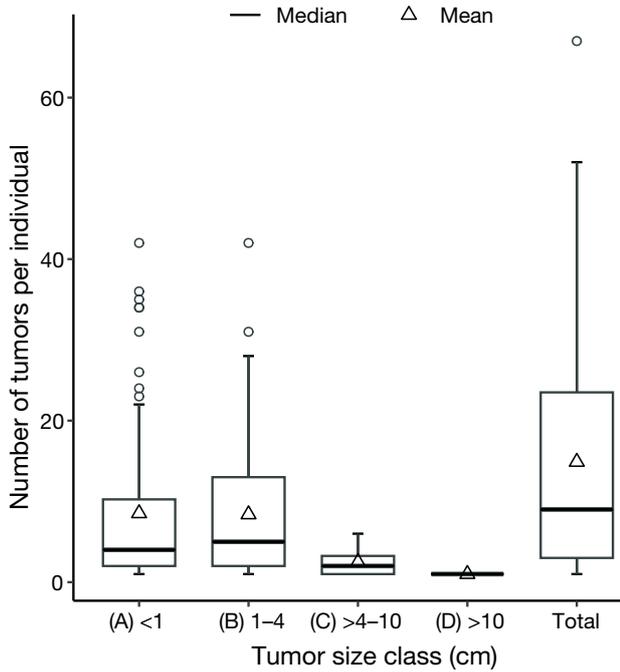
Fig. 5. Number of tumors per green turtle by tumor size class (A: <1 cm; B: 1–4 cm; C: >4–10 cm; D: >10 cm; n = 98) in Babitonga Bay, southern Brazil. Boxes: interquartile range (IQR; 25th–75th percentile); horizontal lines: median; whiskers extend to 1.5× the IQR; circles: outliers; triangles: mean values

lution (Santos et al. 2010). Additionally, a reduced diversity of algae in turtle diets may compromise nutritional intake and increase vulnerability to FP (Bjorndal 1996, Van Houtan et al. 2010). In Babitonga Bay, green turtles feed predominantly on chlorophytes, especially *Ulva*, with limited consumption of red and brown algae (Souza 2016), indicating low dietary diversity. Similar patterns, characterized by high FP prevalence and severity in areas where turtles consume low-diversity algal assemblages, have been reported elsewhere in Brazil (Bastos et al. 2022).

Importantly, even when turtles exhibit normal body condition, reduced diet diversity and altered chemical composition can still impair immune function, growth, and disease susceptibility, including FP (Bjorndal 1996, Van Houtan et al. 2010, Bastos et al. 2022). Maintaining high-quality feeding habitats with diverse algal communities is therefore essential for health, recruitment, and population resilience of green turtles (Worm et al. 2006, Rees et al. 2016, Mazaris et al. 2017).

All turtles in this study were classified as juveniles or subadults (CCL < 85 cm; Chaloupka & Limpus 2005, Lenz et al. 2017). FP prevalence was not evenly distributed across size classes, with the highest probability of occurrence in intermediate individuals and a peak around 40–45 cm CCL. Although sample sizes were uneven among size classes, with fewer individuals at the extremes of the size range, mean size did not differ significantly between affected and unaffected turtles. Similar ontogenetic patterns, with higher FP prevalence in intermediate juveniles fol-

