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Fibropapillomatosis dynamics in green sea turtles *Chelonia mydas* over 15 years of monitoring in Akumal Bay, Quintana Roo, Mexico

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ABSTRACT: Fibropapillomatosis (FP) is a tumor disease that affects all sea turtle species but is mainly seen in green turtles *Chelonia mydas*. The pathology of FP has been described extensively, but its dynamics in populations over time have been less studied. We analyzed the dynamics of FP in a population of green turtles in Akumal Bay on the central coast of the Mexican Caribbean. A total of 475 green turtles were captured over 15 yr (2004–2018). The highest prevalence of FP was found in the largest turtles, and there was a positive relationship between FP prevalence and size of turtles. FP was first detected in 2008 at a prevalence of 1.6%, and annual prevalence increased markedly from 17.9% in 2015 to 54% by 2018. Likewise, severity of FP increased over time, with most turtles falling into moderately to severely diseased categories (tumor score 2). The average size of turtles with FP was significantly larger than the size of individuals without FP. Regression of tumors was seen in 21% of turtles, tumor score was higher in smaller individuals, and only tumor score 2 was present in the largest sea turtles. An increase in the prevalence and tumor score of FP coincided with the massive arrival of *Sargassum* in 2015, suggesting that altered environmental conditions may have played a role. The increased prevalence of FP in Akumal Bay prompts the need to explain what might be driving this phenomenon and how widespread it is in the Caribbean.

KEY WORDS: Green turtle · Fibropapillomatosis · Tumor score · *Sargassum*

1. INTRODUCTION

The destruction, degradation, and contamination of habitats contributes to the outbreak and dispersion of diseases, many of which can reach pandemic proportions (Cunningham et al. 2017). One example of such a disease is fibropapillomatosis (FP), a debilitating chronic tumor disease of sea turtles that affects mainly green turtles *Chelonia mydas*. FP is increasing in prevalence in the southeastern USA and is often associated with eutrophic habitats (Shaver et al. 2019). This disease is characterized by the pro-

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gressive development of cutaneous fibropapillomas or papillomas and visceral fibrosarcomas, myxofibromas, or fibromas of indeterminate etiology that are transmissible through filterable tumor extracts (Herbst et al. 1995, Work et al. 2004). Pathology of FP has been described extensively in the literature (Herbst et al. 1999, Work et al. 2004).

A herpesvirus called chelonid alphaherpesvirus 5 (ChHV5) has been consistently associated with tumors, but its role in FP development is uncertain. This is in part because of difficulties in manipulating the virus in the laboratory (Quackenbush et al. 1998, Greenblatt et al. 2005, Alfaro-Núñez et al. 2014, Work et al. 2015). Recent advances in culturing ChHV5 using an *in vitro* culture system that recapitulates the complex 3-dimensional structure of turtle skin may provide a useful tool to understand the pathogenesis of FP in the future (Work et al. 2017).

Other factors such as marine leeches (Greenblatt et al. 2004, Santoro et al. 2007) and environmental cofactors are also associated with FP. The latter seem particularly important, and several authors have suggested that marine pollution, heavy metals, toxins, and eutrophication by human activity play an important role in the pathogenesis of FP (Herbst 1994, dos Santos et al. 2010, Van Houtan et al. 2010, 2014, Keller et al. 2014, da Silva et al. 2016); however, evidence for this is mixed. Although the highest prevalence of FP is found in waters with poor environmental quality, there are also areas with good environmental quality with a lower but significant prevalence of FP (Foley et al. 2005, Perrault et al. 2020).

Host-related factors also play a role in FP. For instance, FP can preferentially affect medium-sized juveniles (Patrício et al. 2016), and host response to the virus varies with geography (Work et al. 2020). Some studies have reported that up to 60% of animals can have tumors that regress in some juvenile green turtles (Bennett et al. 1999, Hirama & Ehrhart 2007, Chaloupka et al. 2009, Rossi et al. 2016). This evidence of tumor regression and the few cases recorded in adult turtles show that FP can resolve spontaneously, suggesting an important role for immune response in pathogenesis of disease. FP is distributed worldwide; its prevalence varies from region to region, but the highest prevalence has been reported in Florida, USA (Hirama & Ehrhart 2007), and more recently, in Brazil (Rodenbusch et al. 2014, Jones et al. 2016, Tagliolatto et al. 2016), with prevalence of FP declining in Hawaii for unknown reasons (Chaloupka et al. 2009).

