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METHOD

Improving the statistical reporting of hatching success data: the case of sea turtles

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Abstract

Estimating hatching success of egg clutches is essential for quantifying reproductive success in sea turtles. Thus, proper reporting is necessary to provide meaningful information for knowledge acquisition and management. Here we review how hatching success has been reported in the scientific literature and use our own multi-annual multi-species datasets to explore the best ways for describing hatching success data. Despite non normality, the central tendency of hatching success data was most often described using arithmetic means. Only 17 out of 203 (8%) studies reported the median, compared to 192 (95%) that reported the mean (6 studies reported both). In 24% of studies, a dispersion metric was not provided. In our comparison, the arithmetic mean was only a good predictor of central tendency in leatherback turtles (*Dermochelys coriacea*), with the median (0.45) being only slightly above the mean (0.43). In leatherbacks, hatching success was characterized by high variability, and not by a consistently low hatching success, as indicated by the low skewness and large spread of data. On the contrary, hatching success data were strongly skewed and skewed toward high values in green turtles (*Chelonia mydas*) (25% and 75% percentiles: 0.88 and 0.98) and olive ridley turtles (*Lepidochelys olivacea*) (25% and 75% percentiles: 0.75 and 0.97) respectively, with presence of outliers in both cases. Basic statistics, appropriate for characterizing non-normal distributions such as the median, skewness or kurtosis, together with boxplots, provided accurate description of hatching success data. Using these straightforward statistics would greatly improve the ecological understanding of hatching success in sea turtles.

Keywords Embryo mortality · Leatherback turtle · Green turtle · Olive ridley turtle · Non-normality · Median · Mean · Reporting of statistical data

Introduction

Life-history theory predicts that high fecundity in animal species is strongly correlated with low survival of the early stages (Stearns 1992; Einum and Fleming 2000; Rice 2004). Offspring survival determines the reproductive success of the parents and ultimately, influences long-term population trends (Stearns 1976; Caswell 1982; Clutton-Brock and Sheldon 2010). Thus, it is important to characterize offspring survival adequately for each study population and species, especially if conservation actions become necessary.

Sea turtles are long-lived, lay approximately 50 to 130 eggs per clutch depending on the species, nest 2 to 10 times in a season and reproduce several times during their life at intervals that last 2–6 years (Miller 1997). This high investment in reproduction is strongly correlated with high mortality in the early stages (Heppell 1998). In particular, a

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variable proportion of the clutch typically fails to develop into hatchlings (Hirth 1980; Gammon et al. 2020), some hatchlings do not emerge from the nest (Fowler 1979; Perrault et al. 2011), and among those that emerge many are predated on the beach or once they enter the sea (Witherington and Salmon 1992, Santidrián Tomillo et al. 2010). As a rule of thumb, based on the reproductive investment of sea turtles, it has been estimated that approximately 1,000 eggs are needed to produce a single adult turtle, with the very large number of eggs that a female lays over their life just being enough to replace herself and an adult male (Frazer 1986).

Failure of successful hatching in sea turtle clutches can result from embryo mortality or from lack of adult fertility (Bell et al. 2004; Phillott and Godfrey 2020). Sea turtles lack parental care, and successful development of eggs depends on the environmental conditions they experience in the nest (Ackerman 1997). At some high-energy beaches, a large proportion of the clutches can also be lost due to erosion or tidal flooding (Eckert and Eckert 1990; Gammon et al. 2023). Although there is no parental care, nesting turtles can indirectly influence the nest environment and consequently hatching success through nest-site selection by excavating the nest, for example, in cooler areas of the beach or in areas that have a lower risk of erosion (Kamel and Mrosovsky 2006; Heredero-Saura et al. 2022).

Hatching success in sea turtles can vary greatly among species and populations of the same species. For instance, in green turtles (*Chelonia mydas*), hatching success has been reported to be above 80% (0.8) in Cyprus (Broderick and Godley 1996) and Costa Rica (Santidrián Tomillo et al. 2024), and below 50% (0.5) in the Galápagos Islands (Zárate et al. 2013) and the Arabian Sea (Maneja et al. 2023). In turn leatherback turtles (*Dermochelys coriacea*) have typically been described as a species with low hatching success (~ 50%; Bell et al. 2004; Perrault et al. 2011).

