# Long-term Growth Trends of Hawaiian Green Turtles (*Chelonia mydas*): Insights from Tagging Data at Punaluʻu Beach, Hawaiʻi Island (1976–2018)

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**ABSTRACT:** Growth rates are essential for understanding the demographics and dynamics of sea turtle populations but may vary regionally due to variability in habitat quality, food availability, turtle density, and environmental conditions. Punaluʻu Beach on Hawaiʻi Island is a key foraging ground for Hawaiian green turtles (*Chelonia mydas*). In the past decades, declining growth rates within the Hawaiian Archipelago have raised concerns about the long-term stability of turtle populations. From 1976 to 2018, green turtles were captured at Punaluʻu and measured for straight carapace length (SCL) and mass (kg). Recaptured individuals were tracked over time to assess growth rates (GR = (SCL final - SCL initial) / Years) and the body condition index (BCI = (Mass / $SCL^3$) x 10,000). Of 319 turtles captured, 186 were recaptured at least once during the 40 years, and 98 were recaptured three or more times. The average annual growth rate for 167 individuals was 1.07 ± 0.05 cm/year. Average growth rates declined from 2.30 ± 0.37 cm/year in the 1980s to 0.62 ± 0.07 cm/year in the 2010s. The average BCI for 290 individuals was 1.40 ± 0.005. Size-specific data showed that juveniles averaged 24.53 ± 0.69 kg in mass (SCL: 54.62 ± 0.60 cm), subadults 48.54 ± 1.05 kg (SCL: 70.33 ± 0.38 cm), and adults 89.89 ± 3.17 kg (SCL: 86.35 ± 0.87 cm). Additionally, modeling projects SCL asymptotes around 80 cm at 50 years. Understanding these growth trends helps develop management strategies and provides comparable data with other green turtle aggregations in Hawaiʻi.

**KEY WORDS: Growth rates, Straight carapace length, Body condition index, Somatic growth, Growth model**

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## INTRODUCTION

Green turtles *(Chelonia mydas*) somatic growth rates provide insight into demographic and life history patterns to inform conservation efforts (Balazs 1982, Bjorndal & Bolten 1988, Van Houtan et al. 2014, Labrada-Martagón et al. 2017, Zárate et al. 2015). Growth rates can indicate habitat quality, environmental conditions, and anthropogenic pressures that impact turtle survival (Bjorndal & Bolten 1988, Kubis et al. 2009, Labrada-Martagón et al. 2017, Zárate et al. 2015). For green turtles, growth rates vary across regions because of changes in environmental conditions, such as water temperature and diet (Balazs 1982, Balazs & Chaloupka 2004, Eguchi

2012, Frazer & Ehrhart 1985). Food availability and quality can fluctuate in response to sea surface temperature or turtle population density (Labrada-Martagón et al. 2017, McDermid et al. 2007, Nishizawa et al. 2023).

Studies in the Hawaiian Archipelago have recorded variation in growth rates for green turtles that were thought to be a result of resource availability (Balazs 1982, Bjorndal & Bolten 1988, Eguchi 2012, Kubis et al. 2009). In addition, growth rates are impacted by size because growth slows as a turtle reaches sexual maturity (Balazs & Chaloupka 2004, Chaloupka & Balazs 2005). In the Southern Great Barrier Reef, green turtle growth rates peak at specific carapace lengths before slowing down as turtles approach maturity, which can vary (Bjorndal et al. 2000, Carr & Goodman 1970). Similarly, green turtle populations in Florida show individual growth rates that generally decline as turtles grow larger (Kubis et al. 2009). Diseases such as fibropapillomatosis (FP) have been correlated with lower growth rates for turtles with severe cases (Chaloupka & Balazs 2005, Kubis et al. 2009). Analysis of these regional differences is essential to the management of green turtle populations (Bjorndal et al. 2000, Eguchi 2012).

Punaluʻu Beach on the southeast shore of Hawaii Island (19.14°N, 155.50°W) is a prominent foraging ground for green turtles (Balazs 1982, Balazs & Chaloupka 2004). An abundance of red algae, predominantly *Pterocladia capillacea*, grows in the intertidal zone and is found to be a primary food source at this site (Balazs 1982, Balazs et al. 1994). Over many decades, green turtles have been captured, weighed, measured, and released at Punaluʻu (Balazs et al. 1994, Balazs & Chaloupka 2004). These efforts have contributed to understanding demographic patterns by identifying a long-term decline in growth rates with a population incline from 1976 to 2001 across multiple foraging grounds in the Hawaiian Archipelago (Balazs & Chaloupka 2004, Wabnitz et al. 2010). Research from this foraging ground can be applied to other sites in the Hawaiian Archipelago for comparison to develop informed conservation strategies (Balazs 1982, Kubis et al. 2009).

The primary goal of this study was to analyze 40+ years of Hawaiian green turtle tagging data that were recorded at Punaluʻu Beach from 1976 to 2018, thus extending the work of Balazs & Chaloupka (2004). Examination of trends in straight carapace length (SCL), mass (kg), growth rate (cm/yr), and body condition index (BCI) provides long-term data on the demographics of the population. A model based on growth rates was used to predict the size at which individuals will reach sexual maturity, and can provide insight about the viability of this population.

## METHODS

Data were collected at Punaluʻu Beach on Hawaiʻi Island, an exposed shoreline facing south with a subtidal substratum composed of basalt, sand, and rock. Green turtles were captured and released in the nearshore waters of Punaluʻu at depths of 2 to 8 m. Measurements were recorded by George Balazs (National Marine Fisheries Service, Marine Turtle Research Program), assisted by numerous student volunteers from the University of Hawaiʻi at Hilo.

Sampling occurred from August 1976 to July 2018 between 10:00 and 16:00 HST on all days (Fig. 1).

Fig. 1. The study site is Punaluʻu Beach, Hawaiʻi Island, Hawaiʻi, USA. The square on the inset map indicates the geographical location of Hawaiʻi Island in the Hawaiian Islands chain. Data were collected from August 1976 to July 2018.

Capture methods have evolved over the past four decades, transitioning from the use of tangle nets to the current standard protocol of hand-capture by teams of swimmers and snorkelers (Balazs 1982, Balazs et al. 1994, Balazs & Chaloupka 2004). For each captured turtle, tag number, date, sex, straight carapace length (SCL), curved carapace length (CCL), mass (kg), tumor presence, and capture method were recorded. SCL has been reported to be a more accurate measurement for growth rate analysis (Balazs 1982, Eguchi 2012). In instances with SCL not recorded and only CCL, the linear regression function SCL = 1.245 + 0.913 * CCL, $R^2 = 0.996$ (Chaloupka et al. 2008, Dentlinger et al. 2024) was used to convert to SCL. Set as size standards for Hawaiian green turtles, juveniles range from post-hatchling to 65 cm SCL, subadults from 65 to 81 cm SCL, and adults from 81 cm and up (Balazs 1980).

## Statistical Analyses

Kruskal-Wallis and Dunn's test were used to determine whether there were significant differences in growth rate (cm) for 167 individuals, growth rate (kg) for 159 individuals, straight carapace length (SCL) for 318 individuals, and body condition index (BCI) for 290 individuals across 5-year intervals, and in growth rate across 10-year intervals. Spearman correlation test was used to assess the relationships between growth rate and SCL for 168 individuals, growth rate and mass for 155 individuals, mass and SCL for 290 individuals, and SCL and year for three of the four turtles with the highest number of recaptures: R90, 8922, and F12. Pearson correlation test was used to assess the linear relationship between SCL and year for one of the four turtles with the highest number of recaptures: Q223. 4-parameter Bayesian model was used to project SCL over the years for 62 individuals, with parameters set at A (20, 20), B (70, 20), K (0, 5), and t0 (3, 20, 20). All statistical tests were analyzed in R statistical computing software, R v.4.2.2, with an alpha value = 0.05.

