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Effect of predicted sea level rise scenarios on green turtle (*Chelonia mydas*) nesting

Bektaş Sönmez[a,*], Sezgin Karaman[b], Oguz Turkozan[b,*]

[a] *Sivas Cumhuriyet University, Suşehri Timur Karabal Vocational Training School, 58600 Suşehri, Sivas, Turkey*
[b] *Aydın Adnan Menderes University, Faculty of Arts and Science, Department of Biology, 09010 Aydın, Turkey*

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ABSTRACT

There is a growing interest among scientists about climate change and its adverse effects. One of the major adverse effects of climate change is the sea level rise (SLR), which will cause habitat loss for many species and threaten their survival. Sea turtles are an example of animal groups most likely to be threatened by SLR. It is, therefore, critical to predict the effect of SLR on sea turtle habitats to prepare better conservation and management plans that consider the climate change impact. With this aim, we projected the outcomes of SLR on the habitat and nest loss of one of the most important Mediterranean green sea turtle (*Chelonia mydas*) nesting beaches (Samandag, Turkey) using natural nests between 2008 and 2016 nesting seasons. Under the extreme scenario (1.2 m SLR) one-third of the coastal area and up to 18% of natural nests could be lost at a key green turtle nesting beach for this globally unique population.

1. Introduction

There is growing evidence that climate change is adversely affecting nest building animals directly (Mainwaring et al., 2017). Suboptimal temperatures, for example, negatively influence the sex of the offsprings of species with temperature dependent sex determination (TSD) like sea turtles (Hawkes et al., 2007; Laloë et al., 2014), meaning there are female biased hatchling sex ratios or increased embryonic mortality (Hawkes et al., 2007; Reneker and Kamel, 2016; Tanner et al., 2019). Furthermore, climate driven sea level rise (SLR) (Fuentes et al., 2010) could adversely affect habitats of threatened, endangered, and endemic species such as sea turtles in coastal areas (Fish et al., 2005; Hawkes et al., 2009; Varela et al., 2019). Current projections by the Intergovernmental Panel on Climate Change (IPCC) suggest that under realistic scenarios the global SLR will be 0.47 m to 0.63 m by 2100 (Collins et al., 2013). However, SLR may be higher than expected based on quasi-experimental models over the same period (De Conto and Pollard, 2016; Vousdoukas et al., 2018).

Nesting beaches are critical habitat for sea turtles because successful reproduction depends on access to sandy beaches with favorable conditions for embryonic development within buried nests (Ackerman, 1997). It is, therefore, important to understand how SLR will influence the sea turtle nesting beaches. In a study on green turtle (*Chelonia mydas*) populations of the Great Barrier Reef, Australia, flooding of nests as a direct result of SLR was the greatest threat to reproduction (Fuentes et al., 2010). Furthermore, an experimental study with flooding of green turtle nests showed that submergence in saltwater for 1 or 3 h reduced the viability of the eggs by less than 10% (Pike et al., 2015). Under different global SLR scenarios (ranging between 0.18 m and 1.3 m), the loss rate in nesting habitats of different sea turtle species was between 24% and 89% (Fish et al., 2005, 2008; Mazaris et al., 2009; Fuentes et al., 2010; Katselidis et al., 2014; Hiebert et al., 2017). Such a reduction in available nesting area could cause density related problems for successful embryonic development (Limpus et al., 2003; Fish et al., 2008; Fuentes et al., 2010). However, sea turtles may exhibit adaptive responses to ongoing climate change effects such as altering their nesting phenology (earlier nesting), nest site selection (nesting in cooler areas), or nest design (digging deeper nests) (Hays et al., 2002; Mazaris et al., 2009; Weishampel et al., 2010; Mainwaring et al., 2017). Therefore, predicting potential effects of SLR on sea turtle nesting habitats before they occur is important for understanding possible conservation interventions to reduce the negative effects of SLR. This is a key point for achieving effective conservation measures since ignoring potential climate change impacts in conservation plans will probably be unsuccessful (Rilov et al., 2020).

Research on effects of climate change, particularly SLR, on sea turtles

* Corresponding authors.
E-mail addresses: bsonmez@cumhuriyet.edu.tr (B. Sönmez), turkozan@adu.edu.tr (O. Turkozan).