Hatching success has been used to characterize the reproductive performance of sea turtles (Miller 1997), and numerous studies have reported the influence of environmental conditions on it (e.g. Ackerman 1997; Houghton et al. 2007). However, most studies have only reported the arithmetic mean and/or the range to characterize it (see results section). Because the analysis of hatching success involves dealing with proportional data of a relatively large number of eggs, which by definition violate the assumptions of the normal distribution, the arithmetic mean of a dataset may not be appropriate to characterize hatching success. However, the use of a few straightforward descriptive statistics could instead be very useful to characterize it accurately. Importantly, because hatching success data are typically non-normally distributed, basic central tendency statistics such as the median or the mode should be used in lieu of the arithmetic mean, together with a measure of data spread, such as kurtosis, and of level of symmetry/asymmetry of the distribution, such as skeweness (Nick 2007). In normal distributions the arithmetic mean coincides with the median and the mode, but as soon as the distribution of the parameter departs from normality the mean and the median depart from each other. In addition, the mean tends to be very much affected by extreme large or small values, whereas the median (i.e. the 50% percentile) is not (Zar 1999).

The aim of our study was twofold: (1) to review how hatching success has been reported in sea turtle studies to identify shortcomings and potential for better characterization of this component of reproductive performance, and (2) to analyze our own multi-annual data for three species of sea turtles to provide an example on how to characterize it using general descriptive statistics. Finally, we stress what statistics should ideally be reported in hatching success studies to properly describe it, so that they contribute to better acquire ecological knowledge for a better implementation of conservation actions.

Methods

Hatching success in the sea turtle literature

We used Google Scholar and the Web of Science to search for publications that reported hatching success of sea turtle nests to obtain information on how this vital rate was reported. Words and boolean operators used in our search were “sea turtle” OR “marine turtle” AND “hatching success” OR “hatch success”. Screening was done by a single reviewer. Our search only included studies published before 2025 and in English. We only included peer-reviewed publications, excluding theses and reviews. Some of the studies hit in the literature searches tested particular effects of environmental conditions on hatching success, such as the effect of temperature or precipitation, while others just characterized the success of the clutches. Those studies that tested the effect of a particular variable on hatching success without providing a characterization of hatching success were excluded, as well as those that reported data from incubators or were experimental. We included studies that used information from clutches that were left in situ, or that were relocated. Publications performing mathematical modeling that used hatching success information from other studies were also excluded. We specifically extracted information on the way hatching success was reported in each original study, whether the arithmetic mean was reported by itself, with a measure of dispersion (i.e. standard deviation, variance, range), with a measure of precision of the estimate of the population parameter (i.e. standard error, confidence interval), and whether the median was also reported or not or reported instead of the arithmetic mean.

Characterization of hatching success

We analyzed our own multi-annual data on hatching success for three species of sea turtles that nest in the same area of Northwest Costa Rica. Specifically, we used data from leatherback turtles (*Dermochelys coriacea*) that nest at Playa Grande, Las Baulas National Park (10°20 N, 85°51 W) (1,047 clutches), olive ridley turtles (*Lepidochelys olivacea*) that nest at Cabuyal (10°400 N, 85°390 W) (115 clutches) and green turtles (*Chelonia mydas*) that also nest at Cabuyal (171 clutches), spanning 14 nesting seasons (October to March) (2004/05 to 2017/18), 12 nesting seasons (2012/13 to 2023/24) and 13 nesting seasons (2011/12 to 2023/24) in leatherback, olive ridley and green turtles, respectively.

We followed the same monitoring protocols for the three species at the two beaches. We patrolled the beaches at night. When we encountered a nesting turtle, we marked the nest while the turtle was laying eggs and pinpointed the location by triangulation, measuring the distance from the nest to the two closest beach markers to the North and to the South. Beach markers were separated by 25 m and 50 m at Cabuyal and Playa Grande respectively. At Cabuyal, we marked nests by means of a flagging tape with a unique alphanumeric code that was placed immediately above the egg chamber. At Playa Grande, the identification code was placed inside a thermocouple cover. All nests included in the study were in situ nests. We excluded clutches that were either flooded or predated.