## RESULTS

There were a total of 319 turtles captured, 186 were recaptured, and 98 were recaptured three or more times. A significant difference in growth rate (cm/year) over 10-year intervals ($H(3) = 30.81$, $p < 0.001$), with an average growth rate of $1.07 \pm 0.05$ cm/year. During the intervals of the 1980s, 1990s, 2000s, and 2010s, the average growth rates are $2.30 \pm 0.37$ cm/year, $1.26 \pm 0.08$ cm/year, $0.90 \pm 0.08$ cm/year, and $0.62 \pm 0.07$ cm/year. Turtles in the 1980s showed higher growth rates compared to those from the 1990s ($p = 0.028$), 2000s ($p = 0.001$), and 2010s ($p < 0.0001$). Additionally, turtles from the 1990s showed higher growth rates than those from the 2010s ($p < 0.001$) (Fig. 2).

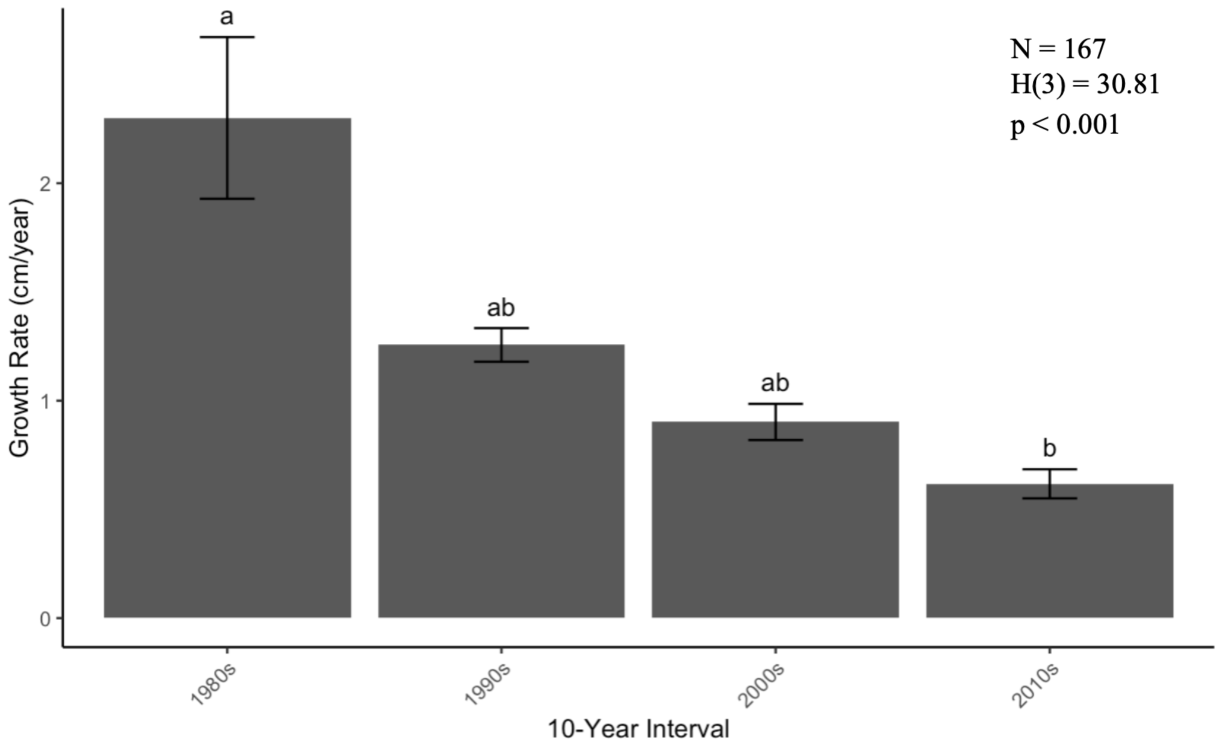


Fig. 2. Barplot showing the Kruskal-Wallis result for differences in growth rate (cm/year) over 10-year intervals. Dunn's test results are denoted by letters above each interval. Data were collected from August 1976 to July 2018.

There was a significant difference in growth rate (cm/year) over 5-year intervals ($H(7) = 33.534$, $p < 0.001$). During the intervals of 1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015, the average growth rates are 2.60 ± 0.48 cm/year, 1.63 ± 0.49 cm/year, 1.39 ± 0.13 cm/year, 1.15 ± 0.09 cm/year, 0.83 ± 0.10 cm/year, 0.96 ± 0.13 cm/year, 0.59 ± 0.08 cm/year, and 0.66 ± 0.11 cm/year. Turtles captured in the 1980 interval showed higher growth rates compared to those from 2000 ($p < 0.001$), 2005 ($p = 0.002$), 2010 ($p < 0.001$), and 2015 ($p < 0.001$). Additionally, turtles captured in the 1990 interval had higher growth rates than those from 2000 ($p = 0.005$), 2010 ($p < 0.001$), and 2015 ($p = 0.003$). Growth rates were also greater for turtles captured in the 1995 interval compared to those from 2010 ($p = 0.005$) and 2015 ($p = 0.017$) (Fig. 3).

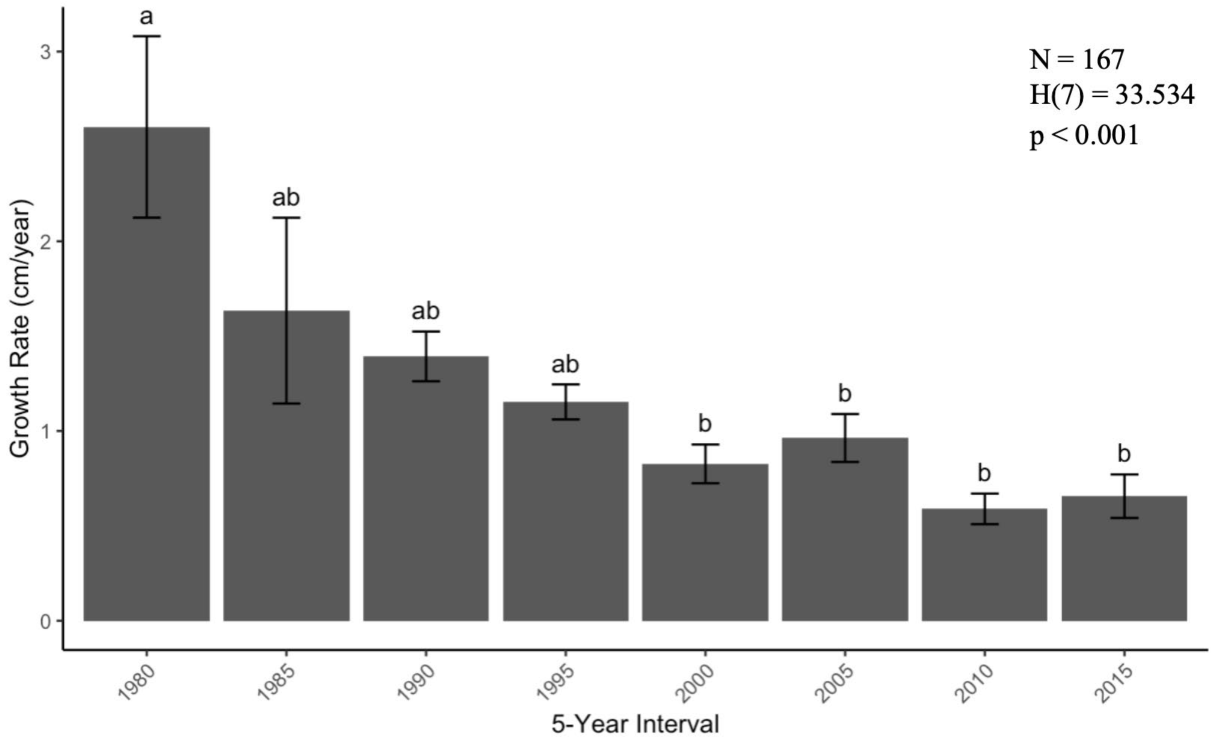


Fig. 3. Barplot showing the Kruskal-Wallis result for differences in growth rate (cm/year) over 5-year intervals. Dunn's test results are denoted by letters above each interval. Data were collected from August 1976 to July 2018.

