sustainability

MDPI

Article

High Loggerhead (*Caretta caretta*) Bycatch Rate along with Several Endangered Target Species: Two Reasons to Look for Alternative to Traditional Large-Mesh Bottom-Set Gillnets (Garrasia) for More Sustainable Fisheries in the Gulf of Gabès (Tunisia)

Maissa Louhichi [1,*], Alexandre Girard [2,†] and Imed Jribi [1,†]

[1] BIOME Lab, Sfax Faculty of Sciences, University of Sfax, P.O. Box 1171, Sfax 3000, Tunisia; imed.jribi@fss.usf.tn
[2] PatriNat (OFB-MNHN-CNRS-IRD), Muséum National d'Histoire Naturelle, 36 rue Geoffroy Saint-Hilaire, CP41, 75005 Paris, France; alexandre.girard@mnhn.fr
* Correspondence: maissa.louhichi7@gmail.com; Tel.: +216-95902206
† These authors contributed equally to this work.

Abstract: Fishery bycatch poses a significant threat to sea turtles. This study provides an updated assessment of Loggerhead turtle (*Caretta caretta*) bycatch in the Gulf of Gabès, focusing on the impact of the Garrasia gillnets. Through 61 onboard observations conducted alongside fishermen in Zarzis deploying a bottom-set gillnet, called "Garrasia", and targeting elasmobranch species, comprehensive data were collected, including the number of sea turtles captured, soak time, length of gillnets, location, and biometric data of sea turtles. Analysis revealed a catch per unit effort (CPUE) for sea turtles of 0.63 (95% CI [0.355–0.893]) turtles per kilometer per 24 h with a notably high mortality rate of 92.06% (95% CI [87.3–96.8]). In the Gulf of Gabès, 23 vessels are reported to use Garrasia, resulting in an estimated annual total capture of 3756.53 turtles with a 95% CI [1907.81–5902.30]. These findings underscore the significant impact of Garrasia on sea turtle populations in the Gulf of Gabès. The study calls for immediate collaborative efforts among researchers, local stakeholders, authorities and fishermen to elaborate balanced conservation strategies that consider both ecological sustainability and socio-economic factors, aiming to achieve a sustainable marine ecosystem.

Keywords: sea turtles; bycatch; Garrasia; Gulf of Gabès; *Caretta caretta*

Citation: Louhichi, M.; Girard, A.; Jribi, I. High Loggerhead (*Caretta caretta*) Bycatch Rate along with Several Endangered Target Species: Two Reasons to Look for Alternative to Traditional Large-Mesh Bottom-Set Gillnets (Garrasia) for More Sustainable Fisheries in the Gulf of Gabès (Tunisia). *Sustainability* **2024**, *16*, 3713. https://doi.org/10.3390/su16093713

Academic Editor: Gioele Capillo

Received: 15 February 2024
Revised: 29 March 2024
Accepted: 11 April 2024
Published: 29 April 2024

1. Introduction

The incidental fishery in the Mediterranean Sea is a significant and pressing threat to the survival of sea turtles, posing dire consequences for marine biodiversity and ecosystem health. Bycatch refers to the unintentional capture of non-target species in fishing gear [1–4], and it is a common problem in many countries. This pervasive issue extends far beyond regional boundaries, plaguing fisheries worldwide and contributing substantially to the decline in marine megafauna populations, with sea turtles bearing a particularly heavy toll [1,2].

The Mediterranean Sea, renowned for its rich biodiversity and ecological significance, is hosting three species of sea turtles (Loggerhead turtle, Green turtle and Leatherback turtle) although three other species have been occasionally observed (Hawksbill turtle, Kemp's Ridley turtle and Olive Ridley turtle). The Loggerhead (*Caretta caretta* [5]) is the most abundant [4,6,7], considering both the oceanic and neritic zones [8,9]. Major Loggerhead neritic foraging grounds are located along the south-east coast of Turkey [4], in the Gulf of Gabès [10], in the north Adriatic Sea [11], off the southeast Egyptian coast [3] and off the Spanish coast [12]. Nesting beaches for Loggerheads predominantly dot the

coastlines of Greece, Turkey, Cyprus and Libya, although sporadic nesting activities have been observed in Egypt, Syria, Lebanon and Tunisia [13].

Estimations by Casale [14] indicate a grim reality, with over 132,000 sea turtles captured and 44,000 deaths attributed to various fishing gears annually in the Mediterranean in 2011. This staggering toll underscores the urgent need for comprehensive conservation efforts and sustainable fishing practices. The ranking of gears by capture frequency reveals pelagic longlines, bottom trawls, set nets and demersal longlines as the most significant contributors to turtle bycatch [14].

Most studies on sea turtle bycatch have focused on large-scale commercial fisheries [6,7,10,14–21] because of the challenges associated with assessing the extensive number of small-scale fisheries.

In Tunisia, sea turtles interact with the majority of fishing gears [22]. Previous studies have already highlighted the high impact of trawlers [10], longlines [15] and set nets [16,17].

Different nets are used by small-scale fisheries and could be a real threat for sea turtles and other species that are caught accidentally. Therefore, sea turtles are one of the most vulnerable to entanglement in coastal nets because they are often set close to the foraging and nesting area of sea turtles. Gillnets, in particular, have emerged as a cause for concern, exhibiting a high interaction rate in the Gulf of Gabès and contributing to elevated mortality among entangled turtles [18,22].

The complexity of sea turtle bycatch dynamics is further compounded by the variability among vessels, influenced by operational parameters such as days at sea, the number of sets and net dimensions [23]. While the majority of set nets have a low catch rate of sea turtles, the collective use of these gear types across a large number of small boats along the Tunisian coastline poses a substantial threat to sea turtles.

Tunisia's small-scale fisheries sector, characterized by its dynamic nature and seasonal variability in gear utilization, presents challenges in accurately quantifying turtle bycatch [23]. Addressing this issue necessitates comprehensive studies that account for the diverse array of gear types employed by fishing units and variability in gear selection during fishing trips.

This study, based on onboard observations, seeks to investigate the interaction of sea turtles with gillnets named "Garrasia", which are employed in the southern region of Tunisia. These gillnets present a significant risk of incidental sea turtle capture. Our primary objective is to provide an updated estimation of the bycatch rate, while simultaneously evaluating the influence of various factors—such as gear specifications, fishing locations, and seasonal variations—on bycatch risk.

Efforts to mitigate the impact of coastal nets on Loggerhead turtles in the Mediterranean Sea are underway. Several initiatives have been introduced, one of which involves the implementation of UV LEDs to address this issue [24,25]. However, despite these efforts, the pervasive threat posed by coastal nets to Loggerhead turtles underscores the urgent need for further research and proactive conservation measures to safeguard these emblematic and endangered species.