We excavated marked nests two days after hatchling emergence to estimate hatching success. If the emergence event was not seen or did not occur, we excavated nests of leatherback, green and olive ridley turtles respectively after 70, 65 and 60 days, when the emergence event was no longer expected, based on the typical duration of the incubation period of each species at the corresponding site. We estimated hatching success using the equation: $H = S/(S + U)$, where "S" is the number of eggshells and "U" the number of unhatched eggs. Eggshells were considered as one, when at least 50% of the eggshell remained, following Miller (1999).

To characterize hatching success, we used descriptive statistics for each dataset. This included the sample size, range, mean, median, trimmed mean, standard deviation, skew and kurtosis of the hatching success, in addition to standard error as a measure of precision of the parameter estimate (i.e. the standard deviation of the sampling distribution instead of the standard deviation of the data) (Table 1). We used a Shapiro-Wilk test to assess normality. We visually represented hatching success for each species in a box plot, because boxplots provide a very complete description of the "center of mass" of the dataset (i.e. median or 50% quartile, 25% and 75% interquartile interval, range and outliers). We used R version 4.1.2 for all statistical analyses (R Core Team 2023), and used the describe.by function from the psych library to generate the descriptive statistics.

Results

Hatching success in sea turtle literature

We hit 423 references in our searches and retained the studies that met our search criteria (203) after initial screening. Although hatching success data were not found to be drawn from normally distributed data populations, it was most often reported using the arithmetic mean, with the median rarely being reported (Fig. 1). Specifically, only 17 out of 203 studies (8%) reported the median, compared to 192 out of 203 studies (95%) that reported the mean (6 studies reported both). Among the studies that reported the mean, 47 studies (24%) reported it without any metric of dispersion, and 117 studies (60%) reported it together with the standard deviation. The standard error was included in 24 studies and the confidence interval only in 7 studies. There were 11 studies that reported the median alone without the mean (Fig. 1).

Characterization of hatching success

None of the hatching success datasets were found to be drawn from normally distributed populations ($p < 0.001$, in all cases). The characteristics of the datasets were markedly different between leatherback turtles and the other two species (Table 1; Fig. 2). Hatching success was skewed toward high values in green (skew: −3.01) and olive ridley turtle (skew: −1.75) clutches, indicating that there were outliers in the lower values of hatching success and a higher concentration of data among the higher values, especially in the case of green turtles where the skew was greater (Fig. 2). The median was high in both species and greater than the arithmetic mean, with 50% of the nests having hatching success values above 0.94 and 0.92 in green and olive ridley turtles respectively, whereas the mean was 0.88 and 0.81 respectively. Boxplots for these two species showed that the 25% and 75% percentiles included higher values and a narrower range of values in green turtles (25 and 75 percentiles: 0.88 and 0.98 hatching success) than in olive ridley turtles (25

Table 1 Descriptive statistics of hatching success of in situ nests for Olive ridley turtles (*Lepidochelys olivacea*), green turtles (*Chelonia mydas*) and leatherback turtles (*Dermochelys coriacea*) that nest in Pacific Costa Rica

	N	Type	Mean	Standard deviation	Median	Trimmed mean	Min	Max	Range	Skew	Kurtosis	Standard error
Ridley	115	in situ	0.81	0.26	0.92	0.87	0	1.0	1.0	−1.75	2.04	0.02
Green	171	in situ	0.88	0.19	0.94	0.93	0	1.0	1.0	−3.01	9.45	0.01
Leatherback	1047	in situ	0.43	0.29	0.45	0.43	0	1.0	1.0	−0.04	−1.34	0.01

and 75 percentiles: 0.75 and 0.97 hatching success). Excluding outliers, the range of values was also narrower between the median and the highest value than between the median and the lowest value (Fig. 2). A similar pattern was observed in the data within the whiskers, with higher values and a narrower range in green turtles (0.77 to 1.0 hatching success) than in olive ridley turtles (0.44 to 1.0 hatching success), and with noticeable high values in green turtles. For example, all clutches had hatching success above 0.77, with the exception of a few outliers (Fig. 2).