Akumal Bay in Quintana Roo, Mexico, in the central part of the Mexican Caribbean coast, is a major area of tourism development, with consolidated areas such as the City of Cancun, as well as areas of incipient growth such as Akumal Bay (Vázquez-Sosa et al. 2015). In recent years, Akumal Bay, an important feeding area for juvenile green turtles, has experienced accelerated growth of tourism due to the attraction of its crystalline waters, coral reefs, sport fishing opportunities and, most importantly, to the possibility of observing and swimming with green turtles that feed in the shallow waters of the bay (Labrada-Martagón et al. 2017). This has resulted in increasing eutrophication of the bay waters with significant adverse effects on marine organisms such as coral reefs (Gil et al. 2015). Akumal Bay was declared a Refuge for the Protection of Marine Life by the Mexican Federal Government on 7 March 2016 (Diario Oficial de la Federación 2016), with the objective of protecting the flora and fauna of the area through sustainable management. A program to monitor the health and ecology of the turtles that inhabit this bay started in 2004 (Labrada-Martagón et al. 2017); it was under this program that the presence of FP was first detected in 2008. The objective of this work was to assess the progression and characteristics of FP based on data collected during 15 yr of monitoring the population of green turtles that inhabit Akumal Bay, and to infer the possible effects of this disease on the green turtle population.

2. MATERIALS AND METHODS

2.1. Study site

The Marine Life Refuge of Akumal Bay (which in the Mayan language means 'place of turtles') is located on the central coast of the State of Quintana Roo (20° 24′ 0″ N, 87° 19′ 16″ W). There is a stable population of green turtles of different sizes that feed on pastures of seagrasses such as *Halodule wrightii*, *Thalassia testudinum*, and *Syringodium filiforme* (Molina Hernández & van Tussenbroek 2014). The bay includes a barrier reef about 300 m offshore that forms part of the Mesoamerican Coral Reef (Baker et al. 2013). The depth of the bay ranges from 1.5 to 4 m, with seagrasses distributed mainly in the northern part and in small reef areas.

2.2. Capture of specimens

Turtles were captured manually by snorkelers working off boats every year from 2004 to 2018 during the summer (July and August), except for 2005 and 2017, using longitudinal mixed capture–recapture sampling (Labrada-Martagón et al. 2017). For all turtles, flexible tape was used to measure maximum curved carapace length (CCL) from the anterior point at the midline (nuchal scute) to the posterior tip of the supracaudals, and curved carapace width at the widest point. A Monel tag (National Band and Tag Company) was affixed between the first and second trailing axial scales of the right forelimb, after cleaning the application site with povidone iodine and 70% alcohol.

2.3. Documenting tumors

For each turtle with external tumors, the number and largest diameter (cm) of tumors on the skin of the head, eyes, oral cavity, dorsal and ventral surfaces of the flippers, and carapace and plastron were carefully recorded, and based on this, turtles received a tumor score as described by Work & Balazs (1999). Tumor regression (tumor size decreased or absent) or progression (tumor size increased) was recorded for each turtle with 2 or more recapture events. As an indicator of annual abundance (Bjorndal et al. 2000), annual catch per unit of effort (CPUE), was estimated as the number of green turtles captured per year divided by the number of units of effort (h yr^{-1}) (Labrada-Martagón et al. 2010, Bjorndal et al. 2017). Sea turtles captured for the first time with no tag or tag scar were considered neophytes (Richardson et al. 1999). Turtles smaller than 86 cm CCL were considered immature individuals of unknown sex (Labrada-Martagón et al. 2017).

2.4. Statistical analysis

Frequency tables and descriptive statistics were evaluated to analyze population structure, number and size of tumors, and prevalence of FP over time. A chi-squared test of goodness of fit was used to evaluate the prevalence of tumors over the years. The assumptions of normality and homoscedasticity were tested for CCL and number of tumors by using Shapiro-Wilk and Bartlett's tests. Differences in the size (CCL) of sea turtles with or without FP were analyzed using a Student's *t*-test. A Kruskal-Wallis test or ANOVA was performed to compare the size of sea turtles between years and tumor score between the years 2012, 2014, 2015, 2016, and 2018 (years with $n > 5$). All analyses were considered significant at an α of 0.05. Univariate statistical analyses were run in Statistica v.8.

2.5. Modeling of FP

Generalized additive model (GAM) analysis was used to assess the non-linear dynamics of the occurrence of FP (presence/absence) and severity of FP (tumor score) in response to the explanatory variables CPUE, size of individuals (CCL, cm), year, and season of capture. The contribution of season was evaluated as an independent variable (Labrada-Martagón et al. 2013). The variable CPUE was considered an indicator of the relative abundance of green turtles (Bjorndal et al. 2000, Labrada-Martagón et al. 2017). Occurrence and severity of FP were modeled as separate dependent variables; different models were tested to assess the contributions of distinct combinations of covariates. Models were fitted by using cubic regression splines, based in third-order polynomials (Stevenson & Woods 2006, Zuur et al. 2009), to characterize the non-linear relationship between covariates and FP (Patrício et al. 2016) and restricted maximum likelihood (REML) for smoothing parameter estimation. REML is preferred for finite sample sizes in order to avoid overfitting (Stevenson & Woods 2006). A binomial error and a 'logit' link function were used when modeling presence/absence of FP; Poisson error and 'log' link were used for tumor score (Zuur et al. 2009). The contribution of each explanatory variable was evaluated for each independent model ($p < 0.05$), and the overall model fit was assessed by considering Akaike's information criterion, the adjusted R^2 estimates, and by hypothesis testing procedures (chi-squared test) (Stevenson & Woods 2006, Zuur et al. 2009). GAM was performed in R using the 'mgcv' package (Stevenson & Woods 2006) in R v.3.1.3 (R Core Team 2016).