2. Materials and Methods

2.1. Study Area

The study was conducted along the southern coast of Tunisia, with a specific focus on the ports of Zarzis and Djerba situated within the Gulf of Gabès, also known as Lesser Syrtis. This Gulf, a prominent geographical feature along Tunisia's eastern seaboard in the Mediterranean Sea, spans the coastline from Chebba in the north to the border with Libya in the south. The Gulf of Gabès is renowned for its distinctive marine ecosystems, boasting rich biodiversity and serving as a crucial habitat for numerous marine species. Moreover, this region holds significant economic and ecological importance within the Mediterranean basin, supporting diverse fisheries and maritime activities while also contributing to the overall ecological balance of the area. Zarzis and Djerba were chosen for

their pivotal positions in the Gulf, offering insights into the interaction between sea turtles and fishing gear.

2.2. Data Collection

Data for this study were collected through onboard observations conducted by trained fishing observers. These observers were tasked with gathering a comprehensive set of information throughout the fishing operations, ensuring the thorough documentation of key variables. This included recording the date and precise geographic coordinates at both the start and the end of each gear set process, thereby offering a clear outline of the spatial distribution and extent of the fishing efforts within the study area.

In addition to spatial data, the observers documented the incidence of turtle bycatch during these operations. Each captured turtle underwent a detailed assessment of its physical condition, allowing for the categorization of each individual as healthy, injured, comatose or deceased [17]. Furthermore, precise measurements of the turtles were taken, focusing specifically on the curved carapace length notch to tip (CCLn-t), following established methodologies [26]. This measurement is crucial for determining the size and age class of captured turtles, which can be instrumental in understanding the demographics of impacted turtle populations [13,27]. All trips were conducted under true fishing conditions over a span of four years, from 2018 to 2022, utilizing three small-scale boats departing from the ports of Zarzis and Djerba. In total, 63 onboard observations were conducted: 9 in 2018, 8 in 2020, 27 in 2021 and 19 in 2022. These boats exclusively employed gillnets known as "Garrasia" for their fishing operations.

The Garrasia is a highly specialized type of gillnet specifically engineered for the capture of elasmobranchs, which include various species such as sharks (*Carcharhinus plumbeus)*, guitarfishes (*Rhinobatos rhinobatos* and *Glaucostegus cemiculus*), eagle rays *(Aetomylaeus bovinus)* and similar species. The Garrasia is composed from a single net panel with a significantly large mesh size, measuring approximately 160 mm. Each individual net of this specialized net measures 50 m in length and consists of 10 vertical meshes, resulting in a vertical drop of 3.2 m. This mesh size is particularly chosen to effectively target larger species of elasmobranchs, ensuring optimal efficacy in the fishing operations.

In terms of deployment, the Garrasia is designed to be set on the seabed, where it remains steadfastly in place for an approximate duration of 24 h. However, under certain circumstances, it may be left deployed for up to two days, amplifying the probability of capturing the targeted and non-target species. The net is secured in its position by ropes and anchored firmly to the sea floor with weights attached to its bottom line. This anchoring mechanism ensures that the net remains in close proximity to the seabed. Additionally, to maintain its desired vertical orientation in the water column, floats are attached to the top line of the net [3,27]. This crafted arrangement not only allows the net to effectively cover a substantial vertical area but also ensures its stability and efficacy in capturing the target marine species.

In addition, we conducted interviews with fishermen using Garrasia across various ports within the Gulf of Gabès. The objective of these interviews was to ascertain crucial information, including the total number of vessels employing Garrasia and the annual frequency of fishing trips undertaken by each vessel. This allowed us to calculate the total capture of sea turtles and the related mortality within the region.

2.3. Data Analysis

Two catch per unit effort (CPUE) calculations were made to estimate the impact of Garrasia on sea turtle populations in the Gulf of Gabès:

$$CPUE1 = n/N$$

n = number of turtles captured
N = number of fishing operations

$$CPUE2 = n/L \times T$$

N = number of turtles captured
L = total net length [km]
T = soak time in hours/24

The total number of sea turtles captured by Garrasia per year in the Gulf of Gabès was then estimated by multiplying the catch per unit effort (CPUE) derived from onboard monitoring through the fishing efforts for all vessels combined, which was expressed as kilometers of net length × days of fishing. This information was obtained from comprehensive survey data outlined in Appendix A.

The number of sea turtles per set is a discrete variable that does not follow a normal distribution pattern. Therefore, confidence intervals were calculated using the bootstrap method, leveraging the 'boot' package in R for statistical analysis.

To obtain insights into the life stages of Loggerhead interacting with gillnets and detect possible changes in the population structure according to the season, the distributions of the curved carapace length (CCL) measured for by-caught sea turtles in the Gulf of Gabès during spring, summer and autumn were compared using a violin plot (ggplot2 R package).

Despite the fact that measuring tail length may not be as precise as laparoscopy for determining the sex of large specimens (those presumed to be adults), it remains a practical method for field conditions and can yield a significant amount of data if a reliable technique is employed [28]. We use this measure on specimens exceeding 70 cm in size to determinate the sex of sea turtles caught.

In our study, we only consider three seasons (autumn, spring and summer) as in the Gulf of Gabès fishermen refrain from using Garrasia during the winter months due to the lack of target species during that season.

3. Results

3.1. CPUE and Total Capture Estimate

During the entire study period, 61 trips were carried out with 63 fishing sets. The map (Figure 1) indicates the locations of the sets in the study area.

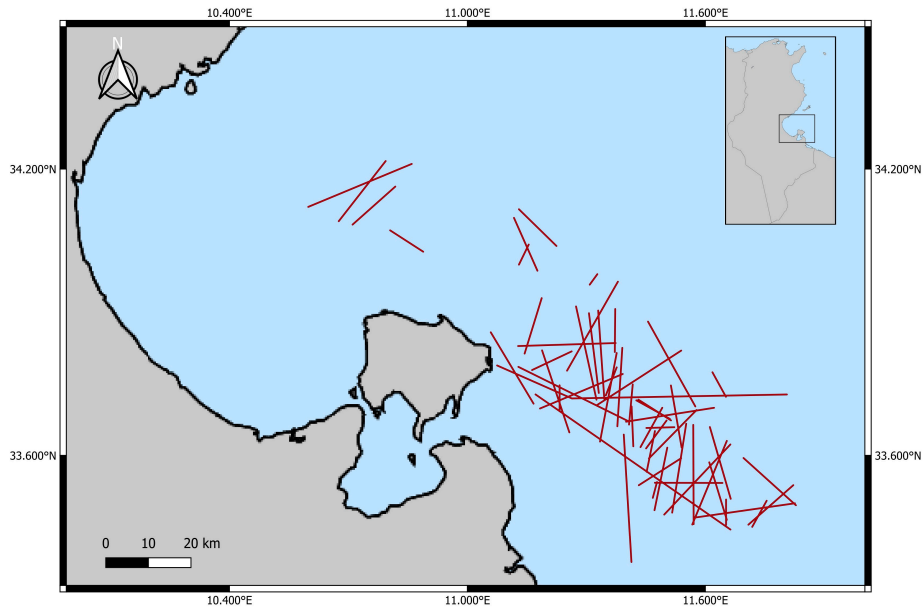

Figure 1. Locations of the sets deployed during the study.