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in the Mediterranean is limited to a few studies (Mazaris et al., 2009; Katselidis et al., 2014; Varela et al., 2019). The main nesting beaches of the Mediterranean green turtle regional management unit (Wallace et al., 2010) are constrained to the eastern Mediterranean (Casale et al., 2018) with the main nesting sites occurring in Turkey, Cyprus, and Syria (Casale et al., 2018). Samandag Beach, Turkey, is one of the most important green turtle nesting grounds in the Mediterranean (Türkozan and Kaska, 2010; Casale et al., 2018) with a mean of 241 nests annually (Yalçın Özdilek and Sönmez, 2011). Samandag Beach is regularly exposed to floods due to the deterioration of the beach slope, which put nests close to the tide line under risk for flooding and erosion. (Kasparek et al., 2001; Yalçın Özdilek, 2007; Sönmez and Yalçın-Özdilek, 2013). Previous studies suggested that relocation of nests at high risk of flooding was a worthwhile conservation activity (Yalçın Özdilek, 2007; Sönmez and Yalçın-Özdilek, 2013). We focused this study on Samandag Beach because the adverse effects of SLR on this beach will likely be reflected across the Mediterranean green turtle population's nesting range. Our aims in this study were (ı) to predict habitat loss; (ıı) to estimate nest loss based on natural nest locations; and (ııı) to create effective conservation measures that account for potential effects of climate change.

2. Material and methods

2.1. Study site and nesting data

Data were collected on Samandag Beach, Turkey (36''07′N, 35″55′E) during the 2008–2016 nesting seasons (between early May to late September). The beach is approximately 14 km in length, extending from the Çevlik Harbour in the north to Sabca Promontory in the south, and is divided into three sub-sections: (1) Çevlik (5.5 km); (2) Şeyh-Hızır, (4 km); and (3) Meydan sub-section, (4.5 km) (Yalçın Özdilek, 2007). The Çevlik sub-section extends between the Çevlik Harbour and the Şeyh-Hızır Tomb and is less used by green turtles for nesting than the other two sub-sections (Fig. 1). The Şeyh-Hızır sub-section extends between the Şeyh-Hızır Tomb and the mouth of the Asi River, and it has the densest nesting among the sub-sections (Fig. 1). The Meydan sub-section extends between the Asi River mouth and the Sabca Promontory and it has the second densest nesting among the sub-sections (Fig. 1). The beach was patrolled on foot every day by a team of 5 people. The precise location of the nests was recorded using a handheld GPS Garmin eTrex 10 (accuracy of ±3 m).

2.2. Creating orthophoto photographs and elevations data along beaches

The orthophotographs were created by a professional company consisting of experts about digital mapping. The methodology applied to obtain these orthophotographs are explained in detail below. To create aerial orthophoto photographs, we used a Vexcel Ultracam X camera with 4810 × 3140 resolutions flown in a Cessna 206 model airplane at an altitude of 1100 m. The airplane was flown along in transect across the northeast-southwest line inshore. We took 60 photographs along the coastal line, and used 70^0 and 80^0 angles to get accurate elevations due to the high difference in height and field conditions. White colour control points with triangular geometry of 20 × 60 cm were determined at the corners of the aerial blocks before the airplane flew and after the creation of the aerial blocks. Thus, the homogeneous distribution of ground control points was achieved with this prior planning. Static measurements in the determined ground control points were made in the ITRF 96 coordinate system (36° 3′ zone) utilizing a JAVAD GPS