3. RESULTS

Table 1 shows annual mean CCL, prevalence of FP, and CPUE in Akumal Bay, Quintana Roo, Mexico. A total of 475 turtles were captured over a period of 15 yr, with 2 interruptions (2005 and 2017). CCL ranged from 21 to 82.8 cm (Fig. 1A). Turtles captured in 2015 and 2016 were significantly larger ($F_{5,331} = 6.76$, $p < 0.001$). The CPUE was higher in the period 2014–2016 (Table 1). Frequency of neophytes remained constant across years ($\chi^2 = 8.4$, $p = 0.25$), and frequency of recap-

Table 1. Annual mean ± SD curved carapace length (CCL), number of turtles sampled (n) in each year, number of tumors per year (with prevalence of fibropapillomatosis [FP] in parentheses), tumor score (based on Work & Balazs 1999), and capture per unit effort (CPUE) for green turtles *Chelonia mydas* captured in Akumal Bay, Quintana Roo, Mexico. No turtles were captured during 2005 or 2017

Year	All turtles CCL (cm) Mean ± SD	All turtles CCL (cm) Range	n	Turtles with FP Prevalence (%)	Turtles with FP CCL (cm) Mean ± SD	Turtles with FP Tumor score Mean ± SD	CPUE Annual
2004	57.6 ± 11.6	32.5–81.0	14	0	–	0	0.9
2006	53.1 ± 13.8	27.8–77.0	40	0	–	0	3.7
2007	58.8 ± 12.5	33.0–72.3	17	0	–	0	3.3
2008	59.3 ± 13.8	32.8–81.3	60	1 (1.6)	65.8	1	2.4
2009	55.4 ± 15.2	31.0–82.5	42	1 (2.4)	78.3	1	4.7
2010	56.6 ± 14.1	29.8–81.8	24	2 (8.3)	60 ± 7.07	1 ± 0	6.2
2011	60.1 ± 7.3	50.3–79.3	18	0	–	0	3.3
2012	61.8 ± 10.2	34.0–80.3	44	3 (6.8)	58.2 ± 20.9	1.6 ± 1.1	
2013	60.0 ± 11.4	21.0–79.0	67	1 (1.5)	64.8	1	6.1
2014	61.1 ± 10.7	37.2–82.8	70	3 (4.2)	63.5 ± 2.2	1.3 ± 0.6	8.9
2015	65.3 ± 9.2	45.0–78.3	28	5 (17.9)	72.3 ± 5.1	1 ± 0	8.5
2016	63.0 ± 8.9	40.7–80.0	38	10 (26.3)	67.8 ± 7.4	1.2 ± 0.6	8.4
2018	61.7 ± 10.6	47.0–75.1	13	7 (53.8)	69.2 ± 6.6	1.6 ± 0.8	5.7

tures during 2012–2018 was twice that of sea turtles recaptured during the period 2004–2011 (χ^2 = 34.4, p < 0.001) (Fig. 2). Of 487 turtles, 33 had FP (6.8%); the highest prevalence of FP was found in the largest turtles, mainly those in the subadult class (range 60.4–80.5 cm of CCL, 5.95%, n = 29 turtles) (Fig. 1A). The first case of FP in the Akumal Bay was detected in 2008; the annual prevalence remained below 10% until 2014. From 2015, the annual prevalence increased steadily until reaching 54% in 2018 (Table 1, Fig. 2). The average (±SD) size of turtles with FP (77.67 ± 15.2 cm CCL) was significantly larger than the size of individuals without FP (65.3 ± 18.1 cm CCL; t = −4.86, p < 0.001) (Fig. 1B).

Of the turtles with FP, 58% were categorized as tumor score 1, 38.5%, as tumor score 2, and 4% as tumor score 3. All tumors were found on soft tissues and mainly in the cranial half of the body (63.6%), including the neck (n = 9 tumors), axillary region (n = 4), and forelimbs (n = 54), as well as on the eyelids and conjunctiva of the eye (31.4%, n = 36). A much smaller proportion (5.1%) of tumors were on the hindlimbs (n = 4), inguinal region or tail (n = 2). No

