

**Spatial Dynamics and Drivers of Nearshore Aggregations in Olive
ridley Sea Turtles along the Gahirmatha Coast**

by

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Under the supervision of

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July 2024

DECLARATION

I, **Arnab Dey Sarkar**, hereby declare that the work conducted under the thesis entitled “**Spatial Dynamics and Drivers of Nearshore Aggregations in Olive ridley Sea Turtles along the Gahirmatha Coast**”, is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Master’s in Wildlife Science** at the **Academy of Scientific and Innovative Research**. This research work has been carried out under the guidance and supervision of **Dr. Nehru Prabakaran, Scientist-D**, and co-supervision of **Dr. R. Suresh Kumar, Scientist-F, Dr. Bivash Pandav, Scientist-G** of Wildlife Institute of India, Dehradun. The work has not formed the basis for the award of any other degree, diploma, or any other qualification. I also declare that the thesis embodies my own work, analysis, observation, understanding and the particulars given in it are true to the best of my knowledge.

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Mr. Arnab Dey Sarkar has put one semester of research work embodied in this thesis under my guidance and supervision. The work presented in this thesis has not been submitted to any other University or Institute for the award of any degree, diploma or distinction.



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Summary

Olive ridley sea turtles (*Lepidochelys olivacea*) exhibit a well-documented phenomenon known as nearshore aggregation during their breeding season. These aggregations, comprising large numbers of turtles in shallow coastal waters, are a common feature observed along most of the mass nesting beaches. The ecological benefits of such aggregations are multifaceted, potentially including enhanced predator avoidance and increased opportunities for mate encounter. The importance of studying these nearshore aggregations stems from their vulnerability during this period. Olive ridley turtles within these aggregations are susceptible to various threats, including bycatch mortality from fishing gear. Understanding the spatial and temporal dynamics of these aggregations is crucial for developing effective conservation strategies.

The Gahirmatha nesting site presents a unique case due to the influence of the Brahmani-Baitarani River system. The substantial freshwater inflow and sediment discharge from this river system have resulted in a vast area of shallow seabed compared to other nesting grounds. This distinct ecological setting necessitates a dedicated investigation into the dynamics and influencing factors of nearshore aggregations specific to Gahirmatha. The study examined the distribution and density of olive ridley sea turtles near Gahirmatha, India, a critical nesting site, with a particular focus on how environmental factors influence the location of these nearshore aggregations.

Surveys were conducted throughout the breeding season, recording turtle sightings and environmental data. The findings reveal that olive ridley turtles are not distributed randomly in the nearshore waters. Instead, they form concentrated aggregations in shallow depths (less than

5 km offshore and 5-15 meters deep) before nesting. The location and density of these aggregations were not static but shifted throughout the breeding season.

During the pre-nesting season, turtles were more dispersed across a wider area. As the season progressed and nesting approached, the aggregation grew denser and shifted closer to the nesting beach. The study also identified distance from the coastline and the nesting beach as the key factors influencing the distribution of these nearshore aggregations. Additionally, the unique shallow seabed near Gahirmatha, created by the discharge from the Brahmani-Baitarani River, might influence the preferred depth range of turtles compared to other nesting sites.

Understanding these dynamic aggregation patterns is crucial for effective conservation efforts. Protecting these areas is essential for the well-being of this globally significant olive ridley population. However, it's important to acknowledge that the exact locations of these aggregations can vary between years. This year's lower nesting numbers suggest fewer turtles arrived in the nearshore waters, potentially impacting the size and distribution of the observed aggregations.

This study emphasizes the need for long-term studies to gain a more comprehensive understanding of these variations and the factors influencing them. The study suggests a targeted approach of focusing on areas with high turtle usage. By implementing stricter patrolling measures within these zones, the forest department can significantly reduce threats like bycatch mortality from fishing activities. This targeted approach would be more effective in safeguarding the turtles compared to focusing on reducing illegal fishing in the entire sanctuary, considering the limited resources available.