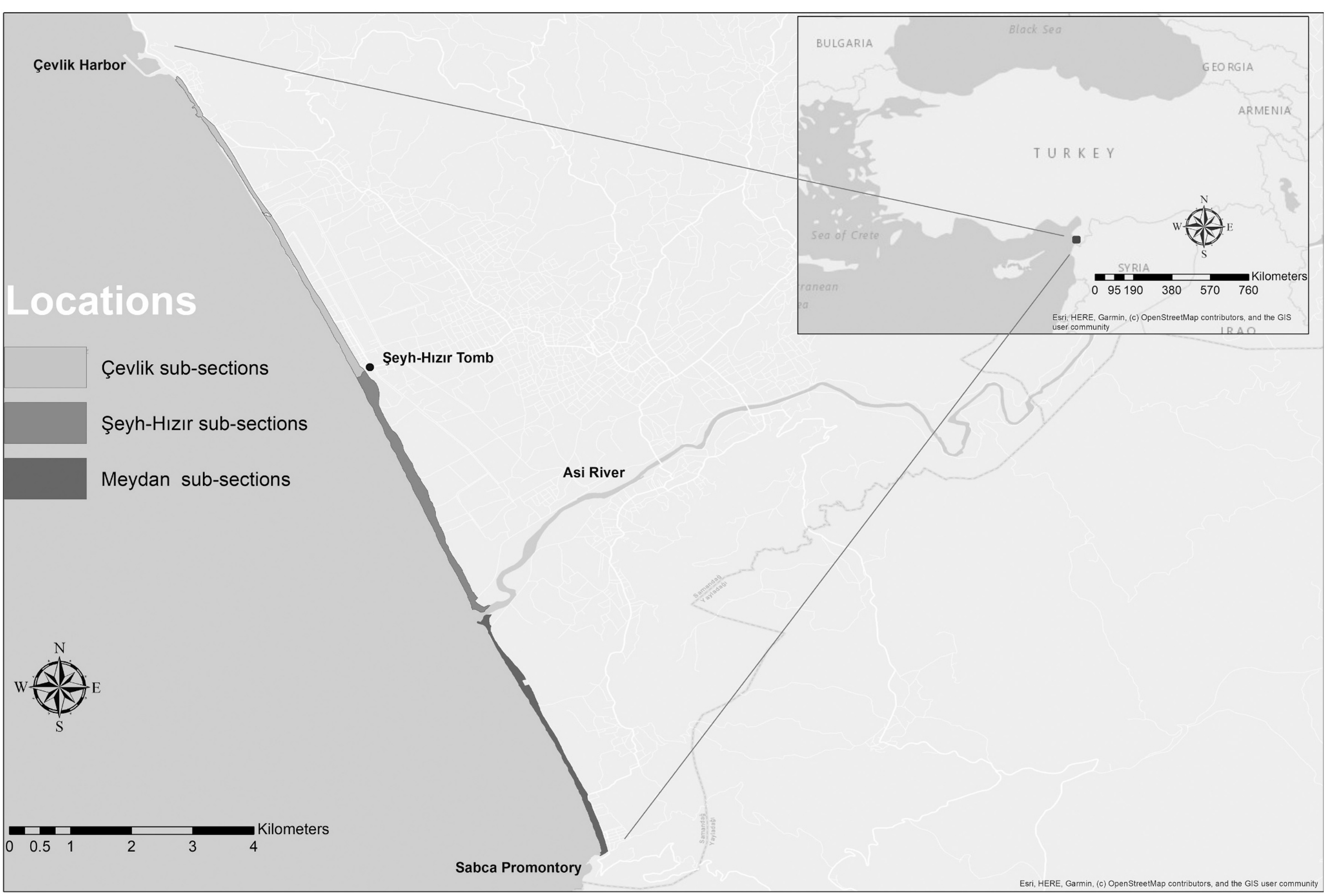

Fig. 1. General view of Samandağ nesting beach and distribution of sub-sections.

device (15–20 cm error). To reduce the error in the coordinates obtained at these control points Turkish National Permanent GNSS Network (TNPGN) was used. Using this network and the Leica Geo Office software, the coordinates of the ground control points were obtained with a smaller error (2–3 cm) and the ellipsoidal elevation data was calculated. To convert ellipsoidal elevation data to orthometric height data, elevation data in the database of the General Command of Mapping in Turkey were used. The photographs were overlapped by 60% and used Inpho Match-AT software to combine the photographs. While photographs were taken during the flight, the coordinates that taken from the air were georeferenced based on ground control points. The MICROSTATION software was used to create orthophoto maps, and to make a DEM modeling for each sub-sections. Through this modeling, orthometric elevation and geographic coordinate data were obtained at intervals of 10 to 15 m for each sub-sections in Samandağ beach. Orthometric elevation and geographic coordinate data with the NCZ extension have been transferred to the ESRI ArcGIS program (v10.3) using the CAD reader extension (CadNcz 2.1). The geographic coordinate data was transformed into the Turef TM 36 projected coordinate system using the ArcGIS program, and the elevation data was appended to this coordinate data. After this, we created a TIN (triangulated irregular network) layer by 3D Analysis Toolbox in ArcGIS. Finally, we developed a raster dataset including elevation values (Z) and coordinates (X and Y) and then calculated the inundated areas using the Spatial Analysis Tool of ArcGIS.

2.3. Determining core areas

Nest locations were converted from WGS 84 geographic coordinate system to TUREF TM36 projected coordinate system, the same datum we used for orthophotos and then plotted on the map. Orthophotos had all topographic data along and behind the beaches. We created new polygons based on orthophotos by excluding buildings, road, and rocky areas that were not part of the beach, and defined remaining areas as nesting habitat for all sub-sections. To determine core nesting areas on the beach we performed Kernel Density Estimation (KDE) interpolation with an output cell size 1 m length and 30 m bandwidth (search radius) (MacLeod, 2014). The density coefficient of the sampling point in KDE was calculated at each grid cell center using core functions within a given radius range (usually bandwidth). In the search radius range, sampling points closer to the grid cell center had a higher density additive value. Bandwidth selection directly affects the smoothness of density patterns. However, there was no clear rule for determining an appropriate bandwidth. When a very small bandwidth is selected, the result highlights separate points with insufficient smoothing (spikes). If the bandwidth was too large, a smoother density surface is obtained (Brimicombe, 2010). Therefore, we chose the 30 m bandwidth used in previous sea turtle studies in the Mediterranean for the compatible with the literature (Varela et al., 2019).