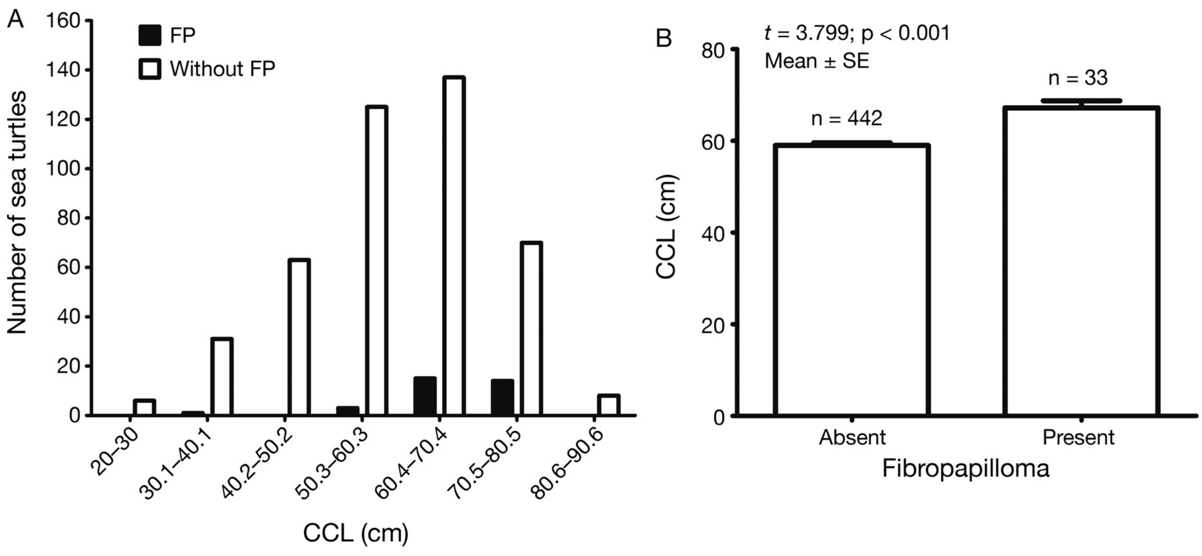

Fig. 1. (A) Frequency distribution of curved carapace length (CCL) and (B) size differences of green sea turtles *Chelonia mydas* with and without fibropapillomatosis (FP) from Akumal Bay, Quintana Roo, Mexico, captured over a 15 yr period (2004–2018)

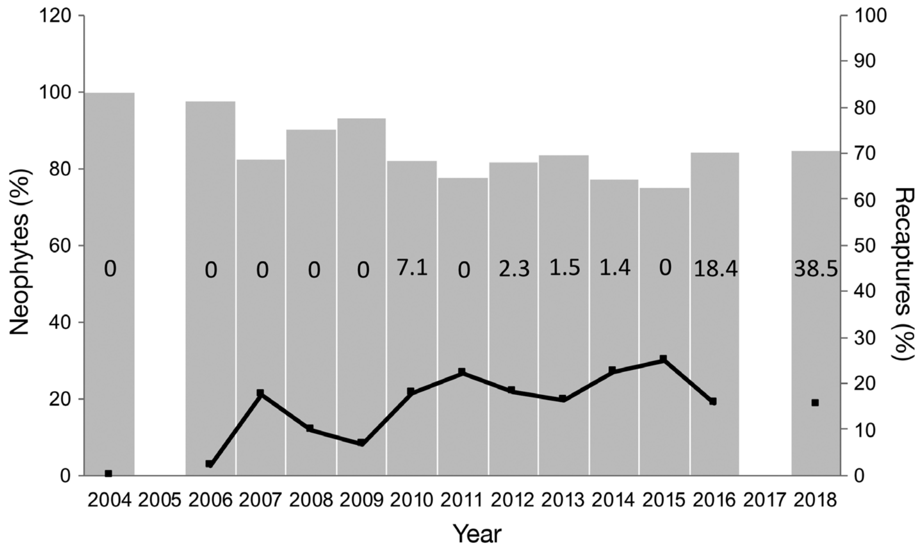

Fig. 2. Frequency of neophyte green turtles *Chelonia mydas* captured (bars), frequency of recaptures (line), and the annual percentage prevalence of fibropapillomatosis (FP) (numbers inside the bars) in neophyte green turtles in Akumal Bay, Quintana Roo, Mexico, during 2004–2018. A notable increase in the prevalence of FP can be observed in 2016 and 2018

tumor was observed on the mouth, carapace, or plastron (Fig. 3).

Based on recapture data, 21% of turtles exhibited tumor regression, with all regressing turtles going from tumor score 1 to score 0; in all cases, tumors were in the conjunctiva or periocular tissues. The mean CCL at recapture of turtles with regression was 74.5 ± 4 cm (SD).

In both GAMs, size of sea turtles (CCL, cm) and year were covariates that together explained, with statistical significance, the occurrence and severity of FP of green turtles in Akumal Bay (Table 2). FP prevalence and tumor score were explained by 28 and 31%, respectively. Season and year (as categorical covariates) and CPUE were not explanatory. There was an increasing trend in both FP prevalence (Fig. 4A,B) and severity (Fig. 4C,D) with CCL and years. There was a noticeable increase in FP after 2015, reaching a peak in 2018. Severity of FP (tumor score) tended to be higher in smaller individuals (<40 cm CCL), and tumor score remained constant in sea turtles >60 cm CCL (Fig. 4C).