1. Introduction:

1.1 Ecological Insights into Animal Aggregation

Animal aggregation is a widespread phenomenon observed throughout the natural world. Traditionally, aggregation has been perceived as an evolutionarily advantageous state, offering benefits such as protection, mate selection, and centralized information, while being balanced by the costs associated with limited resources (Parrish & Edelstein-Keshet, 1999). Aggregation is prevalent among animals of all sizes, from bacteria to whales (Allee, 1931; Schellinck & White, 2011). Often, an aggregation of animals exhibits unique properties that are not merely the sum of individual behaviours. In social animals, this collective behaviour enables functions that individual animals cannot achieve alone, such as nest building or thermoregulation in hives, as seen in bees and termites (Hölldobler & Wilson, 1990).

Many factors can explain the formation of animal aggregations. It is commonly assumed that aggregation occurs when joining a group increases either the survivorship or the reproductive fitness of a new member, or both (Parrish & Edelstein-Keshet, 1999, Pruitt & Riechert, 2011). Protection from predators is a significant selective advantage of group membership, offering benefits such as dilution of predation risk and enhanced group vigilance (Lack, 1954; Hamilton, 1971). Additionally, forming a group can help reduce resource competition in certain species, as demonstrated by Zahavi (1971) with the flocking behaviour of birds. Aggregations can also enhance mate selection, leading to improved reproductive fitness, as observed in various fish species during the spawning season (de Mitcheson & Erisman, 2011). From an energetic standpoint, the relative positions of individuals within a group can reduce overall energy expenditure during long migrations, a phenomenon commonly seen in fish and bird species (Lissaman & Shollenberger, 1970; Weihs, 1973).

1.2 Sea Turtle Aggregation: Foraging and Nesting Grounds

The concept of aggregation is particularly relevant when examining sea turtles' reproductive behaviour. Turtle aggregations in their foraging and nesting areas are common across the world's oceans (Bass et al., 2006; Arendt et al., 2012). For instance, green sea turtles (*Chelonia mydas*) form aggregations at distinct foraging areas (Amarocho et al., 2012; Thomson et al., 2015; Bass et al., 2006). These aggregations have been documented along the Colombian coast in the eastern Pacific (Amarocho et al., 2012), the Brazilian coast (Hays et al., 2002), the Bahamas (Lahanas et al., 1998), and the western Australian coast (Thomson et al., 2015). The prevalence of foraging aggregations among green sea turtles is attributed to their herbivorous diet, primarily consisting of seagrass and microalgae (Esteban et al., 2020). These turtles exhibit high site fidelity, consistently returning to their foraging sites after the breeding season to form aggregations (Shimada et al., 2020).

Other turtle species, such as Loggerhead (*Caretta caretta*), Olive ridley (*Lepidochelys olivacea*), and Kemp's Ridley turtles (*Lepidochelys kempii*), are known for aggregating in nearshore waters before the nesting season (Henwood, 1987; Kalb, 1999; Pandav and Choudhury, 2000; Ram, 2000; Kumar, 2015). Loggerhead turtles, for instance, are observed to aggregate along the Florida coast and in the Mediterranean (Encalada et al., 1998; Shamblin et al., 2011; Arendt et al., 2012). Olive ridley and Kemp's Ridley turtles are particularly noted for their distinctive reproductive behaviour, specifically their synchronized mass nesting events known as arribada (Hughes and Richard, 1974; Carr, 1984). These events occur on beaches in Mexico, Central and South America, as well as in India (Plotkin et al., 1997). Before arribada events, Olive ridley turtles migrate from their foraging grounds to the shallower offshore waters adjacent to mass nesting beaches. Upon arriving in these offshore waters, they form extensive

aggregations, referred to as nearshore aggregations or reproductive patches, consisting of both mating pairs and individual turtles (Pandav, 2000; Ram, 2000). The eastern coast of India, with two active mass nesting sites (Gahirmatha and Rushikulya) and one historic mass nesting site (Devi River Mouth), is of global significance, as it acts as the breeding ground for a significant proportion of the global olive ridley population.

1.3 Olive ridley Sea Turtles in India: Nesting Sites, Distribution, and Importance

Olive ridley sea turtles (*Lepidochelys olivacea*) is the smallest and most abundant species of all sea turtles, inhabiting the warm tropical waters of the Indian and Pacific oceans. The species is known for its migratory behavior, moving between foraging grounds and nesting areas with the onset of the nesting season (Pritchard, 1997). In India, olive ridley sea turtles nest in varying densities along the entire east coast, with the most significant nesting beaches located in the state of Odisha. These include three beaches: Gahirmatha, Devi river mouth, and Rushikulya, where mass nesting, or arribada, occurs (Shanker et al., 2004a).