There was a significant difference in growth rate (kg/year) over 5-year intervals ($H(8) = 25.529$, $p < 0.05$). During the intervals of 1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015, the average growth rates are 10.35 ± 4.32 kg/year, -3.74 ± 6.67 kg/year, -1.02 ± 2.59 kg/year, -1.00 ± 1.66 kg/year, 9.63 ± 2.49 kg/year, 2.38 ± 0.83 kg/year, 0.41 ± 0.19 kg/year, and 0.97 ± 0.34 kg/year. Turtles captured in the 1980 interval showed higher growth rates compared to those from 1990 ($p = 0.001$), 1995 ($p = 0.001$), and 2010 ($p < 0.001$). Additionally, turtles captured in 1995 had higher growth rates than those from 2000 ($p = 0.002$), and turtles from 2000 showed lower growth rates than those from 2010 ($p = 0.001$) (Fig. 4).

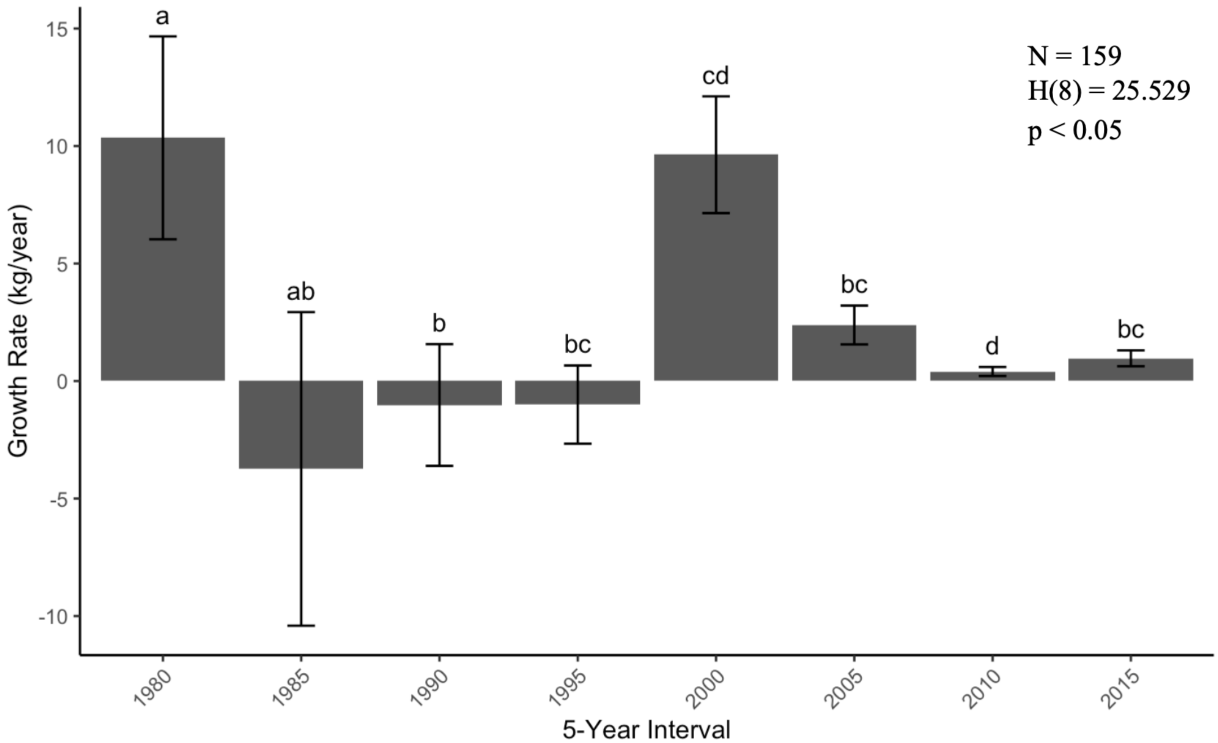


Fig. 4. Barplot showing the Kruskal-Wallis result for differences in growth rate (kg/year) over 5-year intervals. Dunn's test results are denoted by letters above each interval. Data were collected from August 1976 to July 2018.

There was a significant difference in straight carapace length (cm) over 5-year intervals ($H(8) = 52.69$, $p < 0.001$), with an average SCL of 62.29 ± 0.28 cm. During the intervals of 1976, 1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015, the average SCL are 53.67 ± 2.85 cm, 65.13 ± 1.43 cm, 64.41 ± 2.56 cm, 63.38 ± 0.64 cm, 62.30 ± 0.49 cm, 60.97 ± 0.63 cm, 62.56 ± 0.50 cm, 61.21 ± 0.74 cm, and 58.55 ± 0.94 cm. Turtles captured in the 1976 interval had smaller SCLs compared to those from 1980 ($p = 0.002$), 1990 ($p = 0.0008$), and 1995 ($p = 0.031$). Turtles from the 1980 interval also had smaller SCLs than those from 2000 ($p = 0.045$) and 2015 ($p = 0.0003$). Additionally, turtles captured in the 1990 interval were smaller than those from 2000 ($p = 0.005$) and 2015 ($p < 0.0001$) (Fig. 5).