Although hatching success was non normal in leatherback turtles, the median (0.45) was only slightly higher than the mean (0.43). The skew was low (0.04) and the standard deviation was high, indicating substantial data variability, with a small tendency toward values below the median (Table 1). However, the negative value for kurtosis indicated that the distribution had short tails. Boxplots further showed that data within the 25–75% percentiles and within the whiskers corresponded to a very wide range of hatching success values ranging between 0.14 and 0.69 in the first case and practically between 0 and 1.0 in the latter (Fig. 2).

Datasets for both green and olive ridley turtles had many outliers (Fig. 2). The trimmed mean (trim = 0.1) was higher than the untrimmed mean in green and olive ridley turtles, because the trimmed mean reduces the influence of outliers, but the trimmed and untrimmed arithmetic means were the same in leatherback turtles (Table 1). Kurtosis indicated that the hatching success sampling distributions in green and olive ridley turtles had heavy tails, meaning that they had longer tails, and more data in the tails, than those in a normal distribution. Kurtosis was higher for green turtles. Hatching success ranged from 0 to 1.0 in the three species, indicating that in all cases there were clutches representing a complete success and others representing a complete failure.

Discussion

Non-normal distributions of ecological datasets are common, especially if dealing with parameters than can only take particular values, such as clutch size, or represent percentages such as hatching success. Thus, the use of appropriate statistics is needed to describe them accurately. Data that are highly skewed and have extreme values strongly bias both the mean and the standard deviation (Zar 1999). Despite so, researchers often use the mean and the standard deviation as data descriptors in these cases (Sainani 2012), simply because of a matter of inertia or momentum. Lack of normality often indicates that the central tendency of a dataset should be assessed by the median instead of the mean, because of the lack of symmetry (Marshall and Jonker 2010; Mishra et al. 2019). In the sea turtle literature reviewed by

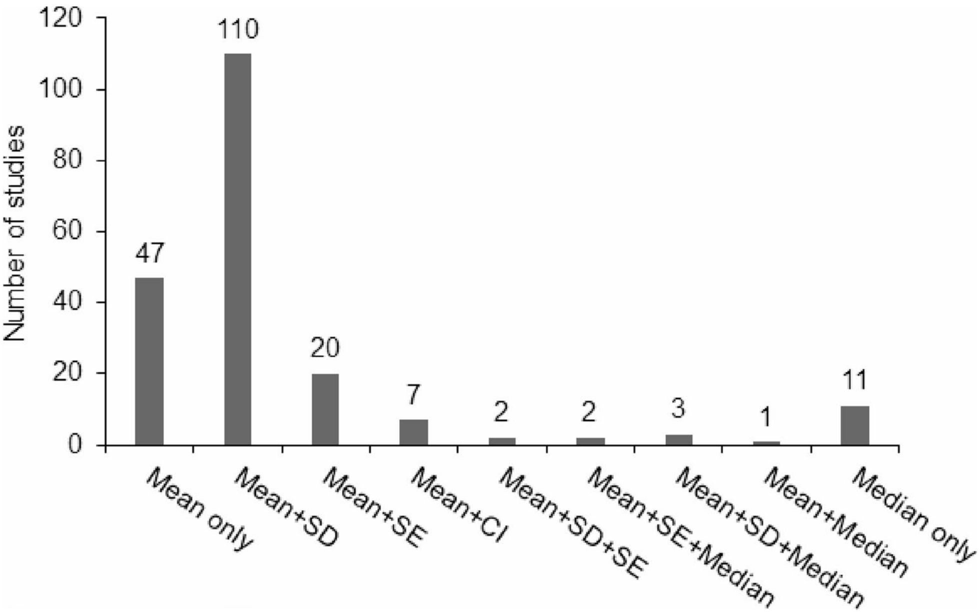

Fig. 1 Number of studies that reported hatching success ($n=$ 203) by the type of statistics they used. SD corresponds to standard deviation, SE to standard error and CI to 95% confidence intervals