The study of olive ridley sea turtles in the Indian context began in 1974 when H.R. Bustard discovered the mass nesting along the Gahirmatha coast. At that time, the mass nesting beach was reported to be 15 km in length (Bustard, 1976). However, this length has since significantly decreased due to beach erosion and cyclones (Pandav and Choudhury, 2000; Prusty et al., 2000). Subsequently, two other mass nesting sites were discovered along the Odisha coast. The Devi River mouth, located 120 km south of Gahirmatha, was identified in 1981 (Kar, 1982), although no arribada has been reported there since the turn of the century. The Rushikulya mass nesting site, 200 km south of Gahirmatha, was discovered in 1994 (Pandav et al., 1994) and continues to support a large number of nesting turtles, with approximately 170,000 turtles

recorded in 2015 (Chandarana et al., 2017). The olive ridley turtles found along the eastern coast of India, are reported to be phylogenetically unique and assumed to be the ancestor of the other distinct populations found globally (Bowen et al., 1997; Shanker et al., 2004b). Studies also suggest that olive ridleys in this area are larger in body size (curved carapace length) (Tripathy, 2008; Kumar et al. 2014).

1.4 Nearshore Aggregations: A Global Phenomenon with Local Variations

Apart from the nesting beaches, the nearshore waters surrounding the mass nesting sites are equally critical, as large numbers of Olive ridley turtles aggregate in these regions prior to mass nesting events. Olive ridley turtles begin arriving at the Odisha coast around early November from their foraging grounds and remain in the offshore waters for over six months, until May (Pandav & Choudhury, 2000; Kumar, 2015). Following their arrival, these turtles form large aggregations, commonly referred to as nearshore aggregations or reproductive patches, which include both mating pairs and individual turtles (Pandav, 2000; Ram, 2000). Upon the completion of nesting, the turtles migrate back to their foraging areas. Studies based on flipper tag recoveries (Dash and Kar, 1990; Pandav and Choudhury, 1998, 2006; Pandav, 2000) and satellite tracking (Shanker et al., 2003; Kumar, 2015) have identified the eastern coast of Sri Lanka as a significant foraging area for these turtles.

Historically, a significant number of turtle mortalities have been attributed to incidental capture in commercial trawl fisheries and gill netting along the Odisha coastline (Silas et al., 1983; Rajagopalan et al., 1996; Pandav et al., 1997; Shanker and Mohanty, 1999; Sridhar et al., 2005). Despite a ban on mechanized fishing up to a distance of 5 km from the Odisha coastline and the mandatory use of Turtle Excluder Devices (TEDs), these regulations have not been

effectively enforced (Gopi et al., 2006; Shanker, 2003; Tripathy 2010; Behera et al., 2016). The increased pressure from mechanized fishing poses serious threats to the turtle population and presents significant challenges to their survival.

Reports of nearshore aggregations of sea turtles are not new. Richard and Hughes (1972) first documented these aggregations off the coast of Nancite, a mass nesting site in Costa Rica. Following this initial observation, Heather Kalb (1992) conducted a study focusing on these aggregations to understand their potential implications for arribada behaviour. They define the reproductive patch as a large aggregation of turtles off the arribada beach. It is widely assumed that turtle aggregation taking place in specific areas is governed by the presence of an external environmental cue, which is the presence of the mass nesting beach (Plotkin et al. 1997). Such aggregation in nearshore waters directly benefits the adults in the form of mate-finding and also provides opportunities for multiple mating (Bernardo and Plotkin, 2007). For female turtles having multiple partners is beneficial as multiple paternity increases the fitness of a clutch and eventually results in better survivorship (González-Cortés et al. 2021). Another benefit of such aggregation, which is extended to both adults and hatchlings is through predator satiation. The large number of turtles present in a relatively small area can increase the survivorship of an individual, even though the group as a whole might be more susceptible to predation (Eckrich and Owens, 1995; Bernardo and Plotkin, 2007).