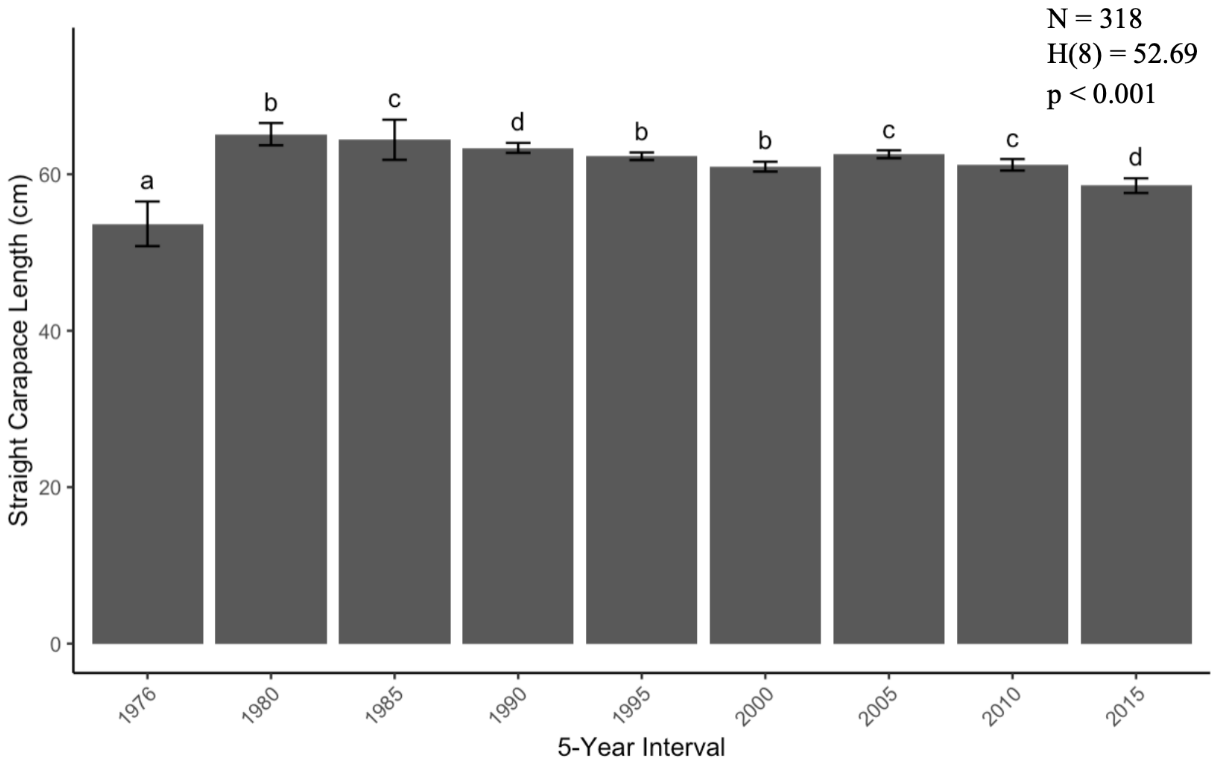


Fig. 5. Barplot showing the Kruskal-Wallis result for differences in straight carapace length (cm) over 5-year intervals. Dunn's test results are denoted by letters above each interval. Data were collected from August 1976 to July 2018.

There was a significant difference in body condition index (BCI) over 5-year intervals ($H(8) = 48.464$, $p < 0.001$), with an average BCI of 1.40 ± 0.005. During the intervals of 1976, 1980, 1985, 1990, 1995, 2000, 2005, 2010, and 2015, the average BCI are 1.46 ± 0.03, 1.46 ± 0.01, 1.48 ± 0.04, 1.42 ± 0.01, 1.38 ± 0.009, 1.37 ± 0.01, 1.38 ± 0.01, 1.38 ± 0.01, and 1.35 ± 0.02. Turtles captured in the 2015 interval had higher BCIs compared to those from 1975 ($p = 0.045$), 1980 ($p < 0.0001$), 1985 ($p = 0.028$), and 1990 ($p = 0.017$). Additionally, turtles captured in the 1980 interval had lower BCIs than those from 1995 ($p < 0.0001$), 2000 ($p = 0.0009$), 2005 ($p = 0.003$), 2010 ($p = 0.012$), and 2015 ($p < 0.0001$) (Fig. 6).

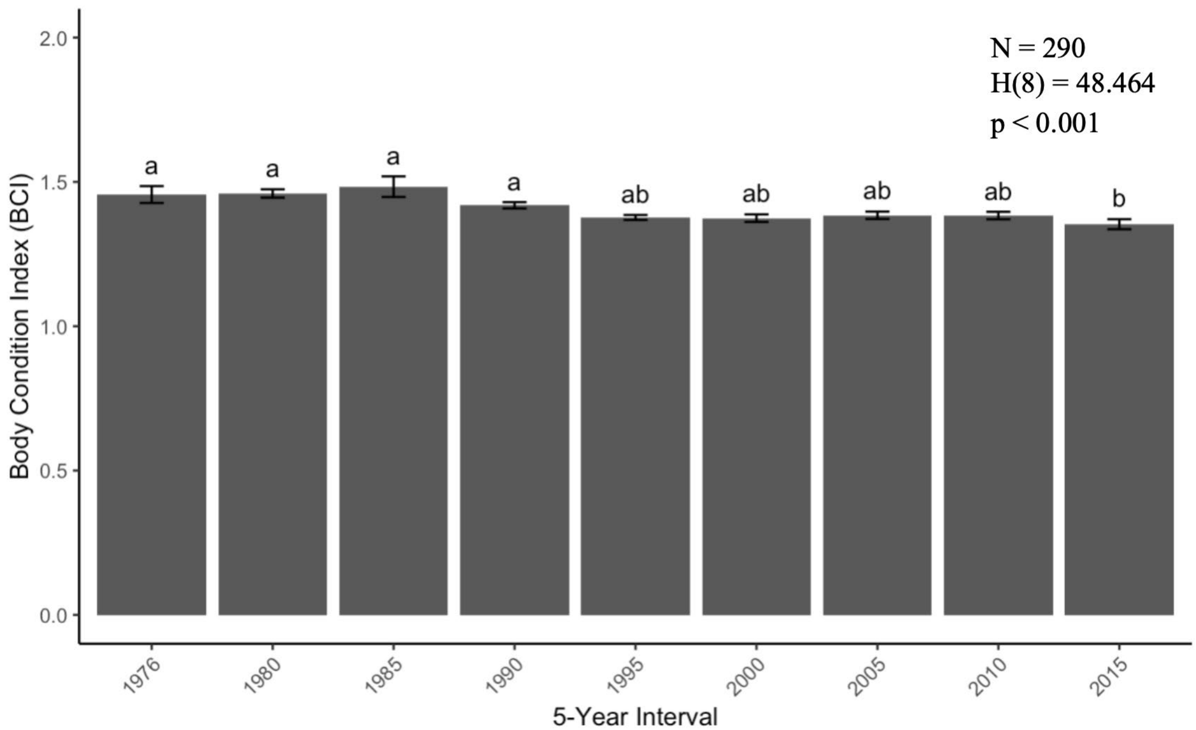


Fig. 6. Barplot showing the Kruskal-Wallis result for the differences in body condition index (BCI) over 5-year intervals. Dunn's test results are denoted by letters above each interval. Data were collected from August 1976 to July 2018.

There was a negative correlation found between growth rate (cm/year) and straight carapace length (cm) (rho = –0.385, $p < 0.001$). In the juvenile size category, there was an average growth rate of 2.04 ± 0.13 cm/year and SCL of 56.11 ± 0.57 cm. The subadult group had an average growth rate of 1.79 ± 0.22 cm/year and SCL of 70.0 ± 0.52 cm. Among adults, there was an average growth rate of 0.24 ± 0.23 cm/year and an average SCL of 87.50 ± 0.76 cm (Fig. 7). Additionally, a negative correlation was observed between growth rate (cm/year) and mass (kg) (r = –0.104, $p < 0.05$) (Fig. 8).