minimally impacted habitats of West Africa, highlighting that FP expression may also depend on ecological and immunological factors beyond direct human disturbance. The elevated prevalence in Babitonga Bay may reflect regional environmental stressors such as chemical, microbiological, and noise pol-
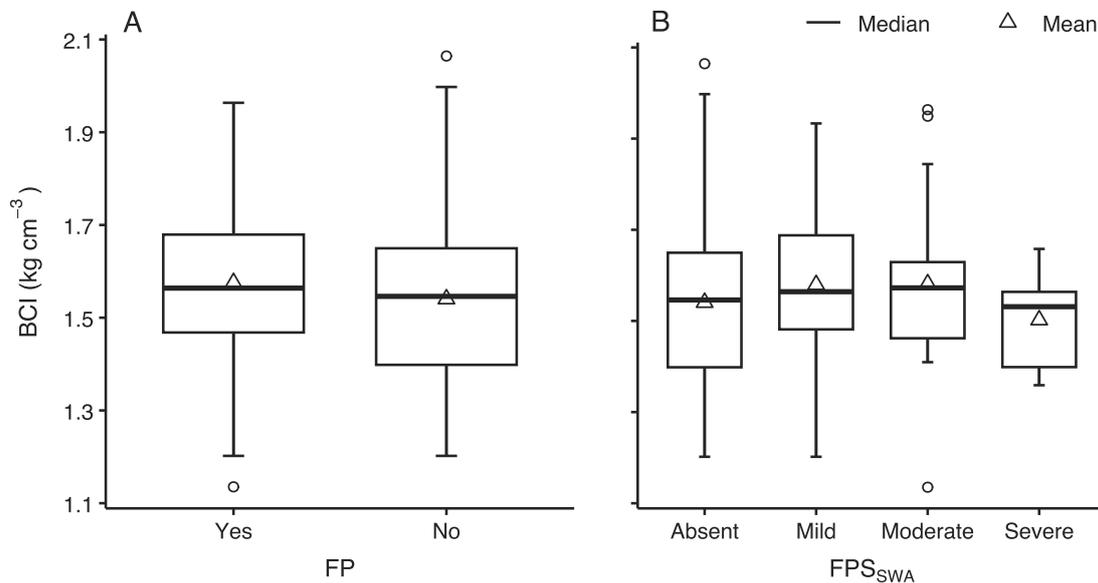

Fig. 6. (A) Body condition index (BCI) of green turtles with and without fibropapillomatosis (FP) in Babitonga Bay, southern Brazil. (B) BCI across Southwestern Atlantic Fibropapillomatosis Severity Score (FPS$_{SWA}$). Boxplot parameters as in Fig. 5

Fig. 7. Tumor progression and regression in 2 individual green turtles from Babitonga Bay, southern Brazil. (A) Progression in the inguinal region and hind flippers (714 d between captures). (B) Regression in the ocular region (red arrows) (832 d between captures)

lowed by reduced occurrence in larger turtles, have been reported in other Brazilian estuarine areas (Santos et al. 2010, Domiciano et al. 2019) and in West Africa (Monteiro et al. 2021), supporting the hypothesis of age-related resistance or a self-limiting disease course with tumor regression over time (Work et al. 2004, Foley et al. 2005, Patrício et al. 2016). The slightly earlier peak in Babitonga Bay compared to other regions may reflect local environmental conditions, such as estuarine productivity, water temperature, or habitat features (Herbst 1994, Zamana et al. 2021, Vanstreels et al. 2023).

FP is typically acquired after recruitment to coastal foraging areas (Herbst 1994, Ene et al. 2005). However, its detection in some newly recruited individuals (CCL <35 cm; Lenz et al. 2017) underscores variability in recruitment sizes and exposure periods. While FP prevalence is generally concentrated in intermediate-size juveniles, these early cases are consistent with turtles that may have already spent close to 1 yr in coastal habitats, allowing sufficient time for infection. In our study, the single individual in the 25–30 cm size class showed no evidence of FP, reinforcing the expectation that newly recruited turtles typically arrive in nearshore waters without visible tumors. Tumor development in juveniles may also be influ-

enced by immunosuppression associated with ontogenetic shifts and local stressors (Santos et al. 2010, Domiciano et al. 2017), although current evidence indicates that immunosuppression is not a prerequisite (Cray et al. 2001, Work et al. 2001).

Molecular studies have shown that ChHV5 can be present in turtles without external tumors, including juveniles and apparently healthy adults (Quackenbush et al. 2001, Page-Karjian et al. 2012, Alfaro-Núñez et al. 2014), indicating that infection may occur before tumors develop. More recent environmental DNA (eDNA) approaches have even detected ChHV5 in sand associated with hatchling crawls, suggesting early exposure and the possibility of horizontal or vertical transmission prior to ocean entry (Farrell et al. 2022). In addition, a study on green turtle hatchlings in Florida found that all 297 sampled hatchlings tested negative for ChHV5 DNA, even when some adult females were positive, supporting the hypothesis that ChHV5 is not necessarily vertically transmitted, and that young turtles can hatch free of detectable infection (Page-Karjian et al. 2022). Together, these findings highlight that absence of visible tumors does not imply absence of infection and that subclinical or early-stage infections may be more common than previously recognized.