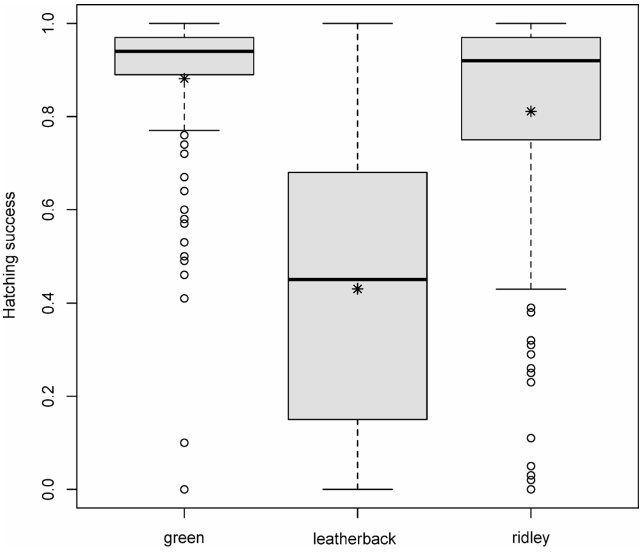

Fig. 2 Hatching success of green, leatherback and olive ridley turtles that nest in the same area of Costa Rica. Data are shown in boxplots. The box includes the 25% and 75% percentiles. The median (50% percentile) is indicated by the black line in the box and the range of data (maximum and minimum), excluding outliers, is limited by the box whiskers. Circles represent the outliers. (*) indicates the arithmetic mean of each dataset

us, hatching success was most often characterized by the mean, despite lack of normality. Additionally, we found that a metric of dispersion was at times not included despite reporting the mean. Consequently, we may conclude that sea turtle hatching success has been frequently reported inaccurately in scientific studies and/or it has been insufficiently characterized.

The interspecific comparison of hatching success based on our multi-annual datasets highlighted the relevance of using the appropriate descriptive statistics to derive ecologically-meaningful information. The mean was only a good descriptor of central tendency in leatherback turtles and yet, this was insufficient to characterize hatching success, because the data spread was large. In green and olive ridley turtles, using the median together with the skew and kurtosis, provided a better and more complete characterization of hatching success than the mean together with the standard deviation. The skewness provides a useful measure of the asymmetry of the sampling distribution, indicating the amount of data that are toward one of the tails (Hair et al. 2017, Hatem et al. 2022), whereas the kurtosis measures the spread of the distribution and the influence of outliers (Hatem et al. 2022). In green turtles especially, our results indicated that hatching success was consistently high, because the greatest amount of data was in the right tail, and there was a tendency toward having high values for all percentiles. However, variability was still found in green turtles, as indicated by the outliers (Fig. 2), but this was the exception rather than the rule. These outliers could correspond to the occasional nest that is flooded or respond to poor health conditions of the embryo or of the mother, or lack of fertility, as these factors are known to reduce hatching success in sea turtle populations (Eckert 1987; Perrault et al. 2011, 2012).

Leatherback turtles have generally been described as a species with low hatching success (Bell et al. 2004; Perrault et al. 2011), but with some variability among populations (Santidrián Tomillo et al. 2015). Our results here indicate that possibly the most important characteristic of the hatching success of leatherback turtles is its high variability, rather than a poor performance. Because hatching success was highly variable, the median had lower values than those of the other species, but hatching success was not consistently low. If this were the case, the dataset would be skewed toward lower values in a similar way that hatching success is skewed toward higher values in green turtles, but it was not.