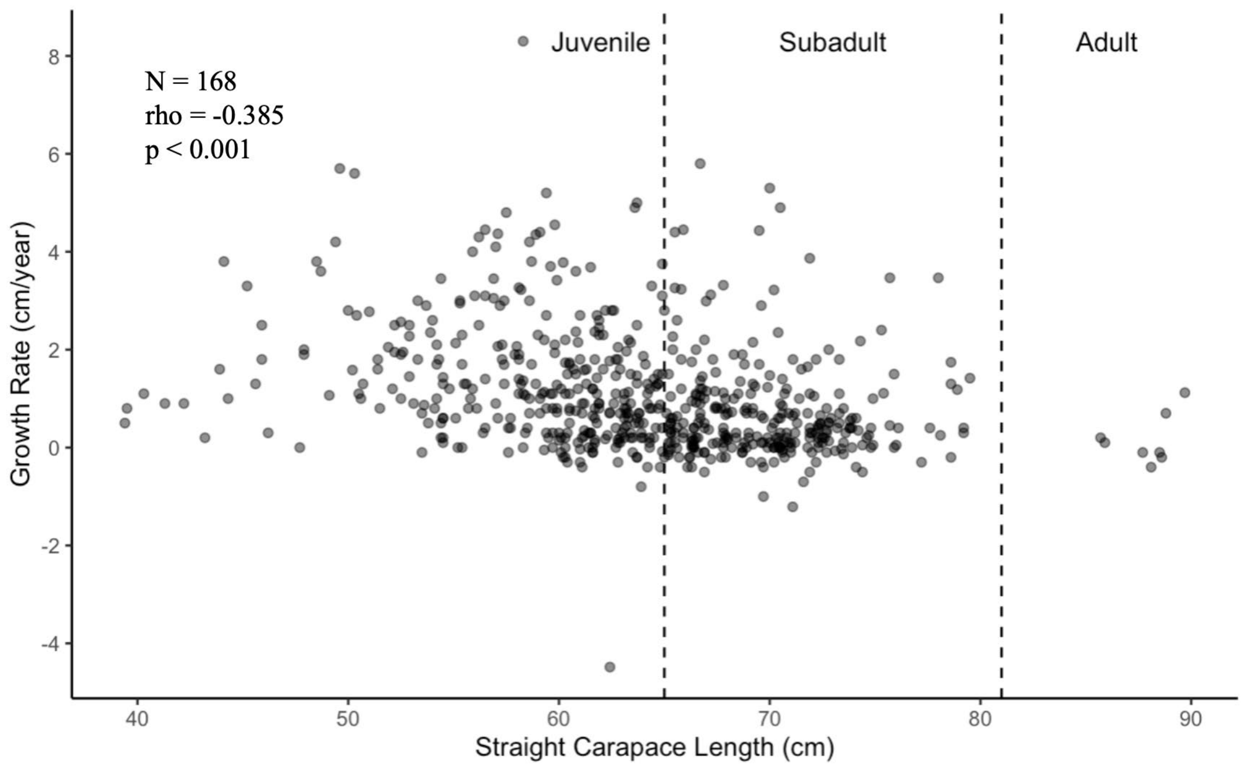


Fig. 7. Scatterplot showing the Spearman correlation between growth rate (cm/year) and straight carapace length (cm). Size categories are denoted by dashed lines ranging from juvenile, subadult, and adult. Data were collected from August 1976 to July 2018.

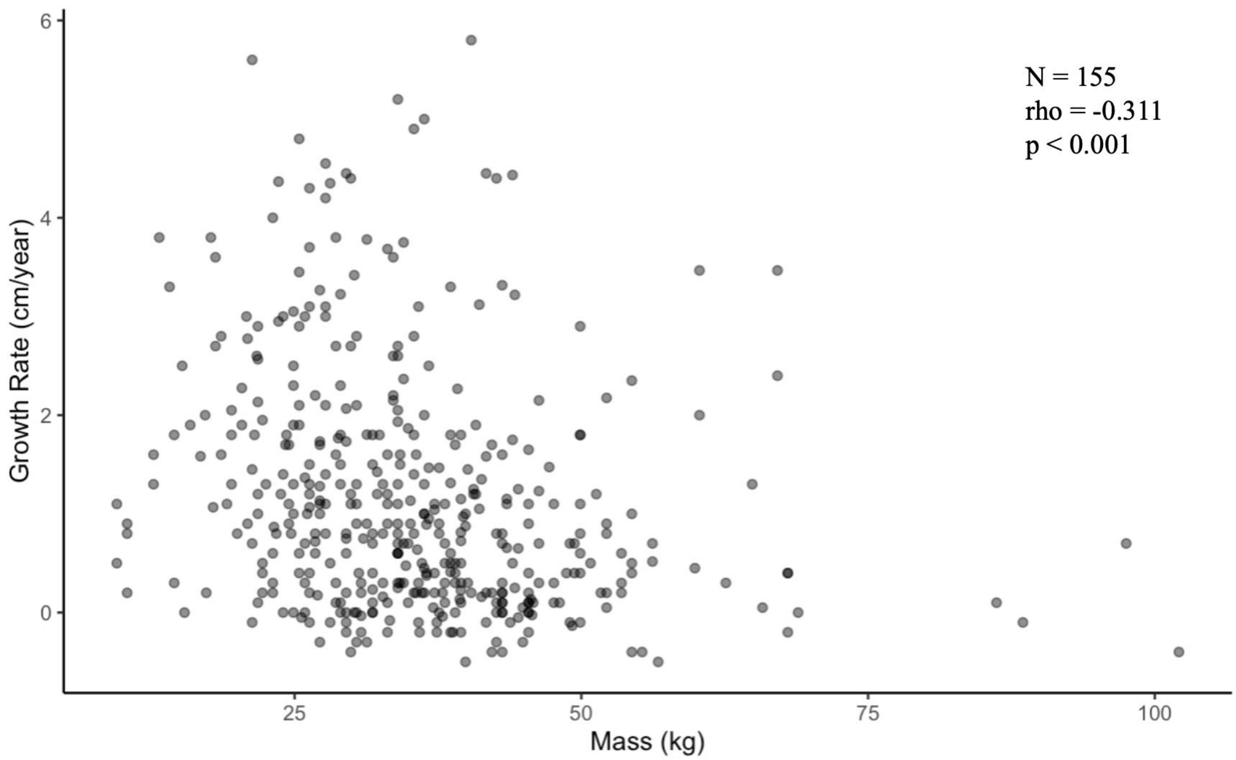

Fig. 8. Scatterplot showing the Spearman correlation between growth rate (cm/year) and mass (kg). Data were collected from August 1976 to July 2018.

There was a strong positive correlation found between mass (kg) and straight carapace length (cm) (rho = 0.976, $p < 0.001$). In the juvenile size category, there was an average mass of 24.53 ± 0.69 kg and SCL of 54.62 ± 0.60 cm. The subadult group had an average mass of 48.54 ± 1.05 kg and SCL of 70.33 ± 0.38 cm. Among adults, there was an average mass of 89.89 ± 3.17 kg and an average SCL of 86.35 ± 0.87 cm (Fig. 9).