The number of sea turtles caught is 126, with 116 of them being found dead. During one of our onboard observations, 43 sea turtles were caught in a single fishing operation.

The total length of gillnets used during the study period was 244.75 km. The CPUE and the total catch estimation obtained during the study are summarized in Table 1.

Table 1. Catch rate of sea turtles caught by gillnets.

Number of turtles caught	162
Number of sets	63
Total duration of soak time (d)	78.14
CPUE1 (95% CI)	2.11 (1.20–3.07)
CPUE2 (95% CI)	0.63 (0.32–0.99)
Number of vessels using Garrasia	23
Total number of fishing trips per year (all vessels combined)	1131
Estimated total capture (95% CI)	3756.53 (1907.81–5902.30)

In the Gulf of Gabès, 23 vessels are currently operating, with Garrasia collectively deploying approximately 91.2 km of nets, with a mean soak time of 1.24 days (estimated from the present study). The total number of fishing trips conducted annually by all vessels combined is calculated to be 1113 (as estimated from the interviews).

Based on these parameters, the total capture of sea turtles is estimated to be 3756.53, with a 95% confidence interval of [1907.81–5902.30] turtles per year.

3.2. Mortality Rate

All the sea turtles captured in this study were identified as Loggerhead turtle *Caretta caretta*. Of the total captured Loggerheads, a significant portion, specifically 116 out of 126, became deceased. This translates into a mortality rate of 92.06%.

3.3. Sex Ratio

We obtained complete morphometric data from 75 individuals. The mean carapace length ($SCCL_{n\text{-}t}$) of caught Loggerheads was 68.16 cm 95% CI [65.27–70.89]). Based on these measurements, it can be inferred that the majority of these turtles were subadults, with 34 individuals likely categorized as adults (larger than 70 cm $SCCL_{n\text{-}t}$).

Tail lengths were obtained for all 34 individuals caught, whose sizes were consistent with those of adult-stage turtles. Among these, 29.41% exhibited male characteristics (a long and large tail), and 70.58% exhibited small tails consistent with those of females.

We calculated sex ratios for two distinct periods: summer and autumn. The observed sex ratios were 54.5% females for summer and 77.3% for autumn.

The two sex ratios do not show a significant difference (Fisher exact test: $p = 0.24$; n = 23), potentially due to the limited sample size.

3.4. Seasonal Variation

In our analysis, we computed two distinct CPUEs: CPUE1 illustrating the catch rate per fishing operation (Figure 2a) and CPUE2 depicted as the catch rate per kilometer of net per 24 h (Figure 2b).

Sets during the autumn exhibited the highest observed CPUE2 with a mean of 0.71 95% CI [0.30–1.22] turtles km^{-1} 24 h^{-1} followed by spring, at CPUE2 = 0.62 95% CI [0–1.25], and summer (CPUE2 = 0.38 95% CI [0.13–0.66]).

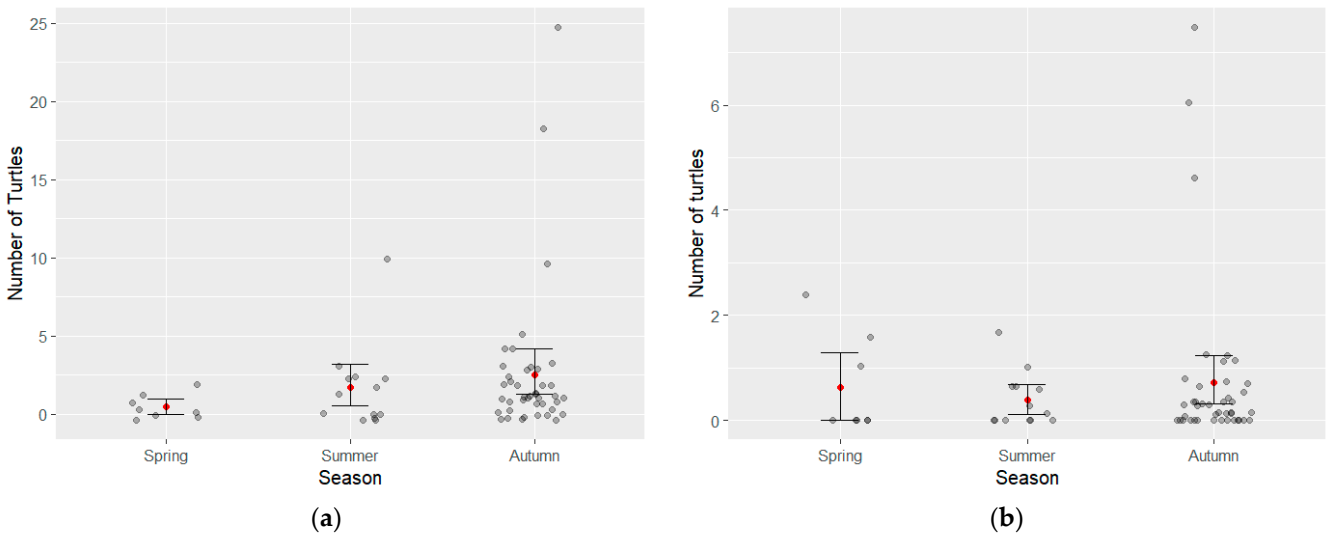

Figure 2. Sea turtles caught with Garrasia in the Gulf of Gabès according to the season. (**a**) CPUE1: number of sea turtles caught per operation; (**b**) CPUE2: number of sea turtles caught per km of net per 24 h.

3.5. Size Variation According to Season

The analysis of the curved carapace length (CCL) of sea turtles in the Gulf of Gabès provided valuable insights into the size distribution within this population across different seasons. Notably, it was observed that during the summer season, the CCL tends to be notably higher, measuring an average of 75.55 cm with a 95% confidence interval (CI) of [68.88–82.72].

In the autumn season, the CCL of Loggerhead turtles averages at 66.24 cm with a 95% CI of [63.48–69.11]. A noticeable drop in average sizes is observed in the spring season, with the CCL measuring 60.25 cm at a 95% CI of [50.00–68.25].