Such a high variability in the hatching success of leatherback turtles could make it difficult to identify the causes behind a partial or total clutch failure. Leatherback turtles are critically endangered in the eastern Pacific (Wallace et al. 2013), and getting to increase hatching success is one of the management strategies that have been proposed to counteract population decline (The Laúd OPO network 2020). High temperatures and droughts are known to reduce hatching success (Santidrián Tomillo et al. 2012, 2020), with the identity of the mother also influencing it (maternal effect, Rafferty et al. 2011). Still, some clutches hatch at critically high temperatures, and variability is found in the response to temperature among clutches laid by different females (Kynoch et al. 2024). The low number of clutches that are currently laid at many beaches in the eastern Pacific (The Laúd OPO network 2020), further hinders the interpretation of data and the ability to detect changes over time. Because there is such a large variability in hatching success, inferring information from a small number of clutches could be unreliable, as it could be low or high just by chance.

The high hatching success of the green turtle nesting population of Cabuyal was recently reported (Santidrián Tomillo et al. 2024), and has been related to a high tolerance to high temperatures in this population. While it would be interesting to know if the current characteristics of hatching success in green turtles are similar in other areas, appropriate information on hatching success is scarce for other populations despite mean values being frequently reported (e.g. Lindborg et al. 2016; Comer Santos et al. 2017; Stewart et al. 2019). Therefore, at this point it is not possible to assess whether these are universal features in green turtles or if they respond to the particular conditions of Cabuyal and/or of the nesting population.

Hatching success in olive ridley turtles also showed a skew toward higher values, with a median that was only slightly lower than that of green turtles (0.92 versus 0.94). However, the skew was not as pronounced, and there was higher variability in olive ridley than in green turtles, with proportionally more nests having relatively low hatching success. It is possible that nests of olive ridley turtles are more vulnerable to external factors compared to those of green turtles. Olive ridley turtles at Cabuyal, nest on the open beach and place their nests at relatively shallow depths, as opposed to green turtles that most often nest in the vegetated area of the dunes, where nests are sometimes shaded (Heredero-Saura et al. 2022). Thus, olive ridley clutches could be more exposed to desiccation, fluctuating climatic conditions and tidal wash than those of green turtles, likely affecting embryo mortality. Hatching success in olive ridley turtles is among the lowest in sea turtles when this species nest in *arribadas*, because of the high bacterial and fungi contamination caused by the extremely high density of nests that occur during these events, as well as by nest destruction caused by other laying turtles (Honarvar et al. 2008; Bézy et al. 2014, 2015). In contrast, hatching success in olive ridley clutches can be high when nesting solitarily (Dornfeld et al. 2015). A correct and complete description of hatching success, both when turtles nest in *arribadas* or solitarily, could also help to better understand the reproductive success of olive ridley turtles associated to each nesting strategy and the evolution of *arribadas*.

In conclusion, hatching success has been reported in an inappropriate way in the sea turtle literature, thus preventing proper knowledge acquisition. However, basic statistics such as the median, the skewness, kurtosis and the trimmed mean can be easily obtained and their use, in lieu of the arithmetic mean, would represent a remarkable improvement. Boxplots additionally provide a complete description of the data for visual assessment. We recommend to avoid using arithmetic means under conditions of non-normality such as in the reporting of hatching success. A straightforward change will improve our understanding of the ecology and evolution of key reproductive performance rates such as hatching success, what might also bring improvements in the management of populations with conservation problems, such as those of the study species.

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Author contributions **PST**: conceptualization, data acquisition, methodology, writing original draft. **AMA**: conceptualization, methodology, review and editing. **VV**: data acquisition, review and editing. **JRS**: review and editing. Project administration. **FVP**: review and editing. Project administration.

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Data availability The data used in this study can be made available on reasonable request.

Declarations

Compliance with ethical standards The authors do not have any conflicts of interest to declare. Data collection for this study was authorized by the Animal Care Committees of Drexel University and Purdue University Fort Wayne, and was conducted under research permits granted by the Ministry of Environment and Energy of Costa Rica.

Competing Interests The authors have no relevant financial or nonfinancial interests to disclose.

Ethics approval Data collection for this study was authorized by the Animal Care Committees of Drexel University and Purdue University Fort Wayne, and was conducted under research permits granted by the Ministry of Environment and Energy of Costa Rica.

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