2.4. Inundation scenarios and statistic analysis

We used three SLR scenarios (0.48 m, 0.63 m, and 1.2 m) as in Varela et al. (2019) on natural nest locations to simulate nesting habitat loss on Samandag Beach. The first two scenarios were based on intermediate (RCP6) and high emission (RCP8.5) scenarios (Collins et al., 2013) by 2100, while the third was the more extreme scenario based on semi-empirical models (0.7–1.2 m SLR by 2100, Horton et al., 2014). We have projected nest loss rates in two ways. We first estimated the nest loss rates in the year that the orthophotograph was generated, and then a total of 9 years nests loss rates under each SLR scenario. In this way, we compared the results from one year against the total 9 years period. The test of normality of these data was performed using the Shapiro-Wilk test. We used the one-sample *t*-test for this comparison because there was one sample on each SLR scenarios. In the comparison of nest loss rate for each SLR scenario in the 2014 nesting season with entire years in one sample *t*-test, the mean nest loss rate of the entire years under each SLR scenario was taken as the test value. Also, we used the Kruskal-Wallis H test to compare elevation among sub-section beaches. All statistical tests were performed using IBM SPSS Statistics 23 software.

3. Results

We recorded 3479 green turtle nests during nine breeding seasons (between 2008 and 2016), with a mean of 387 nests annually. The total beach area was 1,140,690 m^2 and the mean beach elevation was 1.42 m. The total beach area and elevation for each sub-sections are presented in Table 1. The largest beach area was in Şeyh-Hızır with having 39.6% of the total beach area. The sub-sections of the beach differ in terms of mean elevation (Kruskal–Wallis: chi-squared = 2922.78, df = 2, P = 0.001) with the highest mean elevation belong to the Meydan sub-section. The images of simulations for the habitat losses under three SLR scenarios are presented for each sub-section in Fig. 2 (also see Supplement Fig. S1 for detail). In terms of habitat loss rate, the largest habitat loss among sub-sections would be on the Çevlik sub-section with a rate of 45% under the 1.2 m SLR scenario (see Fig. 3 for detail). Similarly, the largest overall nesting habitat loss would be 31.8% in the 1.2 m SLR scenario on the entire Samandag Beach (Fig. 3).

The orthophotograph was generated in 2014, and the number of nests for this year was 361. The distribution of nest density according to each sub-section in 2014 nesting season was mostly in Şeyh-Hızır (75.3%), followed by Meydan (21.3%) and Çevlik (3.4%) sub-sections, respectively. We projected a 2.8%, 4.4%, and 17.7% nest loss in the 2014 nesting season on the entire nesting beach under 0.48 m, 0.63 m, and 1.2 m SLR scenarios, respectively (Fig. 4). The 3479 natural nests between 2008 and 2016 nesting seasons were distributed in different proportions on each sub-section. The Şeyh-Hızır sub-section had the highest density with having 77.5% of the natural nests, followed by Meydan (16.3%) and Çevlik (6.2%) sub-sections. Across the entire nesting area, we projected 3.4%, 4.5%, and 18.1% nests loss under 0.48 m, 0.63 m, and 1.2 m SLR scenarios, respectively (Fig. 4). The highest nest loss was projected at Çevlik under all three SLR scenarios (7.4%, 9.3%, 25.1% for 0.48 m, 0.63 m, and 1.2 m, respectively) (Fig. 4). There were no significant differences in terms of nest loss rates under 0.48 m, 0.63 m, and 1.2 m SLR scenarios between the 2014 nesting season and the entire years (One sample *t*-test, $p > 0.05$).

The core nesting areas at Samandag Beach are generally concentrated on both sides of the Asi River (Fig. 2). The 25% nest density core areas of Şehy-Hızır and Çevlik sub-sections were not affected under the 0.48 m and 0.63 m SLR scenarios, while the Meydan sub-section had the highest percentage of nest loss for all nest density core areas on all SLR scenarios (Table 2).