Figure 3 illustrates the size distribution of sea turtles caught with Garrasia in the Gulf of Gabès across different seasons, providing a visual representation of the observed variations in sea turtle sizes throughout the year.

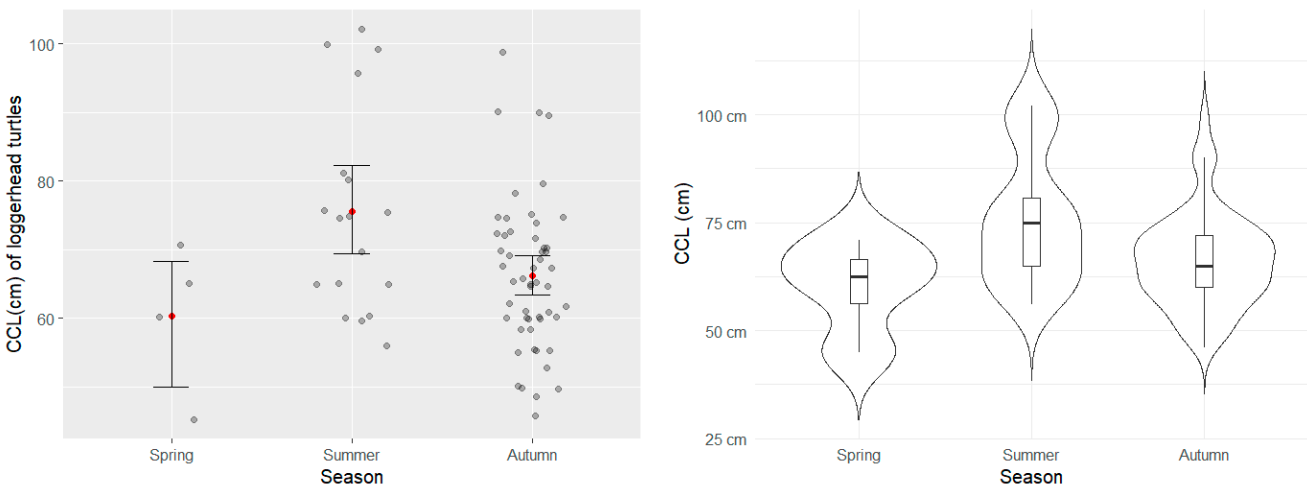

Figure 3. Size of sea turtles caught with Garrasia in the Gulf of Gabès according to the season.

4. Discussion

4.1. Bycatch Rate per Unit Effort (CPUE) and Annual Total Capture

In Tunisian marine waters, Loggerhead turtles are the most commonly observed species, constituting the vast majority of sightings, while encounters with green and

leatherback turtles are regular but relatively rare [10,15,17]. This observation was further corroborated by our study, where all sea turtles encountered as bycatch were identified as Loggerhead turtles (*Caretta caretta*).

Sea turtles are known to be incidentally captured by various types of fishing gear, including trawl nets, gillnets and both pelagic and bottom longlines [1,14,29]. Gillnet fisheries have been identified as potentially posing the most significant threat to sea turtle populations, as highlighted in studies by Wallace et al. and Gilman et al. [2,30]. Notably, in Tunisia, Louhichi et al. [22] emphasized the importance of conducting interviews at fishing ports to estimate the level of interaction between fisheries and sea turtles. The results from these interviews revealed that Garrasia exhibited the highest sea turtle catch per unit effort (CPUE) compared with other fishing gears, as indicated in the previous study [22]. The ongoing study, conducted through onboard campaigns to directly observe the CPUE of Garrasia, corroborates the previous interview findings, further underscoring the significant impact of this gear on sea turtles in the Gulf of Gabès.

The CPUE for Garrasia, based on on-board observations, reached 0.63 turtles per km per 24 h, with a 95% CI of [0.32–0.99]. Within the Gulf of Gabès, the fleet using Garrasia comprises 23 vessels, resulting in a cumulative yearly fishing effort of 5961.92 net-km $\times$ 24 h (Appendix A). This operation leads to an estimated annual bycatch of 3756.53 turtles, with a 95% CI of [1907.81–5902.30]. These figures highlight the considerable impact of Garrasia fishing on turtle populations in the Gulf of Gabès. With a staggering 92.06% mortality rate associated with this bycatch, the significant loss inflicted by this relatively small fleet of just twenty-three boats is particularly concerning. The high catch rate CPUE suggests the possibility that the vessel encountered a migratory path of turtles. Alternatively, it could indicate that the vessel came across a gathering of turtles in a reproductive aggregation. These scenarios could explain the unusually elevated number of captures. The cumulative Garrasia bycatch surpasses 40% of the total estimated bycatch from trawling activities, which are conducted by 272 trawl vessels in the Gulf of Gabès, totaling an estimated 8208.96 turtles per year (95% CI [0–29,036]), calculated from the raw data (source: [25]).

The Garrasia CPUEs substantially exceed those previously reported for sea turtle bycatch in Tunisian gillnet fisheries. Specifically, Echwikhi et al. [17] documented a bycatch rate of 0.8 turtles per fishing set, with a 95% confidence interval (CI) of [0.65–0.90]. In contrast, our study reveals a higher catch rate per fishing operation, with a CPUE1 of 2.11 turtles per operation and a 95% CI of [1.2–3.07].

The notable increase in the catch per unit effort (CPUE) of sea turtles by Garrasia in the Gulf of Gabès can be attributed to the heightened frequency of fishing trips undertaken by individual vessels each year, indicative of an intensified fishing effort employing Garrasia. In fact, the fishing period utilizing Garrasia has been extended beyond the previously reported months of April May, and June, as documented by Echwikhi et al. [18]. It is worth considering that the observed rise in CPUE may also be influenced by the growing population of Loggerhead turtles in the Mediterranean, thus suggesting it as a potential additional contributing factor.

In terms of total captures, it is important to note that Echwikhi et al. [17] considered only three ports, whereas our study includes all ports in the Gulf of Gabès where Garrasia nets are used. This broader scope likely contributes to our study's higher total Loggerhead capture estimates, surpassing both Echwikhi and collaborators' figure and documented bycatch in other Mediterranean countries. For instance, Egypt estimated a total capture of 754 turtles per year [31], while Croatia estimated 393 turtles per year [32].

The CPUE derived from our study, conducted through onboard observations, is nevertheless geographically confined to the port of Zarzis and Djerba. This geographical limitation necessitates a cautious extrapolation of our findings. However, given the substantial impact observed in these areas, we advocate for further onboard observations to be conducted across various ports within the Gulf of Gabès. Expanding the sampling to encompass a wider range of ports will enable a more comprehensive understanding of sea turtle interactions with Garrasia and minimize potential biases in our findings. Such an

approach would enhance the robustness and applicability of our study's recommendations for mitigating sea turtle bycatch in the region.