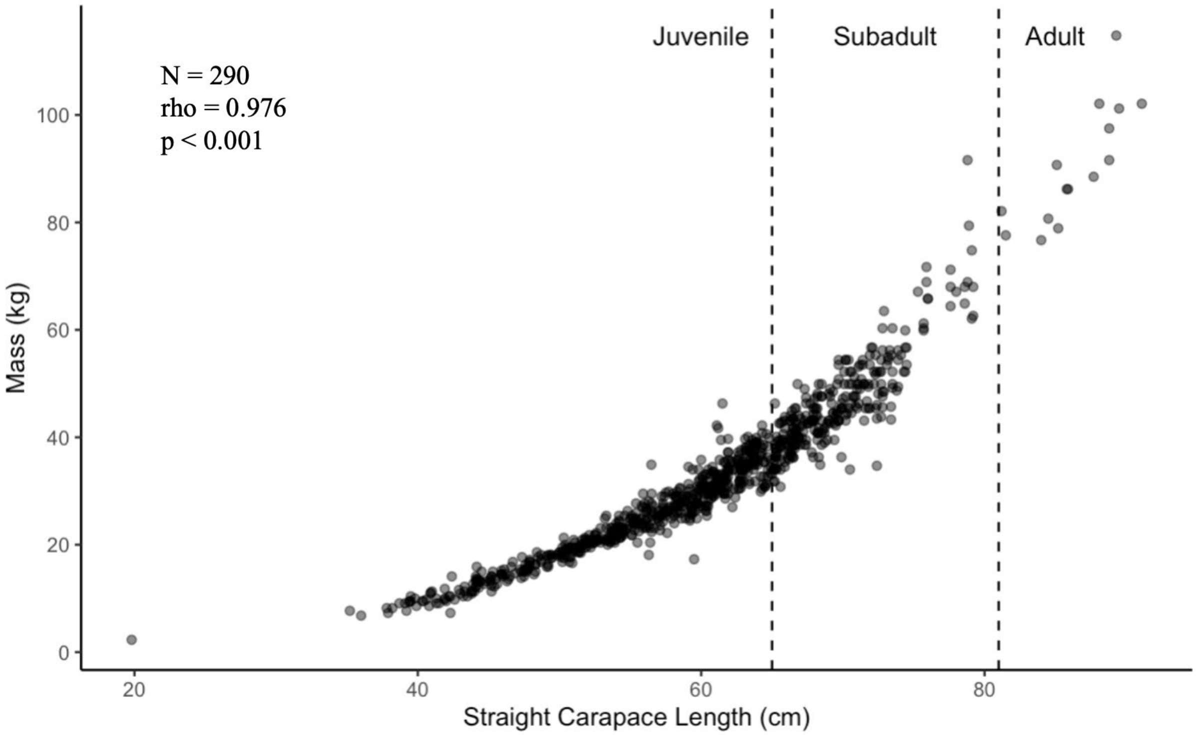

Fig. 9. Scatterplot showing the Spearman correlation between mass (kg) and straight carapace length (cm). Size categories are denoted by dashed lines ranging from juvenile, subadult, and adult. Data were collected from August 1976 to July 2018.

The four turtles with the highest number of recaptures were R90, 8922, F12, and Q223. A positive correlation was found for all of these turtles between straight carapace length (cm) over the years. Turtle R90 had an initial straight carapace length (cm) of 40.4 cm and a final SCL of 66.2 cm (rho = 0.958, $p < 0.001$) (Fig. 10). Turtle 8922 had an initial SCL of 48.7 cm and a final SCL of 73.8 cm (rho = 0.938, $p < 0.001$) (Fig. 11). F12 had an initial SCL of 63.7 cm and a final SCL of 72.7 cm (rho = 0.867, $p < 0.001$) (Fig. 12). Finally, Q223 had an initial SCL of 50.6 cm and a final SCL of 70.6 cm ($r = 0.947$, $p < 0.001$) (Fig. 13).

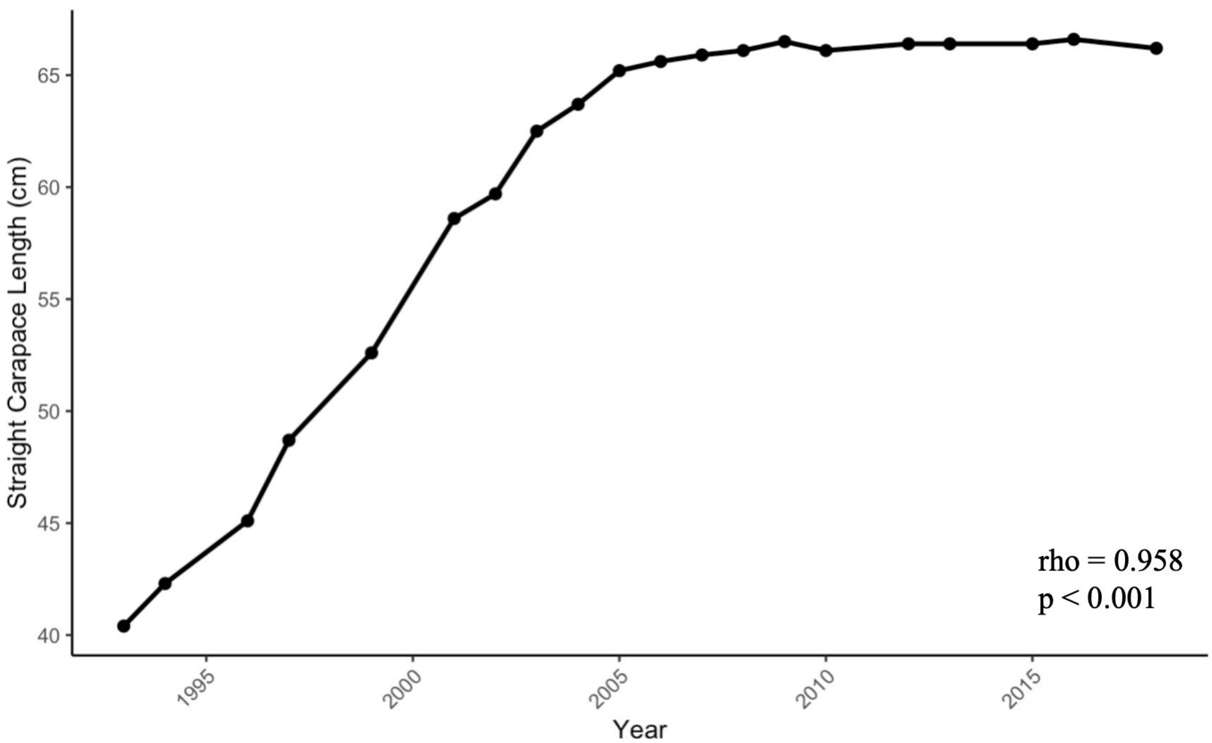


Fig. 10. Scatterplot showing the Spearman correlation between straight carapace length (cm) and year for turtle R90. Data were collected from August 1976 to July 2018.

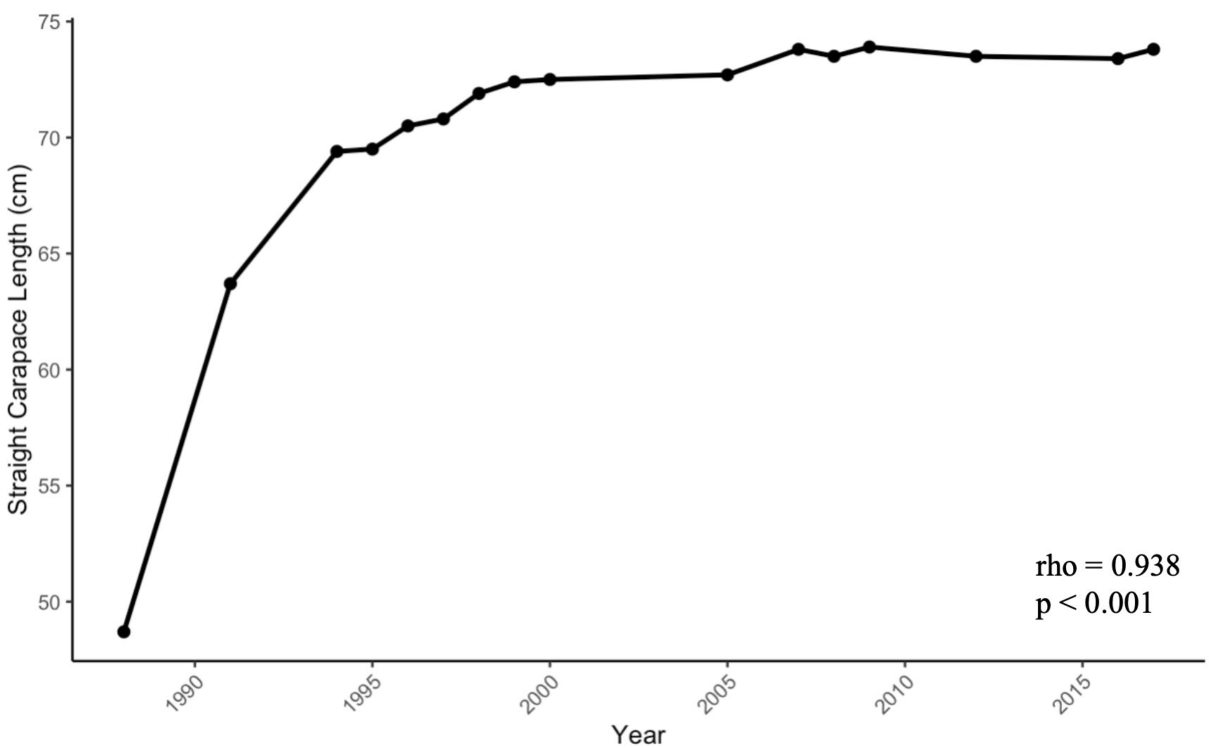


Fig. 11. Scatterplot showing the Spearman correlation between straight carapace length (cm) and year for turtle 8922. Data were collected from August 1976 to July 2018.