Turtles had tumors predominantly in specific body regions, with the highest frequency in the anterior (head, neck, front flippers) and posterior (rear flippers, tail, inguinal) regions. The larger surface area of soft tissue in the anterior region may account for this pattern, providing more suitable sites for tumor development (Baptistotte 2007). This anatomical distribution is commonly reported along the Brazilian coast, including Espírito Santo, Rio de Janeiro, São Paulo, and the northeastern region (Baptistotte 2007, Santos et al. 2010, Tagliolatto et al. 2016, Silva-Júnior et al. 2019, Miguel et al. 2022), as well as in Venezuela (Espinoza-Rodríguez & Barrios-Garrido 2021) and Hawai'i (Work et al. 2004). By contrast, an exception has been reported in Indonesia, where tumors predominantly occur in the posterior region (Adnyana et al. 1997), suggesting potential regional differences in tumor distribution. Tumors on the anterior flippers may impair swimming and foraging abilities, potentially reducing predator evasion and increasing mor-

Fig. 8. FP progression and regression in a green turtle recaptured 10 times in Babitonga Bay, southern Brazil, between 5 May 2019 and 11 December 2023. (A) First capture, showing no external tumors; (B) fifth recapture, 1001 d after first capture, with multiple new fibropapillomas; (C) ninth recapture, 680 d after fifth recapture, with partial tumor regression

Table 2. Transition matrix of fibropapillomatosis severity in recaptured green turtles (Southwestern Atlantic Fibropapillomatosis Severity Score, FPS$_{SWA}$) from Babitonga Bay, southern Brazil. Rows indicate the FPS$_{SWA}$ score at the first capture, and columns indicate the score at the subsequent capture. Values represent the number of recapture events observed for each transition

FPS$_{SWA}$	Absent	Mild	Moderate	Severe
Absent	54	17	1	0
Mild	20	54	3	1
Moderate	0	2	3	3
Severe	0	1	0	1

bidity (Aguirre & Lutz 2004, Flint 2013, Jones et al. 2016). Ocular tumors were also observed, though infrequently and typically small (<1 cm), making visual impairment unlikely. This contrasts with historical reports from Hawai'i, where FP was observed to often affect the eyes and can lead to severe visual impairment (Work et al. 2004), highlighting possible geographic differences in tumor expression and severity.

Most tumors observed in our study were small (<1 cm), especially among individuals with CCL < 45 cm. This predominance of small tumors in smaller turtles suggests early-stage infections and is consistent with expectations for juveniles recently exposed to the virus. Although no significant relationship between turtle size and tumor size was found, similar patterns have been documented elsewhere and are often interpreted within the context of viral pathogenesis (Baptistotte 2007, Tagliolatto et al. 2016, Bastos et al. 2022, Miguel et al. 2022). Previous studies suggest that ChHV5 replication peaks during the early stages of infection (Rodenbusch et al. 2014, Work et al. 2015), contributing to the emergence of small tumors during the initial disease phase. As the disease progresses, viral replication may decrease, even as tumors continue to enlarge and persist (Work et al. 2004), supporting the hypothesis that FP follows an initial phase of intense viral activity followed by chronic tumor development.

According to FPS$_{SWA}$ criteria, most turtles exhibited mild forms of the disease. This finding is compatible with reports from several feeding areas (Baptistotte 2007, Patrício et al. 2016, Tagliolatto et al. 2016, Rossi et al. 2019, Silva-Júnior et al. 2019, Monteiro et al. 2021, Vanstreels et al. 2023), while severe cases appear more frequent in Espírito Santo, Brazil (Santos et al. 2010, Miguel et al. 2022). Geographic differences in disease severity may reflect variation in local environmental conditions or in host-pathogen dynamics, including potential variation in the pathogenicity of

circulating ChHV5 strains (Ene et al. 2005, Zamana et al. 2021). While viral genotyping was not conducted in this study, genomic analyses of ChHV5 in other regions have demonstrated broad divergence between geographic strains and evidence of recombination, suggesting that viral variation may contribute to differences in disease manifestation (Morrison et al. 2018).