Assessing the impact of fisheries on sea turtle mortality requires an in-depth analysis encompassing both direct mortality from bycatch and subsequent post-release mortality. Mortality risks vary significantly depending on the type of fishing gear and associated practices. Drowning stands out as a primary cause of mortality of sea turtles, occurring when they become entangled in fishing gear and are unable to surface for air [33].

In this study, the average soak time for Garrasia was 29.76 h, far surpassing the apnea tolerance limits of turtles. This prolonged entanglement correlates with a strikingly high estimated mortality rate of 92.06%. Compounding this issue is fishermen's frequent inability to differentiate between dead and comatose turtles, further increasing the likelihood of mortality for turtles that might otherwise have had the chance to recover if properly identified, treated and released.

Furthermore, inadequate removal of turtles from nets can result in injuries, necrosis and heightened mortality rates. These findings emphasize the critical impact of Garrasia on sea turtle mortality, underscoring the urgent need for mitigation measures [33]. An expanded understanding of these mortality factors across various fishing practices and locations within the Gulf of Gabès is imperative to developing targeted strategies aimed at reducing sea turtle bycatch and safeguarding these endangered species for future generations.

4.2. Seasonal Variation in CPUE and Size Variation

A slight seasonal variation in the number of bycatch was observed, with the CPUE reaching its peak in autumn (Figure 2b). The Gulf of Gabès has been formerly described as a foraging and wintering area [14,21,34–38]. The distribution of size observed among bycatches in autumn tended to show that the majority of individuals are subadult and juvenile during this season. Adults of a large size are more frequently observed in summer, which is probably linked to the reproductive activity occurring in the Gulf of Hammamet north of the Gulf of Gabès and in Lybia south of the Gulf of Gabès. Medium-size individuals observed in autumn may stay in winter, but it was not possible to explore the CCL size structure during this season due to the absence of Garassia activity during winter. Small-size individuals observed in spring may embark on migration to another region. Medium-size individuals are present all throughout the year. The findings on population structure are very preliminary and emphasize the need for genetic sampling and analysis (micro-satellite, single=nucleotide polymorphism and RadSeq) to further address population structure and connectivity.

The curved carapace length (CCL) of Loggerhead turtles observed in Garrasia averaged 68.16 cm 95% CI [65.27–70.89]). These results are consistent with those of previous studies [17,33,39], affirming the consistency of our results across different investigations. Notably, larger Loggerheads, which tend to forage on benthic preys, were predominantly captured in waters shallower than 50 m, where gillnets are more likely to ensnare larger turtles (over 60 cm CCL in 80% of cases). This selectivity poses a significant concern as older, larger turtles play a crucial role in population growth [40–43]. Moreover, our findings corroborate that the average size of Loggerhead turtles caught in neritic areas does not significantly differ between the use of various fishing gears, pointing to a general risk to larger turtles in these habitats [44]. This underscores the importance of considering habitat-specific impacts and implementing targeted conservation measures to mitigate the risks faced by larger, older Loggerhead turtles in the Gulf of Gabès.

The variation in the size of sea turtles observed in the Gulf of Gabès across different seasons can be attributed to several ecological and biological factors, including long-term warming trends likely associated with climate change. Previous research has indicated that seasonal changes in water temperature, food availability and breeding patterns can significantly influence the distribution of and size variation in sea turtle populations [45]. In line with these findings, during warmer months, such as summer, larger sea turtles are often observed in coastal waters, including the Gulf of Gabès. This could be linked

to the increased availability of food resources, which supports larger body sizes, and the preference for warmer waters for breeding activities [46,47]. The shallow depth of the Gulf of Gabès may further exacerbate the effects of climate change on sea turtles, as these waters are more susceptible to rapid warming. During warmer months, such as summer, larger sea turtles are often observed in coastal waters, including the Gulf of Gabès. This could be linked to the increased availability of food resources, which supports larger body sizes, and the preference for warmer waters for breeding activities [46,47].

Additionally, juvenile sea turtles present in the Gulf of Gabès during the spring season may decrease in number during the summer months compared with adults. This decrease in juvenile presence could be attributed to several factors, including potential migration patterns, changes in habitat utilization and competition for resources with larger, more dominant adults. Moreover, juveniles may be less competitive for food resources and living space compared with larger, more dominant adults, which could also influence their seasonal distribution in the coastal waters of the Gulf of Gabès.

In the Mediterranean, coastal nets predominantly capture large juvenile Loggerhead turtles on the verge of reaching sexual maturity, a critical stage for the species population dynamics. These turtles, primarily in their neritic phase, may originate from both Mediterranean and Atlantic stocks, highlighting the interconnection of sea turtle populations across regions [3,48,49]. Their migratory behavior, driven by factors such as sea temperature, food availability and reproductive cycles, prompts them to embark on extensive journeys. Such migrations, coupled with seasonal reproductive activities, can lead to variations in sea turtle abundance in certain areas, as a result influencing bycatch rate [50].

4.3. Sex Ratio

Sex ratios vary between the summer period, characterized by reproductive migration, and the colder autumn period, when reproductive Loggerheads may migrate to other areas. The larger proportion of males observed during summer could be attributed to male recruitment for mating purposes, while the sex ratio in autumn (cold period) might be considered more indicative, as suggested by Wibbels [51], who indicated that adult sex ratios can be influenced by sex-specific patterns of reproductive migration. The female-dominated sex ratios that align with estimates derived from tail dimorphism in our study are consistent with sex ratios reported in studies on adult Loggerhead turtles in the Mediterranean [52].

Our findings are consistent with previous research on Loggerhead turtles in the Mediterranean, supporting the observation that both adult and juvenile populations tend to have more balanced sex ratios compared with hatchlings [53–56].

5. Conclusions

The pervasive interaction between Loggerhead turtles and coastal nets, particularly gillnets, stands as a critical conservation concern in the Mediterranean Sea. Our study underscores the Gulf of Gabès as a crucial foraging and developmental habitat for Loggerhead turtles. The elevated bycatch rates observed in Garrasia emphasize the urgent need for targeted conservation efforts. Beyond Loggerheads, the impact extends to other vulnerable species targeted by Garrasia, such as the critically endangered Bull ray (*Aetomylaeus bovinus*) and the guitarfishes *Rhinobatos rhinobatos*, which is endangered in the Mediterranean, and *Glaucostegus cemiculus*, which is critically endangered globally.