4. DISCUSSION

Long-term monitoring of FP in sea turtle populations is crucial for understanding the dynamics of the disease and elucidating its epizootiology and pathogenesis (Chaloupka et al. 2009). The prevalence of FP varies by geography. For instance, in some regions, such as Hawaii and Puerto Rico, a rapid increase in prevalence of FP was observed, reaching a maximum peak (>90% in Hawaii), followed by a slow decrease in case numbers (Chaloupka et al. 2009, Patrício et al. 2016). In Brazil, a sustained increase has been reported (Tagliolatto et al. 2016), while a high prevalence has been observed in Florida, where it has remained stable (Foley et al. 2005). Our monitoring project is the first of its kind in Mexico, and the results demonstrate that at one site in the Yucatan peninsula, FP prevalence has undergonea recent, steady increase at least through 2018, the last year monitored.

One potential explanation for the increase in FP prevalence is that the population structure of the green sea turtles of Akumal Bay has changed over the years, mainly in the last decade. Size of the captured specimens significantly increased over time, especially in 2015 and 2016, and larger turtles in Mexico seem more prone to have FP, a phenomenon similar to that seen in green turtles from Brazil (Tagliolatto et al. 2016). In contrast, in other regions like Florida, Texas, Puerto Rico, and Brazil, medium-sized turtles were the most affected by the disease (Herbst 1994, dos Santos et al. 2010, Shaver et al. 2019). In places such as Puerto Rico and Brazil, where small turtles (30–45 cm CCL) predominate and where turtles affected with FP are in the medium size range (40–60 cm CCL), it appears that turtles acquire the disease shortly after recruitment to coastal foraging grounds, which would explain why FP affects mainly juveniles (Herbst 1994, Patrício et al. 2016, Tagliolatto et al. 2016). In Akumal Bay, the green turtle population consists of individuals between 25 and 85 cm CCL (Labrada-Martagón et al. 2017), with the highest number of turtles in the medium to large size classes (50–80 cm CCL) that possibly develop tumors after recruitment in the bay. The hypothesis that larger turtles acquire FP in Aku-