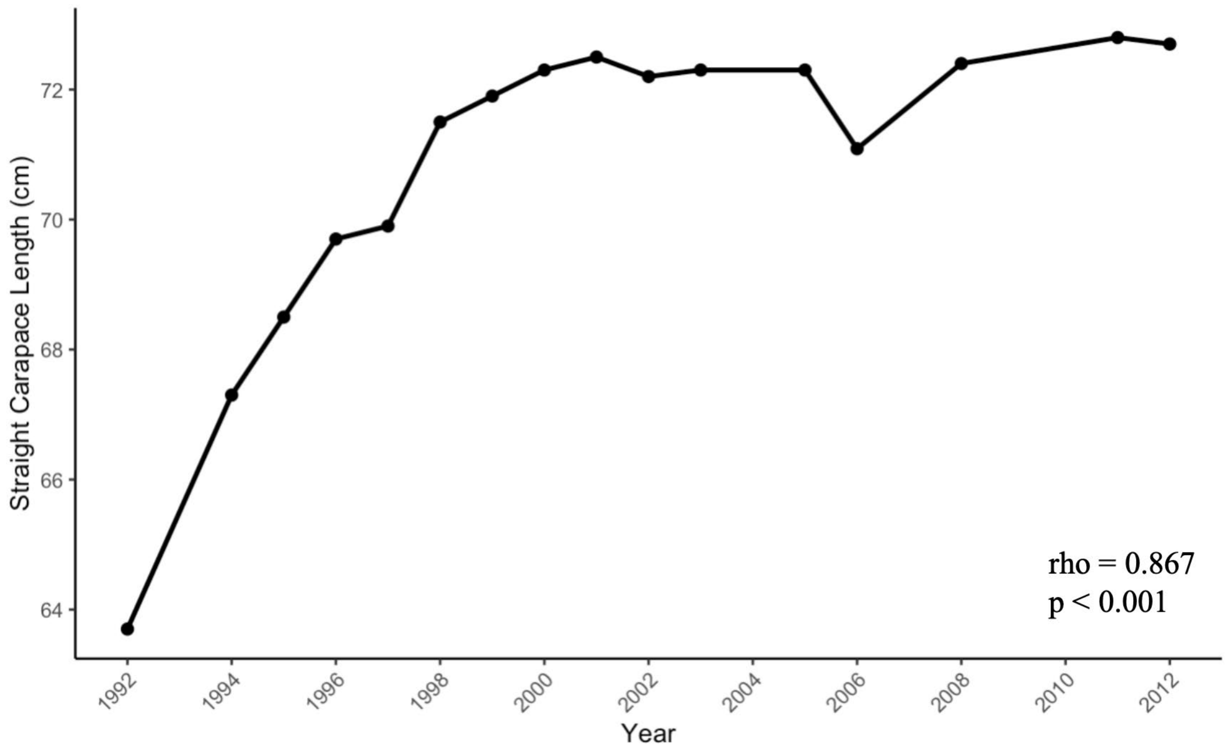


Fig. 12. Scatterplot showing the Spearman correlation between straight carapace length (cm) and year for turtle F12. Data were collected from August 1976 to July 2018.

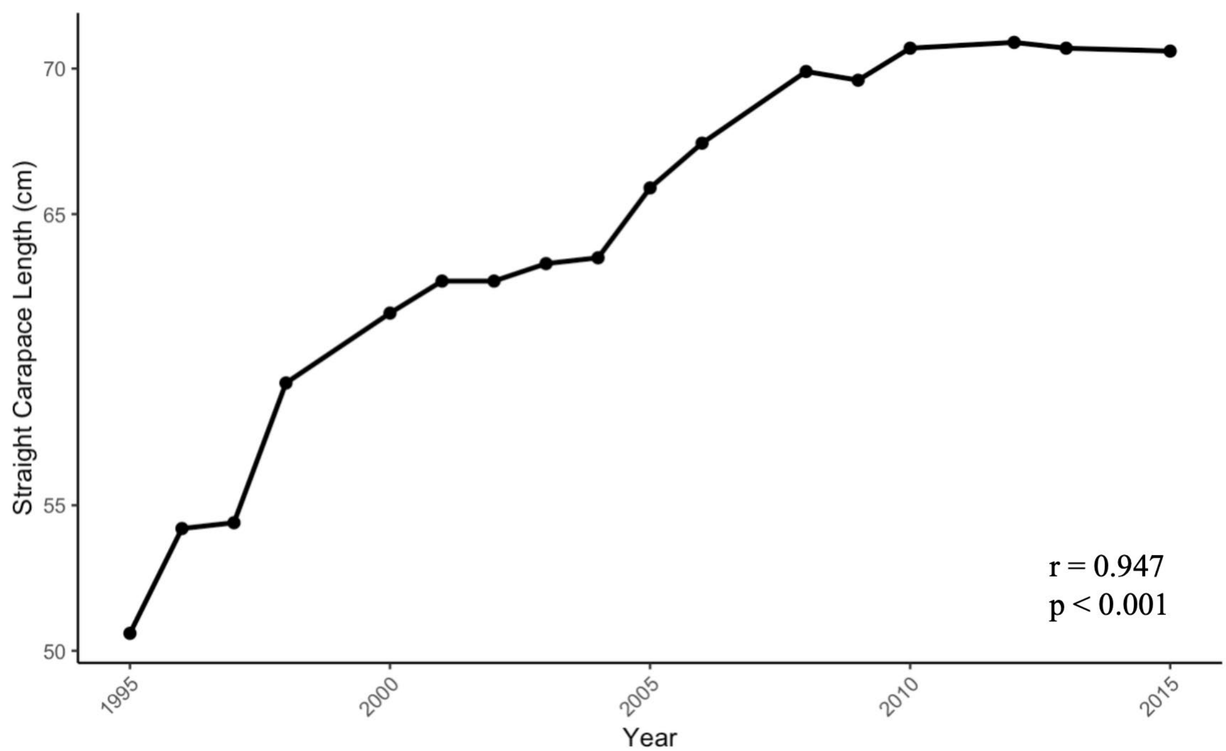


Fig. 13. Scatterplot showing the Pearson correlation between straight carapace length (cm) and year for turtle Q223. Data were collected from August 1976 to July 2018.

Model projects straight carapace length (cm) asymptotes around 80 cm. Parameter A had an average initial size of 34.14 cm ± 1.31 and an 80% confidence interval range from 31.33 to 36.42. Parameter B had an average final size of 68.87 cm ± 0.70 and an 80% confidence interval range from 67.54 to 70.23. Parameter K had an average growth rate constant of -1.08 cm/year ± 0.07 and an 80% confidence interval range from -1.23 to -0.93. Parameter t0 had an average growth rate constant of 9.41 cm/year ± 0.63 and an 80% confidence interval range from 8.48 to 10.84 (Fig. 14).