Our findings underscore the pressing need for conservation strategies to address sea turtle bycatch in gillnets, drawing from successful interventions documented in the literature [31,57–59] that propose practical measures such as the use of illuminated nets with LED lights, the deployment of shark silhouettes and the adoption of float lines without buoys. However, it is important to note that while these mitigation measures may be beneficial for certain types of nets, they may not be effective for Garrasia nets, as they specifically target vulnerable species in addition to accidental turtle captures. Instead, the solution may lie in promoting alternative fishing practices that have lower impacts on vulnerable turtles and sharks.

Finally, the successful implementation of solutions necessitates collaborative efforts among scientists, stakeholders and decision-makers. They need to consider the socio-economic context, so providing alternative economic opportunities for fishermen emerges as a crucial component of sustainable conservation. By offering viable alternatives, we can simultaneously address the ecological impact on sea turtles and endangered species while respecting the livelihoods of local communities.

Author Contributions: Study conception and design, M.L., A.G. and I.J.; data collection, M.L.; analysis and interpretation of results, M.L., A.G. and I.J.; draft manuscript preparation, M.L., A.G. and I.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by RUFFORD, grant number 21699-1, a FORD environmental grant, and a SWOT grant.

Institutional Review Board Statement: Ethical review and approval were waived for this study due to the approval of the Biological Sciences Commission of the Faculty of Sciences of Sfax.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We are grateful to those organizations. Special thanks go to all the fishermen involved in the survey who collaborated with us and accept us on board of their vessels. We are indebted to the personnel in different administrations in the ports who facilitated our field work. We would like to thank my colleagues for their support especially Wiem Bousellaa and Arij Sadraoui.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Total capture of sea turtles in the Gulf of Gabès per year.

Port	Number of Vessels	Number of Fishing Net Pieces	Total Length of Gillnets (km)	Number of Sets	Fishing Effort per Year (Length × Set × Mean Soak Time)
Zarzis	1	160	8	58	575.36
Zarzis	1	180	9	58	647.28
Zarzis	1	100	5	58	359.6
Zarzis	1	100	5	58	359.6
Zarzis	1	120	6	58	431.52
Zarzis	1	80	4	58	287.68
Zarzis	1	90	4.5	58	323.64
Zarrat	1	70	3.5	30	130.2
Zarrat	1	50	2.5	30	93
Zarrat	1	50	2.5	30	93
Gabès	1	50	2.5	60	186
Gabès	1	50	2.5	60	186
Gabès	1	50	2.5	60	186
Gabès	1	50	2.5	60	186
Kerkannah	1	12	0.6	30	22.32
Kerkannah	1	12	0.6	30	22.32
Ghannouch	1	20	1	30	37.2
Elketef	1	100	5	50	310
Boughrara	1	100	5	45	279
Boughrara	1	80	4	45	223.2
Houmet Souk	1	100	5	55	341
Houmet Souk	1	100	5	55	341
Houmet Souk	1	100	5	55	341