4. Discussion

Under the 0.48 m, 0.63 m and 1.2 m SLR scenarios, 9.7%, 13.1%, and 31.8% of the total available nesting area on Samandag Beach would be lost, respectively. The densest nesting sub-section, Şeyh-Hızır, would be the least affected, while Çevlik would be the most affected. Almost half of the total nesting area (45%) on the Çevlik will be lost under the most extreme SLR scenario (1.2 m) due to lower mean beach elevation (mean 0.8 m) compared to the other sub-sections. Concordantly, previous studies reported flooding on the Çevlik sub-section during nesting seasons (Yalçın Özdilek, 2007; Sönmez et al., 2013; Sönmez and Yalçın-Özdilek, 2013). Furthermore, coastal erosion along the Samandag coastline was reported to cause 3 to 14 m of annual habitat loss on the beach (Kasparek et al., 2001). Thus, because the structure of the existing beach has apparently been under negative influence for the past 20 years, the effect of SLR on Samandag Beach as a result of climate change until 2100 could be devastating.

Based on different SLR scenarios (ranging between 0.18 m and 1.3 m), the loss rate in nesting habitats of different sea turtle species around

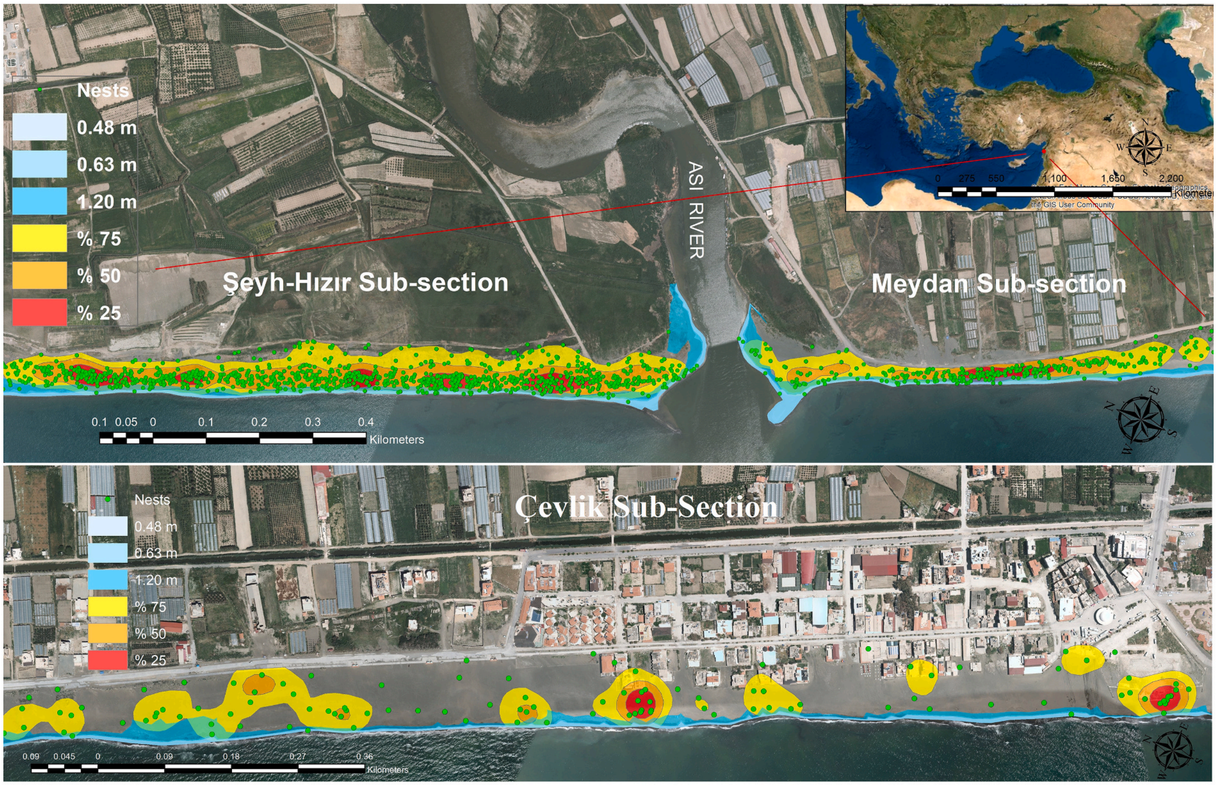

Fig. 2. Green turtle nest locations (green points) with kernel density estimation (KDE), and inundations area under each of three SLR scenarios according to sub-sections of Samandag Beach, Turkey (The red, orange and yellow colors indicates percentage of core areas, and blue and tones indicates inundation under each SLR scenarios).