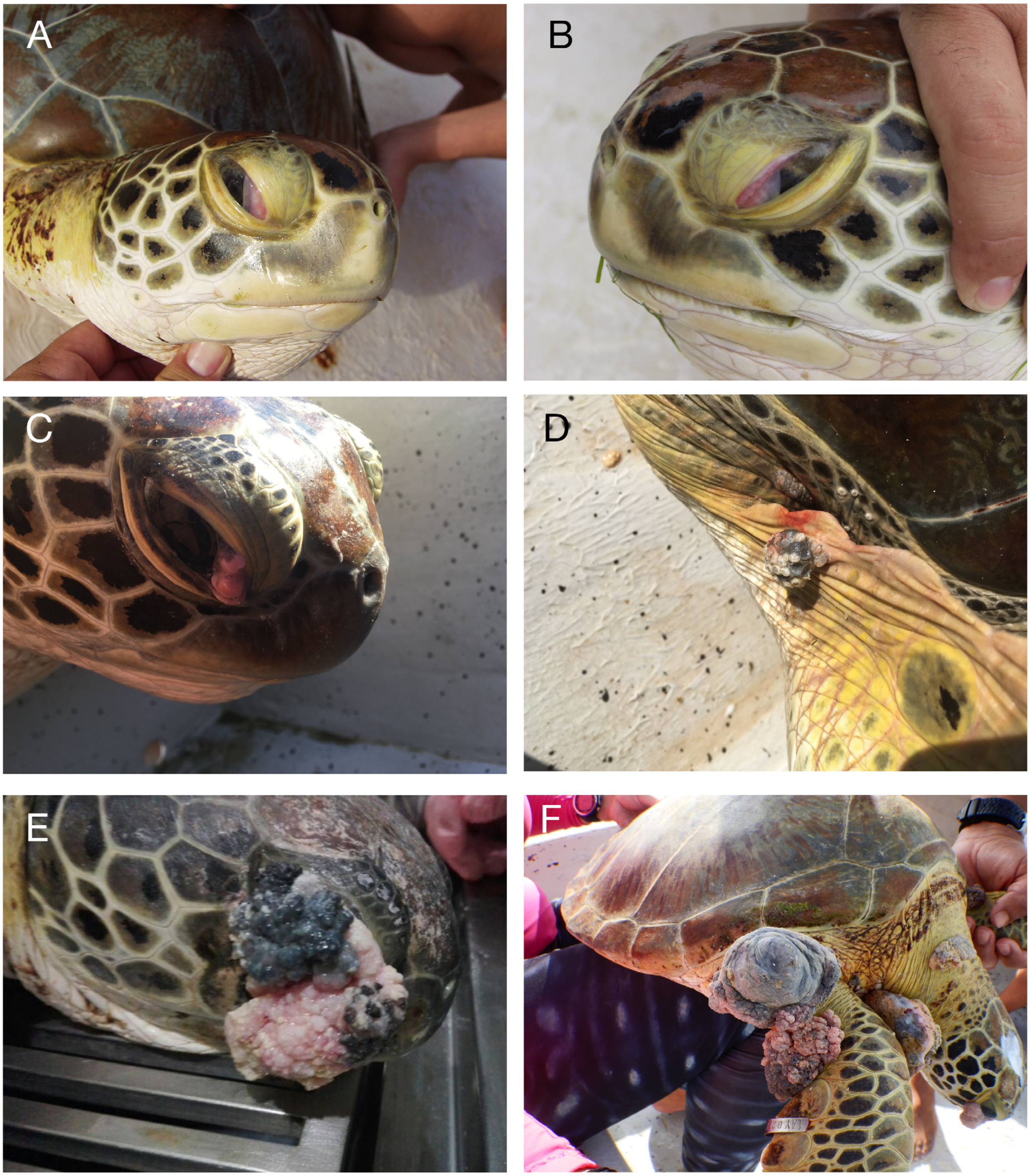

Fig. 3. Increasing severity of fibropapillomatosis (FP) over time in 5 different turtles (panels A & B show the same turtle). (A,B) First tumors detected in 2008 were restricted to the conjunctiva. (C,D) Marked increase in tumor size, involving eyes and neck skin, detected in 2015. (E,F) Detection of specimens severely affected by FP in 2018, encompassing eyes and external soft tissues, as well as weakness and emaciation

mal Bay is anecdotally supported by a case of a 53.7 cm turtle found dead on the beach of Akumal Bay on 18 February 2019, with multiple tumors larger than 5 cm in the eyes and neck; this animal had been previously captured in 2016 (53 cm CCL) with no tumors. The prevalence of FP, observed mainly in subadult turtles (60–80 cm CCL) in Akumal Bay, suggests that unlike other regions like Florida or Hawaii where turtles develop FP as juveniles, development of FP in Akumal Bay occurs much later, probably because the proportion of turtles <50 cm has been low since the start of monitoring in Akumal Bay (2004),

Table 2. Summary of generalized additive models of prevalence of fibropapillomatosis (FP) in green sea turtles *Chelonia mydas* captured in Akumal Bay, Quintana Roo, Mexico. Fitted models are shown after model selection for fibropapillomatosis presence and number of tumors. CCL: curved carapace length; AIC: Akaike's information criterion; edf: estimated degrees of freedom

Model	N	R^2	AIC	Deviance explained (%)	Fixed effects				Smooth terms			
						Estimate	SE	p	Variable	edf	χ^2	p
Presence FP ~ CCL + Year[a]	462	0.28	144.5	34.5	Intercept	−4.20	0.53	<0.001	CCL	2.23	9.39	0.02
									Year	3.80	36.3	<0.001
Tumor Score ~ CCL + Year[b]	462	0.31	178.4	43.1	Intercept	−4.11	0.50	<0.001	CCL	3.58	11.89	0.03
									Year	3.58	42.72	<0.001

[a]Binomial error distribution and logit link function; [b]Poisson error distribution and log link function