References

1. Lewison, R.L.; Crowder, L.B.; Read, A.J.; Freeman, S.A. Understanding Impacts of Fisheries Bycatch on Marine Megafauna. *Trends Ecol. Evol.* **2004**, *19*, 598–604. [CrossRef]
2. Wallace, B.P.; Lewison, R.L.; McDonald, S.L.; McDonald, R.K.; Kot, C.Y.; Kelez, S.; Bjorkland, R.K.; Finkbeiner, E.M.; Helmbrecht, S.; Crowder, L.B. Global Patterns of Marine Turtle Bycatch. *Conserv. Lett.* **2010**, *3*, 131–142. [CrossRef]
3. Casale, P. Incidental Catch of Marine Turtles in the Mediterranean Sea: Captures, Mortality, Priorities. In *WWF Mediterranean Marine Turtle Programme*; WWF Italy: Burano, Italy, 2008.
4. Casale, P.; Margaritoulis, D. *Sea Turtles in the Mediterranean: Distribution, Threats and Conservation Priorities*; IUCN: Gland, Switzerland, 2010.
5. Shoop, C.R.; Dodd, C.K. Synopsis of the Biological Data on the Loggerhead Sea Turtle *Caretta caretta* (Linnaeus 1758). *Copeia* **1989**, 534. [CrossRef]
6. Casale, P.; Heppell, S. How Much Sea Turtle Bycatch Is Too Much? A Stationary Age Distribution Model for Simulating Population Abundance and Potential Biological Removal in the Mediterranean. *Endanger. Species Res.* **2016**, *29*, 239–254. [CrossRef]
7. Casale, P.; Broderick, A.; Camiñas, J.; Cardona, L.; Carreras, C.; Demetropoulos, A.; Fuller, W.; Godley, B.; Hochscheid, S.; Kaska, Y.; et al. Mediterranean Sea Turtles: Current Knowledge and Priorities for Conservation and Research. *Endanger. Species Res.* **2018**, *36*, 229–267. [CrossRef]
8. McClellan, C.M.; Read, A.J. Complexity and variation in loggerhead sea turtle life history. *Biol. Lett.* **2007**, *3*, 592–594. [CrossRef] [PubMed]
9. Casale, P.; Abbate, G.; Freggi, D.; Conte, N.; Oliverio, M.; Argano, R. Foraging ecology of loggerhead sea turtles *Caretta caretta* in the central Mediterranean Sea: Evidence for a relaxed life history model. *Mar. Ecol. Prog. Ser.* **2008**, *372*, 265–276. [CrossRef]
10. Jribi, I.; Bradai, M.N.; Bouain, A. Impact of Trawl Fishery on Marine Turtles in the Gulf of Gabès, Tunisia. *Herpetol. J.* **2007**, *17*, 110–114.
11. Casale, P.; Laurent, L.; De Metrio, G. Incidental Capture of Marine Turtles by the Italian Trawl Fishery in the North Adriatic Sea. *Biol. Conserv.* **2004**, *119*, 287–295. [CrossRef]
12. Gómez de Segura, A.; Tomás, J.; Pedraza, S.N.; Crespo, E.A.; Raga, J.A. Abundance and Distribution of the Endangered Loggerhead Turtle in Spanish Mediterranean Waters and the Conservation Implications. *Anim. Conserv.* **2006**, *9*, 199–206. [CrossRef]
13. Margaritoulis, D.; Argano, R.; Baran, I.; Bentivegna, F.; Bradai, M.; Camiñas, J.; Casale, P.; Metrio, G.; Demetropoulos, A.; Gerosa, G. Loggerhead Turtles in the Mediterranean Sea: Present Knowledge and Conservation Perspectives. In *Loggerhead Sea Turtles*; Bolten, A.B., Witherington, B.E., Eds.; Smithsonian Institution Press: Washington, DC, USA, 2003.
14. Casale, P. Sea Turtle By-catch in the Mediterranean. *Fish Fish* **2011**, *12*, 299–316. [CrossRef]
15. Jribi, I.; Echwikhi, K.; Bradai, M.N.; Bouain, A. Incidental capture of sea turtles by longlines in the Gulf of Gabès (South Tunisia): A comparative study between bottom and surface longlines. *Sci. Mar.* **2008**, *72*, 337–342. [CrossRef]
16. Echwikhi, K.; Imed, J.; Bradai, M.; Bouain, A. Overview of Loggerhead Turtles Coastal Nets Interactions in the Mediterranean Sea. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2012**, *22*, 2270. [CrossRef]
17. Echwikhi, K.; Jribi, I.; Bradai, M.N.; Bouain, A. Gillnet Fishery-Loggerhead Turtle Interactions in the Gulf of Gabes, Tunisia. *Herpetol. J.* **2010**, *20*, 25–30.
18. Lucchetti, A.; Vasapollo, C.; Virgili, M. An Interview-Based Approach to Assess Sea Turtle Bycatch in Italian Waters. *PeerJ* **2017**, *5*, e3151. [CrossRef] [PubMed]
19. Wallace, B.P.; Heppell, S.S.; Lewison, R.L.; Kelez, S.; Crowder, L.B. Impacts of Fisheries Bycatch on Loggerhead Turtles Worldwide Inferred from Reproductive Value Analyses. *J. Appl. Ecol* **2008**, *45*, 1076–1085. [CrossRef]
20. Lucchetti, A.; Sala, A. Review of Loggerhead Turtle (*Caretta Caretta*) Bycatch and Technical Mitigation Measures in the Mediterranean Sea. *Mar. Res. CNR* **2011**, *DTA/06-2011*, 1839–1855.
21. Pulcinella, J.; Bonanomi, S.; Colombelli, A.; Fortuna, C.M.; Moro, F.; Lucchetti, A.; Sala, A. Bycatch of loggerhead turtle (Caretta caretta) in the Italian Adriatic midwater pair trawl fishery. *Front. Mar. Sci.* **2019**, *6*, 365. [CrossRef]
22. Louhichi, M.; Girard, A.; Jribi, I. Fishermen Interviews: A Cost-Effective Tool for Evaluating the Impact of Fisheries on Vulnerable Sea Turtles in Tunisia and Identifying Levers of Mitigation. *Animals* **2023**, *13*, 1535. [CrossRef]
23. Cambiè, G.; Jribi, I.; Cambera, I.; Vagnoli, P.; Freggi, D.; Casale, P. Intra-gear variation in sea turtle bycatch: Implications for fisheries management. *Fish. Res.* **2020**, *221*, 105–405. [CrossRef]
24. Virgili, M.; Vasapollo, C.; Lucchetti, A. Can ultraviolet illumination reduce sea turtle bycatch in Mediterranean set net fisheries? *Fish. Res.* **2018**, *199*, 1–7. [CrossRef]
25. Lucchetti, A.; Bargione, G.; Petetta, A.; Vasapollo, C.; Virgili, M. Reducing Sea Turtle Bycatch in the Mediterranean Mixed Demersal Fisheries. *Front. Mar. Sci* **2019**, *6*, 387. [CrossRef]
26. Bolten, A.B. Techniques for measuring sea turtles. In *Research and Management Techniques for the Conservation of Sea Turtles*; Eckert, K.L., Bjorndal, K.A., Abreu-Grobois, F.A., Donnelly, M., Eds.; IUCN/SSC Marine Turtle Specialist Group Publication No.4; IUCN: Gland, Switzerland, 1999; pp. 110–114.
27. Nédélec, C.; Prado, J. *Definition and Classification of Fishing Gear Categories*; FAO Fisheries Technical Paper; FAO: Rome, Italy, 1990.
28. Casale, P.; Freggi, D.; Basso, R.; Argano, R. Oceanic habitats for loggerhead turtles (*Caretta caretta*) in the Mediterranean Sea. *Mar. Turtle Newsl.* **2005**, *107*, 10–11.