the world was between 24% and 89% (Fish et al., 2005, 2008; Mazaris et al., 2009; Fuentes et al., 2010; Katselidis et al., 2014; Hiebert et al., 2017), similar to our results. If sea level rises >1 m by 2100, some nesting beaches may be completely inundated (Turner and Batianoff, 2007), while others may be partially inundated. However, such a reduction in available nesting areas could cause density related problems, such as nest infection due to increased bacterial activity among adjacent nests (Fish et al., 2008) and destruction of nests by conspecifics (Limpus et al., 2003), which would decrease hatchling production and thus affect population dynamics (Fuentes et al., 2010). The effect of SLR would not only cause the destruction of the beach areas, but also increased frequency and severity of storm events, increased flood frequency, accelerated coastal erosion, increased saltwater intrusion, increased water table height, and flooding of the nests (Gornitz, 1991; Fenster and Dolan, 1996; Fuentes et al., 2010). Because embryonic mortality is already high due to intense flooding and coastal erosion even in the current situation (Sönmez and Yalçın-Özdilek, 2013; Sönmez et al., 2013), any incrase in these effects further would have negative consequences for the overall reproductive success of the Samandag green turtle population.

The projected extreme SLR scenario (1.2 m) on Samandag beach could lead to nearly one-fifth of the natural nests (18.1%) becoming inundated. At another important Mediterranean green turtle beach, Alagadi Beach, Northern Cyprus, Varela et al. (2019) projected that 57% of the natural green turtle nests will be affected under 1.2 m SLR scenario. Furthermore, Ussa (2013) reported the loss of 22.7% of the natural green turtle nests at 0.18 m SLR and 24.7% extreme scenario (1.4 m) on the Archie Carr National Wildlife Refuge, Florida. The higher percentage of nest loss in Cyprus (Varela et al., 2019) than in Florida (Ussa, 2013) and in Turkey (present study) could result from a lower mean beach elevation or higher nest concentration on these beaches; beaches with higher elevation are more protected against inundation caused by SLR (Fuentes et al., 2010; Katselidis et al., 2014). Indeed, Alagadi Beach (Cyprus) has a lower mean elevation (0.76 m) (Varela et al., 2019) than Samandag Beach (Turkey) (1.2 m).

Our results show the importance of accounting of fine-scale variation in physical features of nesting beaches within and among seasons in beach-based conservation efforts. For example, the Meydan sub-section was projected to lose the highest percentage of core nesting areas (Table 2). Although the mean elevation of the Meydan sub-section is higher than the others, the 1 km stretch of beach with the densest nesting is narrower than the other sub-sections. This high nest density in a narrow area may cause more losses in core nesting areas on the Meydan sub-section. Furthermore, core areas at all three sub-sections not affected under SLR scenarios may provide target areas for nest relocation activities to save nests at high risk of being lost to inundation or erosion. Previous work at Samandag recommended nest relocation as a conservation practice for nests less than 20 m from the tide line (Sönmez and Yalçın-Özdilek, 2013).

As an adaptive response, sea turtles may shift their nest site selection away from the high tide line in search of more suitable nesting habitat (Fish et al., 2005; Limpus et al., 2006; Fuentes et al., 2010). However, this is impossible for the Meydan and Çevlik sub-sections, as urban development is higher behind the beach, leaving no room for beach rollback to occur over time. In this case, turtles might choose nesting locations on the Şeyh-Hızır sub-section or other nearby nesting sites, where urban development is currently low. However, such a shift would increase nest density on the Şeyh-Hızır sub-section. Furthermore, the increasing density combined with the significant projected reductions of nesting areas in Cevlik and Meydan under the most extreme SLR scenario (Table 2) would cause density related problems, as described above. For example, on Raine Island and the northern Great Barrier Reef, Australia, premature use of somatic energy stores and resorption of ovarian follicles by nesting females unable to find available nesting habitat is apparently resulting in reduced reproductive output (Hamann et al., 2002; Limpus et al., 2003).