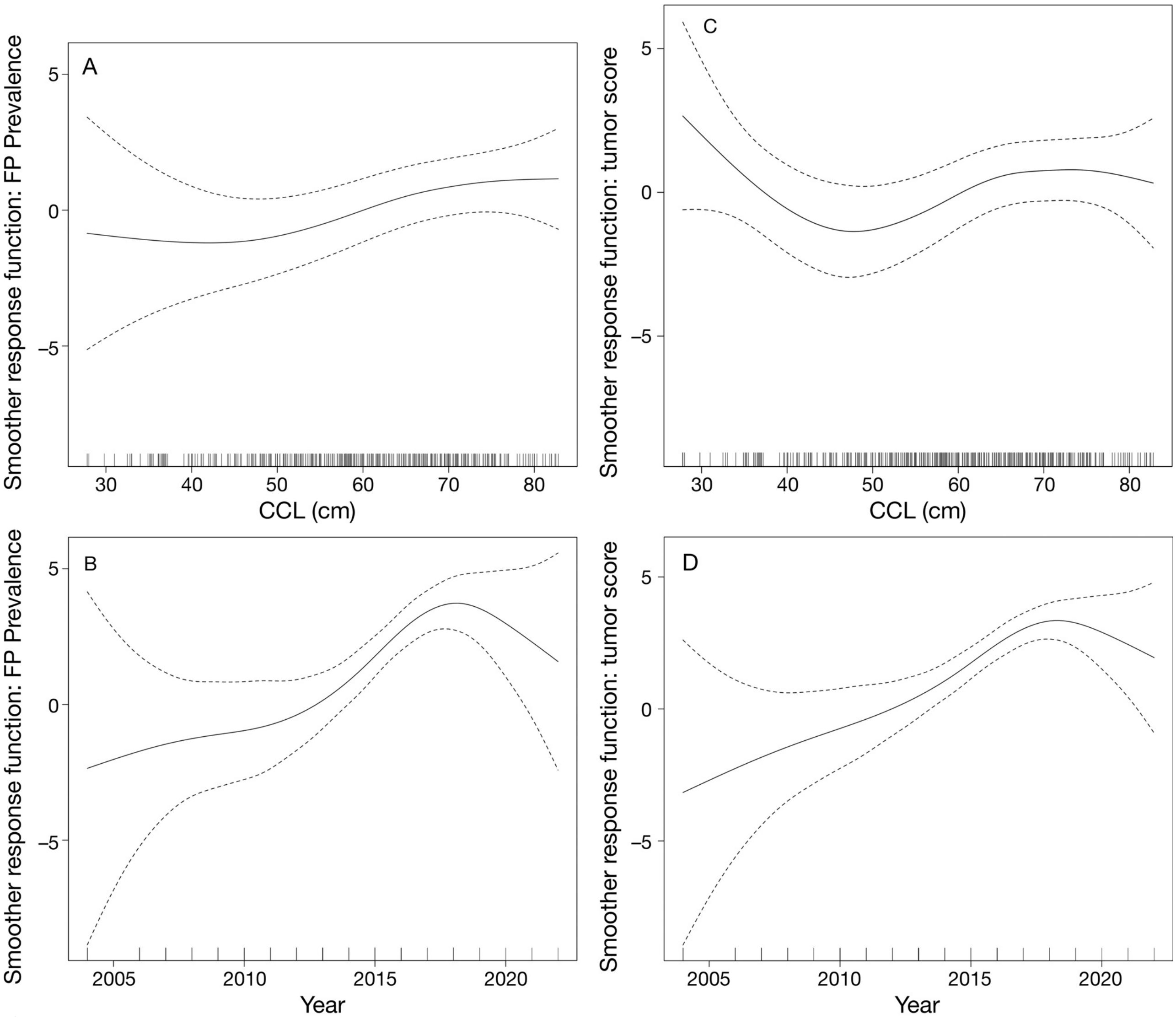

Fig. 4. Estimated smoothing curves by generalized additive models of (A,B) prevalence and (C,D) tumor score of fibropapillomatosis (FP) in green sea turtles *Chelonia mydas* captured in Akumal Bay, Quintana Roo, Mexico during 2004–2018, by size (curved carapace length, CCL; A,C) and year (B,D). Solid line is the smoother fit, dotted lines are 95% confidence bands. Vertical hatches (rug plot) along the *x*-axis in panels A and C represent covariate distributions

indicating that Akumal Bay has characteristics that are not conducive to allowing smaller turtles to thrive in that habitat (Fig. 2).

The increase in the prevalence and tumor score of FP observed, from 4.23% in 2014 to 53.85% in 2018 (Table1, Fig. 4) coincides with the massive arrival of *Sargassum* to the Caribbean coasts, which began in 2014, an event that has caused drastic changes in coastal and neritic waters, including accelerating the already ongoing eutrophication process caused by tourism development (Barrera Escorcia & Namihira Santillán 2004, Foley et al. 2005, Gil et al. 2015, van Tussenbroek et al. 2017). Many studies have shown the relationship between habitat degradation (urban and maritime developments) and a higher prevalence of FP (dos Santos et al. 2010, Van Houtan et al. 2010). There is evidence of a relationship between tourism development in Akumal Bay and increased mortality and adverse effects to marine life such as corals and fishes, associated with a greater amount of organic matter and human aquatic activity (Baker et al. 2013, Gil et al. 2015). The unusual arrival of large quantities of *Sargassum* to the coasts of the Mexican Caribbean has greatly increased the amount of organic matter in the water, which is already contaminated by organic leachates from land (van Tussenbroek et al. 2017). This suggests that the altered environmental conditions of the last decade in this green turtle foraging area may have played a role in the dramatic increase in the prevalence of FP, although this remains to be confirmed. If prevalence levels of FP continue to remain as elevated as those seen in 2018, then those levels are at least as high as those reported at other turtle foraging sites in the Gulf of Mexico, Caribbean, and the Atlantic (Foley et al. 2005, Patrício et al. 2016, Tagliolatto et al. 2016, Shaver et al. 2019). However, while the severity of FP has increased in Akumal Bay over the years (Figs. 3 & 4b), the disease is generally much less severe than in other regions; for example, no individuals with tumors >10 cm (tumor score 3) were captured, in contrast to sites like Hawaii (Work & Balazs 1999). It is possible that the severity of disease in in-water studies is underestimated, because we have seen much larger tumor sizes in stranded turtles with FP from the region undergoing rehabilitation.