Although FP-affected turtles had slightly higher average BCI values than unaffected individuals, the difference was not statistically significant. This result is consistent with findings from other studies in Brazil (Tagliolatto et al. 2016, Santos et al. 2017, Rossi et al. 2019, Miguel et al. 2022) and elsewhere (Espinoza-Rodríguez & Barrios-Garrido 2021), which have reported either similar or unexpectedly higher BCI values in FP-affected turtles. This contrasts with earlier assumptions that FP would negatively affect body condition. In the Pacific, for example, FP has been associated with moderate to severe emaciation, cachexia, and other signs of poor condition in tumored turtles (Work et al. 2001), suggesting geographic variation in disease impacts. Several authors have suggested that the presence of numerous or large tumors can artificially inflate body mass, leading to elevated BCI values and potentially masking physiological impairment (Rossi et al. 2019, Vanstreels et al. 2023). In our case, most tumors were small, potentially minimizing this effect. Nevertheless, because BCI does not differentiate between muscle, fat, and abnormal tissue mass, it may lack the sensitivity needed to accurately reflect nutritional or health status in FP-affected individuals (Santos et al. 2015, Patrício et al. 2016, Domiciano et al. 2019, Vanstreels et al. 2023). This reinforces the need for caution in interpreting BCI values in the context of FP and suggests that future assessments might benefit from integrating tumor burden indices (e.g. FPI) to improve accuracy and diagnostic sensitivity.

Tumor progression occurred most frequently; however, we also documented tumor regression more often than previous studies reported in coastal areas such as Itaipu (Rio de Janeiro, Brazil; Machado Guimarães et al. 2013, Tagliolatto et al. 2016), Akumal Bay (Quintana Roo, Mexico; Muñoz Tenería et al. 2022), and Kwale County (Kenya; Hancock et al. 2023). This may reflect contextual differences in environmental or immunological factors affecting disease dynamics, such as local water quality, pollutant loads, or nutritional stressors that can influence immune competence and viral expression in sea turtles (Aguirre & Lutz 2004, Herbst et al. 2004, Bastos et al. 2022). Alternatively, regression in some individuals may indicate an intrinsic capacity to mount an effective immune

response capable of reducing or eliminating tumors over time. A similar case was recently described by Pérez et al. (2024), who documented complete regression of skin tumors in a juvenile green turtle in Itapirubá (Santa Catarina, southern Brazil) using photo-identification and histopathological analysis. These findings underscore the value of longitudinal monitoring, which enables the detection of such trends and provides insights into the timing and progression of FP lesions, patterns only discernible through repeated, long-term observations.

Stage transitions based on FPS$_{SWA}$ scores indicated several events of turtles shifting from mild to absent categories. However, only 6 cases were classified as complete remission in the photographic analysis. This difference reflects that FPS$_{SWA}$ transitions capture all recorded events, including repeated transitions for the same individual, whereas the photographic assessment was restricted to recaptures with high-quality images and to cases without subsequent relapse. Occasional inconsistencies in field records may also contribute. Therefore, the remission events reported here should be considered conservative estimates.

In our study, one individual (Fig. 6A) exhibited a skin marking in the femoral fossa region upon initial capture, possibly representing an early stage of tumor development. Similar markings are frequently observed in captured individuals; however, it remains unclear whether these represent incipient fibropapillomas or unrelated skin conditions, as this has not yet been formally investigated. Additionally, in another case (Fig. 8), a tumor developed at the site of a metal flipper tag. Although this was not examined in detail, field observations suggest that tumor development near tagging sites may be relatively common, highlighting the need for further research into possible associations between tagging procedures and the FP onset. We recorded a rare long-term FP trajectory in this individual, with tumors progressing and later regressing over intervals of several years, underscoring the potential for natural reversal of disease even after prolonged progression.

5. CONCLUSIONS

Patterns of FP observed in Babitonga Bay, including high prevalence among juveniles, predominance of small anterior tumors, and mostly mild clinical forms, are consistent with reports from other Brazilian coastal regions (Espírito Santo, Rio de Janeiro, São Paulo, and Paraná), suggesting common ecological drivers of FP across foraging grounds. Tumor progres-

sion was the most frequent outcome among recaptured individuals, although cases of regression, including complete remission, were also documented, indicating individual variation in disease trajectories.

These findings highlight the importance of long-term monitoring using capture—recapture data to track FP dynamics and inform conservation. Environmental stressors such as climate change, rising ocean temperatures, ongoing ecosystem degradation, and expansion of port activities may exacerbate FP outbreaks in the future, emphasizing the need to understand and mitigate both ecological and anthropogenic drivers. Continued monitoring of key foraging habitats like Babitonga Bay is essential to safeguard juvenile green turtles, refine population models, and support evidence-based management actions aimed at reducing disease impacts and promoting population resilience.

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