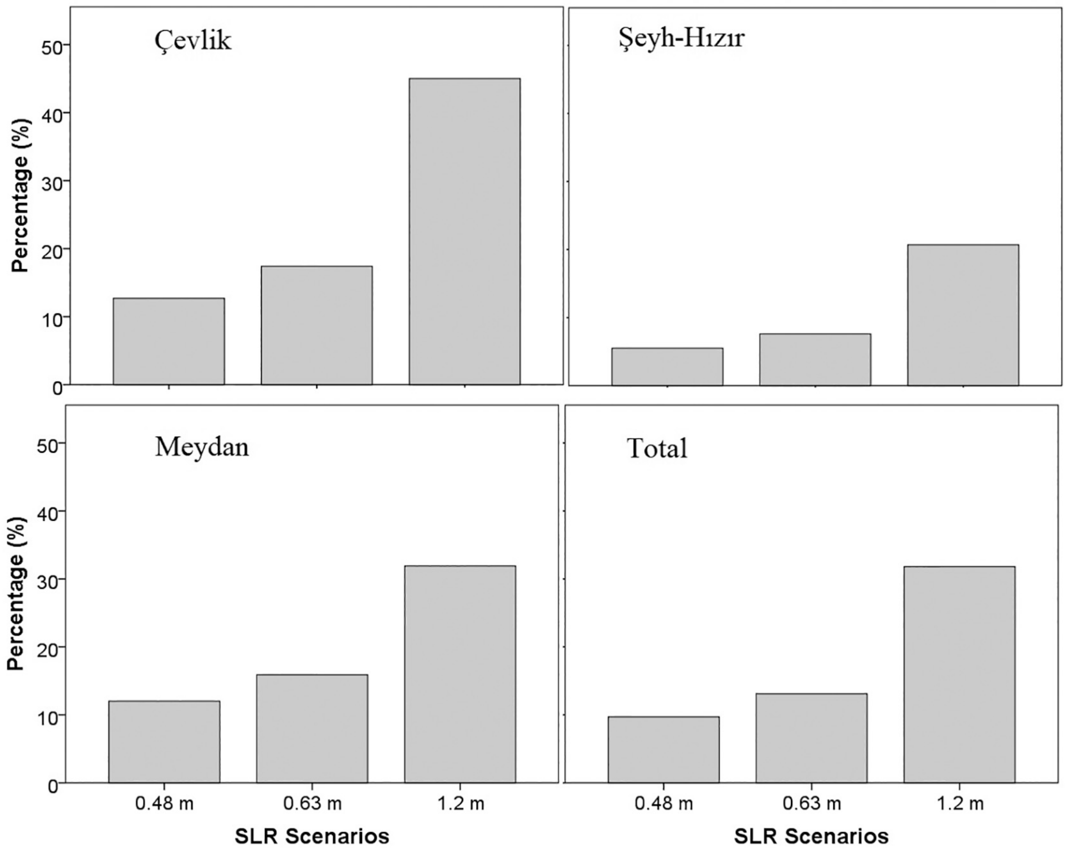

Fig. 3. The percentages of green turtle nesting habitat loss across different sub-sections of Samandag Beach, Turkey, under three SLR scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Descriptive statistics of total beach areas and beach elevations of each sub-sections at Samandag Beach, Turkey.

Sub-Sections	BeachArea (m^2)	BeachArea (%)	N	Elevation (m) Mean ± Sd	Range
Çevlik	375,627	32.9	6173	0.8 ± 1.06	0–4.8
Şeyh-Hızır	452,152	39.6	4547	1.7 ± 1.08	0–5
Meydan	312,911	27.4	3335	2.2 ± 1.32	0–5.5
Total	1,140,690	100	14,055	1.42 ± 1.27	0–5.5

4.1. Implications for conservation and management

Samandag Beach is one of the most important nesting beaches for green turtles in the Mediterranean with having over 1000 nests in the last 5 years (B. Sönmez, unpublished data). Therefore, conservation measures need to be implemented to protect the beach for the survival of green turtles. The most urgent actions are to prevent further habitat loss, especially on Çevlik and Meydan sub-sections, and to restore beach habitat. This could be handled by protecting and restoring the dune ecosystem behind the beach (Mazaris et al., 2009). Beach nourishment and restoration studies have been widely practiced in northern Europe (Healy and Doody, 1995) and on Mediterranean coastlines (Gomez-Pina, 1999; Gomez-Pina et al., 2002). However, the sustainability of this approach in natural dune systems is unknown (De Lillis et al., 2004). Dune construction can be an alternative measure to reconstruct natural systems, but, it should be carefully implemented, taking into account all possible consequences for sea turtles and other fauna and flora in these habitats (Mazaris et al., 2009). Urgent protection measures should be taken to reduce the clay, stone, and dead organic material accumulation in all three sub-sections at the Samandag Beach, and activities that accelerate beach erosion should be immediately prohibited. In addition, setback arrangements that prohibit construction within some proximity from the shoreline to reduce habitat loss and maintain ecological conditions on the beach can significantly reduce habitat loss by providing a buffer zone (Fish et al., 2008). Setback arrangements and beach restoration would undoubtedly provide effective protection in the sub-section of Çevlik and Meydan, where urban development is already intense. The most realistic and efficient solution(s) will require detailed information on practical issues related to ethical and ecological factors, as well as cost-benefit analysis (Fuentes et al., 2010). Finally, areas under apparently low risk of inundation under extreme SLR scenarios are reasonable targets for relocation of nests from high-risk areas to promote continued hatchling production.