Sea turtle density was not related to prevalence of FP in a previous study of the disease in green turtles from Puerto Rico (Patrício et al. 2016), a finding that accords with those of this study which showed no relationship between CPUE and prevalence of FP. Neophytes are those turtles not previously tagged and thus assumed to have no known history of residence at the foraging site (Richardson et al. 1999). A major increase (39%) in neophyte green turtles with FP was observed during the last 2 years of monitoring (2016 and 2018), suggesting a pulse of recruitment to Akumal Bay (Fig. 2). Neophyte green turtles with FP contributed 69.96 and 71.56% of the total prevalence of FP in 2016 and 2018, respectively, thus explaining the high increase of FP in those 2 years (Fig. 2). If the trend of increasing annual percentage of FP depends on a large percentage of neophyte green turtles with FP, it will be very important to constantly survey in the next years to determine if this correlation is maintained, and more importantly, to determine if these neophyte turtles acquire FP in Akumal Bay or are already recruited with FP and where they come from, which will contribute a lot to a better understanding of the epidemiology of FP.

Green turtles typically reside at Akumal Bay for 1–4 yr, and a density-dependent effect on their somatic growth has been suggested for this foraging area (Labrada-Martagón et al. 2017). A study of seagrass dynamics of Akumal Bay in 2011 concluded that there was excessive foraging with no rotation of pastures and thus a reduced chance of seagrass bed recovery (Molina Hernández & van Tussenbroek 2014). Overgrazing of seagrass beds by sea turtles has been seen elsewhere. For instance, seagrass beds in marine protected areas are degraded by overgrazing in Indonesia and the Indian Ocean (Christianen et al. 2014). The CPUE data presented here agree with these previous data (Molina Hernández & van Tussenbroek 2014), observing a greater abundance of sea turtles over time. It is important to understand how a bay with excessive foraging supports a sea turtle population that appears to be steadily increasing. One possible explanation is that Akumal is experiencing increased migration of green turtles from elsewhere that are being displaced as result of poor foraging habitat. There has been a notable decrease in the quality and/or quantity of food available in other feeding grounds near Akumal Bay as a result of masses of *Sargassum*, which began arriving off the coast of Quintana Roo in 2014 leading to degradation of coral reefs and seagrass beds along the Mexican Caribbean coast (Molina Hernández & van Tussenbroek 2014). Moreover, in Akumal there is a shift in the dominant seagrass species, favoring a greater abundance of *Syringodium* and *Halodule*, and decreasing *Thalassia*, with an apparent change in the feeding preference of turtles foraging in the bay (van Tussenbroek et al. 2017, Christianen et al. 2021). Although it is tempting to incriminate higher densities of sea turtles as a factor contributing to FP, a reasonable conjecture given that ChHV 5 is shed in tumors and the disease is likely transmitted by direct contact (Curry et al. 2000, Lloyd-Smith et al. 2005, Work et al. 2015), in our study, the covariates of relative turtle abundance turtle and season of capture did not significantly contribute to explaining prevalence of FP. Our findings accord with those elsewhere, for instance Puerto Rico, where no relationship between turtle density and FP was seen (Patrício et al. 2016).

The fact that year and size explained only 28 and 31% of the variability in prevalence and severity of FP suggests that additional factors such as environmental variables (e.g. level of contaminants, eutrophication) or endogenous factors (e.g. metabolic and immune status) might be involved in the development of FP in green turtles in Akumal Bay, as suggested elsewhere (Aguirre & Lutz 2004, Foley et al. 2005, Jones et al. 2016). The immune response to FP differs among geographic areas and severity of disease can affect immune response (Work et al. 2001, 2019). How these factors play out in Akumal remains to be determined.

The locations of tumors on the eyes and soft tissues of the more cranial aspects of affected turtles in Akumal Bay reported here were consistent with the pathologic features reviewed in the literature (Herbst 1994, Work et al. 2004, Van Houtan et al. 2014, Jones et al. 2016). Notably, we saw no tumors on the carapace or plastron. Interestingly, we recorded a tumor regression rate of 21% in recaptured turtles, similar to that found in other studies (Chaloupka et al. 2009, Machado Guimarães et al. 2013, Patrício et al. 2016). However, the results of the present study differ in terms of the size of the tumors, since tumor regression only occurred in all small tumors (<4 cm) present in the conjunctiva and periocular tissues of subadult turtles. Tumor regression likely occurred in <1 yr, as turtles were found to be tumor-free at the subsequent recapture (1 yr later).

5. CONCLUSIONS

Although FP does not seem to pose an immediate threat to sea turtle populations worldwide (Chaloupka et al. 2009, Jones et al. 2016), the increasing prevalence of FP in Akumal Bay is an important ecological signal that merits further investigation. Given the high visibility of this disease in a charismatic species like the green sea turtle in a nationally renowned ecological reserve frequented heavily by the public, a need exists to better understand underlying drivers of this trend.

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