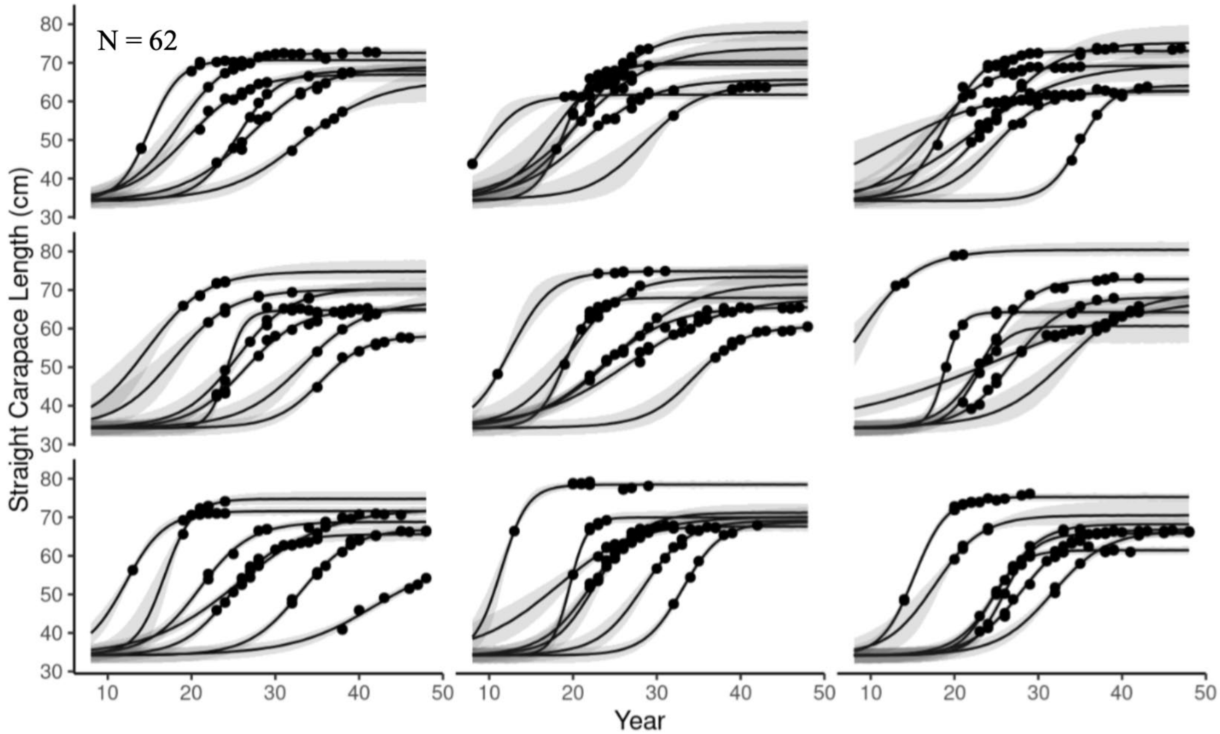


Fig. 14. Scatterplots with asymptotes showing the results of a 4-parameter Bayesian model between straight carapace length (cm) and year. Data were collected from August 1976 to July 2018.

## DISCUSSION

The findings of this study provide insight into the growth rates of Hawaiian green turtles at Punaluʻu Beach on Hawaiʻi Island from 1976 to 2018 and contribute to a growing body of literature on sea turtle demographic patterns. Growth rates over these 40+ years averaged 1.07 ± 0.05 cm/year, which is consistent with the rates reported at Kaʻū in the Hawaiian Archipelago by Balazs (1982), ranging from .38 to .52 cm/month. Van Houtan (2014) projected an average growth rate of 3.8 cm/year to reach sexual maturity at 23 years in Hawaii. Another study reported rates ranging from 0 to 2.5 cm/year from other various foraging grounds within the Hawaiian Islands (Balazs & Chaloupka 2004). Thus, growth rates for Punaluʻu fall on the lower end of the mean range.

In the Caribbean, green turtle growth rates ranged from 6.2 to 6.3 cm/year, which is much higher than the rates at Punaluʻu Beach (Van Houtan et al. 2014). In the Galápagos Islands, green turtle growth rates were lower than Hawaiian green turtle growth rates (Zárate et al. 2015). Frazer & Ehrhart (1985) found that the time it takes to reach maturity can vary due to location and are found to range between 25 to 30 years for green turtles. Slower growth observed in Hawaiian green turtle populations compared to Caribbean populations raises important questions about habitat quality and/or resource availability that could impact growth rates (Van Houtan et al. 2014). Factors such as food availability and food quality could be impacting growth at the Punaluʻu foraging ground. Furthermore, food can be impacted by environmental conditions such as water quality or sea surface temperature. The higher growth rates observed in the 1980s may reflect lower turtle densities, showing less competition for food and more favorable foraging conditions. Similar trends have been recorded in the Archipelago, where increasing turtle density over time was linked to declining growth, pointed towards a density-dependent effect (Mortimer et al. 2025).

The increase in population of green turtles in the Hawaiian Islands (Balazs & Chaloupka 2004) following the ban on commercial harvesting in 1974 (Bennett & Keuper-Bennett 2008) may contribute to the observed decline in growth rates at some foraging sites (Wabnitz et al. 2010). A peak between 60 to 70 cm SCL followed by a decline in growth has been observed for this sample at Punaluʻu. In the Hawaiian Archipelago, growth was reported to peak at 65 cm SCL and then decline as turtles near sexual maturity at 81 cm (Balazs & Chaloupka 2004). Similarly, growth rates in the Caribbean begin to decline after turtles reach 60 cm SCL (Labrada-Martagón et al. 2017), while in Florida, this decline occurs earlier, around 50 to 55 cm SCL (Kubis et al. 2009). Additionally, a study suggested that Hawaiian green turtles may begin breeding at 23 years old rather than 35 to 50 years, but slow growth rates, which could now be impacted by these slower growth rates, and cause a shift towards slower maturity time (Van Houtan et al. 2014).

The average body condition index (BCI) for green turtles at Punaluʻu was 1.40 ± 0.005. In Malaysia, turtles from Kudat had a higher average BCI of 1.49 ± 0.13, while those from Balambangan Island matched Punaluʻu with 1.40 ± 0.09 (Nishizawa et al. 2023). Most individuals at both sites were juveniles, and differences were correlated with habitat quality and size. Although BCI is an indirect measure for nutritional status and was not statistically supported in linear models, it still reflects variation in foraging conditions. The Punaluʻu average falls within the broader BCI range of 1.26 to 2.24 reported across life stages (Nishizawa & Joseph 2022).

The four-parameter Bayesian growth model projected an asymptotic straight carapace length (SCL) of approximately 80 cm, with initial and final sizes averaging 34.14 cm ± 1.31 cm and 68.87 cm ± 0.70 cm. This range is consistent with global patterns where turtles recruit to foraging grounds around 25 to 35 cm and mature between 70 to 88 cm (Balazs 2000, Bjorndal & Bolten 1988, Frazer & Ehrhart 1985). The decreasing growth rate with increasing size observed supports findings from other regions, where smaller turtles grow more quickly than larger individuals (Eguchi 2012, Zárate et al. 2015). Growth rates are key indicators of habitat quality and overall population health, influenced by environmental factors such as temperature, diet, and density (Bjorndal et al. 2000, Zárate et al. 2015). The growth patterns observed at Punaluʻu align with trends reported in Hawaii, where juvenile growth slows with age. Regional differences show how local habitat conditions shape turtle development. These findings present the need for site-specific data to support effective conservation and management planning.

## ACKNOWLEDGMENTS

I thank K. McDermid, G. Balazs, and G. Weyenberg for being my advisors on the project. To K. McDermid and J. Turner for being my class advisors. To G. Balazs for recording measurements on the turtles captured. To students volunteers from the University of Hawaii at Hilo for capturing and releasing turtles. To O. Jarvis for previously doing analyses on the data as a MOP project.

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