5. Conclusions

In conclusion, the habitat loss and, as a result, nest destruction due to inundation or density dependent factors are inevitable during SLR because of climate change. The overall Samandag beach may lose one-third of the coastal habitat under the worst scenario (1.2 m). The core ideas identified by KDE may be used as a potential nest relocation points in case of inundation in the future. However, sea turtles may give adaptive responses to decrease the effect of SLR and increase the survival chance.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jembe.2021.151572.

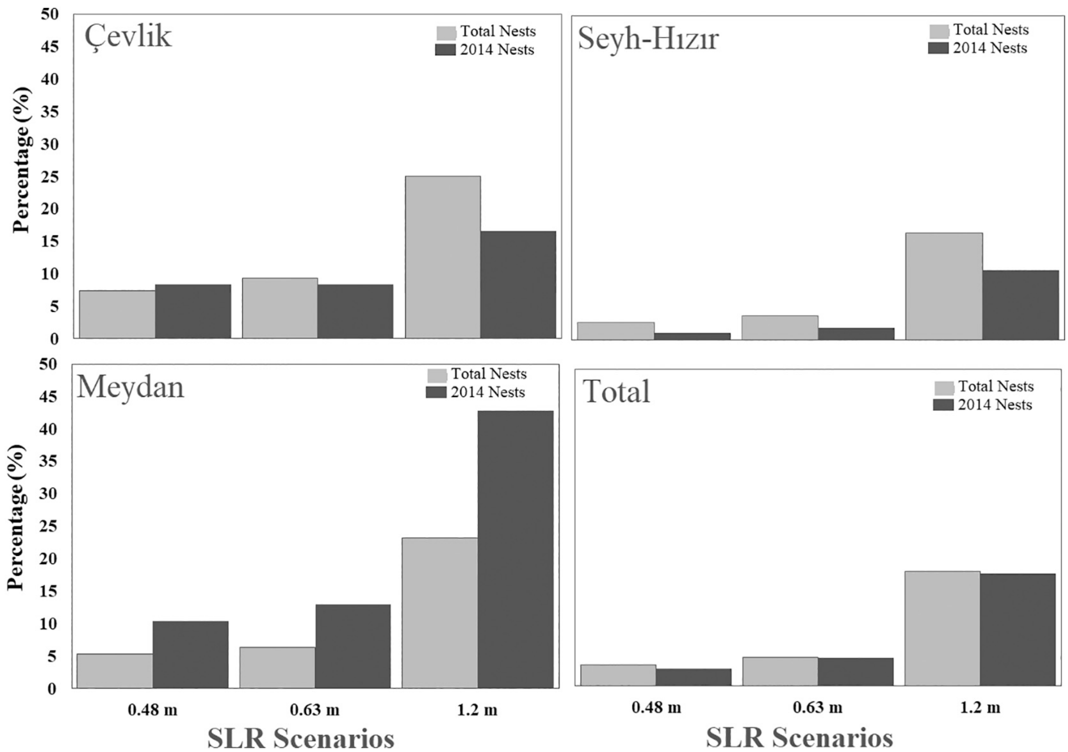

Fig. 4. The percentages of natural green turtle nests affected for the nine (2008–2016) years and one (2014) year at each sub-section of Samandag Beach, Turkey, under three different SLR scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Core green turtle (*Chelonia mydas*) nesting areas at Samandag Beach, Turkey, calculated using Kernel Density Estimator at sub-sections and percentage of affected areas under different SLR scenarios.

Nest density	Total area (m^2)	Sub-section	0.48 m (%)	0.63 m (%)	1.2 m (%)
25%	18,666	Çevlik	0.0	0.0	0.0
		Şeyh-Hızır	0.0	0.0	2.1
		Meydan	5.6	8.5	25.5
50%	55,655	Çevlik	1.9	3.0	11.2
		Şeyh-Hızır	2.9	4.5	16.3
		Meydan	5.5	7.8	19
75%	139,343	Çevlik	2.4	3.2	19.8
		Şeyh-Hızır	5.1	6.7	20.2
		Meydan	6.8	9.6	26.6

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Author statement

Corresponding author (BS) collected field data. All authors worked together to create orthophoto photographs, elevation data and determine core areas. In addition, in the writing of MS, all three authors acted together and wrote simultaneously.

Declaration of Competing Interest

We declare no conflicts of interest.

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