29. Rosales, C.; Vera, M.; Llanos, J. Varamientos y captura incidental de tortugas marinas en el litoral de Tumbes, Perú. *Rev. Peru. Biol.* **2010**, *17*, 293–301. [CrossRef]
30. Gilman, E.; Bianchi, G. Guidelines to Reduce Sea Turtle Mortality in Fishing Operations. In *FAO Technical Guidelines for Responsible Fisheries*; FAO: Rome, Italy, 2010; ISBN 978-92-106226-5.
31. Nada, M.; Casale, P. Sea Turtle Bycatch and Consumption in Egypt Threatens Mediterranean Turtle Populations. *Oryx* **2011**, *45*, 143–149. [CrossRef]
32. Lazar, B.; Ziza, V.; Tvrtkovic, N. Interactions of gillnet fishery with loggerhead sea turtles Caretta *Caretta* in the northern Adriatic Sea. In Proceedings of the 26th Annual Symposium on Sea Turtle Biology and Conservation, Athens, Greece, 11–13 April 2006.
33. Gerosa, G.; Casale, P. *Interaction of Marine Turtles with Fisheries in the Mediterranean*; UNEP/MAP, RAC/SPA: Nairobi, Kenya, 1999.
34. Casale, P.; Freggi, D.; Basso, R.; Argano, R. Interaction of the static net fishery with loggerhead sea turtles in the Mediterranean: Insights from mark-recapture data. *Herpetol. J.* **2005**, *15*, 201–203.
35. Argano, R.; Basso, R.; Cocco, M.; Gerosa, G. Nuovi Dati Sugli Spostamenti Di Tartaruga Marina Comune (*Caretta caretta*) in Mediterraneo. *Bollettino Dei Musei e Degli Istituti Biologici Dell'Università Di Genova* **1992**, *56–57*, 137–164.
36. Margaritoulis, D. Post-Nesting Movement of Loggerhead Sea Turtles Tagged in Greece. *Rapp. De La Comm. Int. Pour L'exploration Sci. De La Mer Méditerranée* **1988**, *31*, 284.
37. Laurent, L.; Nouira, S.; Jeudy De Grissac, A.; Bradai, M.N. Les Tortues Marines de Tunisie: Premières Données. *Bull. Soc. Herpétol. Fr.* **1990**, *53*, 1–17.
38. Laurent, L.; Lescure, J. L'hivernage Des Tortues Caouannes *Caretta Caretta* (L.) Dans Le Sud Tunisien. *Rev. Ecol. Terre Vie* **1994**, *49*, 63–86. [CrossRef]
39. Laurent, L. Synthèse historique de la présence de tortues marines sur les côtes de France (cotes méditerranéennes). Observatoire du Patrimoine Naturel. Groupe Tortues Marines. Direction de la nature et des Paysages. In *Sous Direction de la Chasse, de la Faune et de la Flore Sauvages*; Ministère Française de l'Environment: Paris, France, 1996.
40. Crouse, D.T.; Crowder, L.B.; Caswell, H. A stage based population model for loggerhead sea turtles and implications for conservation. *Ecology* **1987**, *68*, 1412–1423. [CrossRef]
41. Laurent, L.; Clobert, J.; Lescure, J. The demographic modeling of the Mediterranean loggerhead sea turtle population: First results. *Rapp. Comm. Int. Pour I E'Xploration Sci. Mer Medit.* **1992**, *33*, 300.
42. Crowder, L.B.; Deborah, T.C.; Heppell, S.S.; Martin, T.H. Predicting the Impact of Turtle Excluder Devices on Loggerhead Sea Turtle Populations. *Ecol. Appl.* **1994**, *4*, 437–445. [CrossRef]
43. Heppel, S.S.; Limpus, C.J.; Crouse, D.T.; Frazer, N.B.; Crowder, L.B. Population Model Analysis for the Logger-head Sea Turtle, Caretta *Caretta*, in Queensland. *Wildl. Res.* **1996**, *23*, 143–161. [CrossRef]
44. Polovina, J.J.; Howell, E.A.; Parker, D.M.; Balazs, G.H. Dive-depth distribution of loggerhead (*Caretta caretta*) and olive ridley (*Lepidochelys olivacea*) sea turtles in the central North Pacific: Might deep longline sets catch fewer turtles? *Fish. Bull.* **2003**, *101*, 189–193.
45. Hays, G.C.; Fossette, S.; Katselidis, K.A.; Schofield, G.; Gravenor, M.B. Breeding periodicity for male sea turtles, operational sex ratios, and implications in the face of climate change. *Conserv. Biol.* **2010**, *24*, 1636–1643. [CrossRef]
46. Schofield, G.; Dimadi, A.; Fossette, S.; Katselidis, K.A.; Koutsoubas, D.; Lilley, M.K.S.; Luckman, A.; Pantis, J.D.; Karagouni, A.D.; Hays, G.C. Satellite tracking large numbers of individuals to infer population level dispersal and core areas for the protection of an endangered species. *Divers. Distrib.* **2013**, *19*, 834–844. [CrossRef]
47. Mansfield, K.L.; Wyneken, J.; Porter, W.P.; Luo, J. First satellite tracks of neonate sea turtles redefine the 'lost years' oceanic niche. *Proc. R. Soc. B* **2014**, *281*, 20133039. [CrossRef]
48. Carreras, C.; Pont, S.; Maffucci, F.; Pascual, M.; Barcelo, A.; Bentivegna, F.; Cardona, L.; Alegre, F.; SanFelix, M.; Fernandez, G.; et al. Genetic structuring of immature loggerhead sea turtles *(Caretta caretta*) in the Mediterranean Sea reflects water circulation patterns. *Mar. Biol.* **2006**, *149*, 1269–1279. [CrossRef]
49. Carreras, C.; Pascual, M.; Cardona, L.; Marco, A.; Bellido, J.J.; Castillo, J.J.; Tomás, J.; Raga, J.A.; Sanfélix, M.; Fernández, G.; et al. Living Together but Remaining Apart: Atlantic and Mediterranean Loggerhead Sea Turtles (*Caretta caretta*) in Shared Feeding Grounds. *J. Hered.* **2011**, *102*, 666–677. [CrossRef]
50. Broderick, A.C.; Coyne, M.S.; Fuller, W.J.; Glen, F.; Godley, B.J. Fidelity and Over-Wintering of Sea Turtles. *Proc. R. Soc. B Biol. Sci.* **2007**, *274*, 1533–1539. [CrossRef]
51. Wibbels, T. Critical approaches to sex determination in sea turtles. In *The Biology of Sea Turtles*; Lutz, P.L., Musick, J.A., Wyneken, J., Eds.; CRC Press: Boca Raton, FL, USA, 2003; Volume II, pp. 103–134.
52. Casale, P.; Freggi, D.; Basso, R.; Argano, R. Size at male maturity, sexing methods and adult sex ratio in loggerhead turtles (*Caretta caretta*) from Italian waters investigated through tail measurements. *Herpetol. J.* **2005**, *15*, 145–148.
53. Casale, P.; Freggi, D.; Maffucci, F.; Hochscheid, S. Adult sex ratios of loggerhead sea turtles (*Caretta caretta*) in two Mediterranean foraging grounds. *Sci. Mar.* **2014**, *78*, 303–309. [CrossRef]
54. Rees, A.F.; Margaritoulis, D.; Newman, R.; Riggall, T.E.; Tsaros, P.; Zbinden, J.A. Ecology of loggerhead marine turtles *Caretta caretta* in a neritic foraging habitat: Movements, sex ratios, and growth rates. *Mar. Biol.* **2013**, *160*, 519–529. [CrossRef]
55. Kaska, Y.; Ilgaz, C.; Ozdemir, A.; Başkale, E.; Türkozan, O.; Baran, I.; Stachowitsch, M. Sex ratio estimations of loggerhead sea turtle hatchlings by histological examination and nest temperatures at Fethiye beach, Turkey. *Naturwissen-Schaften* **2006**, *93*, 338–343. [CrossRef]

56. Godley, B.J.; Broderick, A.C.; Mrosovsky, N. Estimating hatchling sex ratios of loggerhead turtles in Cyprus from incubation durations. *Mar. Ecol. Prog. Ser.* **2001**, *210*, 195–201. [CrossRef]
57. Wang, J.; Fisler, S.; Swimmer, Y. Developing visual deterrents to reduce sea turtle bycatch in gill net fisheries. *Mar. Ecol. Prog. Ser.* **2010**, *408*, 241–250. [CrossRef]
58. Wang, J.; Barkam, J.; Fisler, S.; Godinez-Reyes, C.; Swimmer, Y. Developing ultraviolet illumination of gillnets as a method to reduce sea turtle bycatch. *Biol. Lett.* **2013**, *9*, 20130383. [CrossRef]
59. Ortiz, N.; Mangel, J.; Wang, J.; Alfaro-Shigueto, J.; Pingo, S.; Jiménez, A.; Suarez, T.; Swimmer, Y.; Carvalho, F.; Godley, B. Reducing green turtle bycatch in small-scale fisheries using illuminated gillnets: The cost of saving a sea turtle. *Mar. Ecol. Prog. Ser.* **2016**, *545*, 251–259. [CrossRef]