Depth is a crucial factor that drives the turtle aggregations, which are frequently found within 5 km of the coast where the depth ranges from 15 to 30 m (Pandav & Choudhury, 2000; Tripathy, 2013; Kumar, 2015; Rao et al., 2023). Despite the commonality of nearshore aggregations across various mass nesting beaches, there are notable site-specific differences.

For instance, in the Pacific Ocean, turtles are present in offshore waters year-round, although the density and spatial extent of these aggregations fluctuate (Bezy, 2019). In contrast, along the Odisha coastline, aggregations form in early December and dissipate by May, corresponding with the turtles departing to their foraging areas (Pandav & Choudhury, 2000; Kumar, 2015; Rao et al., 2023).

Systematic studies focusing on nearshore aggregation in India are limited. The first documentation of nearshore aggregation was provided by Pandav & Choudhury (2000), from the Gahirmatha coastline. This study found the turtle aggregation to occupy a 52 sq. km area. Following this, a study by Ram (2000), looked into the spatial distribution of only mating pairs in Gahirmatha, and reported that the aggregation to occupy a 32 sq. km area. These studies suggested that turtles usually aggregate closer to the coast. They also assumed that water current can influence the spatial distribution of the turtle aggregation. Similar studies from the Rushikulya reinforced that turtles aggregate closer to the coast (within 5 km) and also provide strong evidence that the aggregations are dynamic and shift towards the mass nesting beach as the breeding season progresses. Specifically, research indicates that these aggregations move closer to the coast over time, and the area of core use by turtles decreases (Tripathy, 2013; Kumar, 2015; Rao et al., 2023). Additionally, inter-rookery movements of female turtles among the three mass nesting sites in Odisha have been documented (Pandav & Choudhury, 2000; Tripathy & Pandav, 2008). Although it was assumed that female turtles move from one aggregation to another, this behaviour has only recently been confirmed through satellite telemetry studies initiated along the Odisha coastline (Kumar, 2015; Behera et al. 2018). These studies provide definitive evidence of inter-rookery movements, documenting turtle movements between Gahirmatha and Devi, as well as between Devi and Rushikulya.

1.5 A Case Study of Gahirmatha: Can a Large River System Impact Aggregation

Dynamics Differently?

It is well known that arribada usually takes place on beaches that are close to a river mouth (Shanker, 2021). Although there is no solid evidence to suggest any specific reason for this, multiple hypotheses have been proposed. Mass nesting results in an increase in soil microbes as a result of decomposing eggs as well as dead hatchlings. Nesting at a similar site in huge numbers increases the chance of potential infection. There is evidence that hatching success is affected by an increase in microbial load (Bezy et al. 2015), in mass nesting beaches in Costa Rica. Studies suggest that the reduced microbial load could be an important factor that determines the location of mass nesting beaches. As river mouths are very dynamic, natural event causes beaches near a river mouth to be dynamic as well, through either erosion or accretion or both, resulting in a reduction in microbial load which can increase the hatching success (Bezy et al. 2015; Shanker, 2021). Another alternate hypothesis proposes that river mouths may help in the dispersal of hatchlings, as it might be easier for a hatchling to transport away from the nesting beach, which in turn will increase their fitness (Putman et al, 2010).

Most of our understanding of the ecology of olive ridleys and associated conservation efforts is derived from a disproportionately large number of studies focusing on nesting beaches, while relatively few studies address offshore waters (Rao et al., 2023). Only a handful of studies have examined the dynamic nature and drivers of nearshore aggregations (Richard and Hughes, 1972; Kalb et al., 1992; Ram, 2000; Tripathy, 2013; Kumar, 2015; Behera et al., 2019; Rao et al., 2023). Understanding turtle aggregations before mass nesting is paramount, as these turtles are highly vulnerable to exploitation during this period (Plotkin et al., 1996). Arribada typically

occurs on beaches close to river mouths (Shanker, 2021), highlighting the critical role of these areas for turtle aggregations. Studies on nearshore aggregations have shown that turtles are predominantly found closer to the coastline, with depth being a significant factor determining their distribution. Furthermore, these aggregations are highly dynamic, generally moving closer to the mass nesting beach as the breeding season progresses (Tripathy, 2013; Kumar, 2015; Bezy, 2019; Rao et al., 2023). Keeping in mind most of the mentioned studies were conducted in Rushikulya (an important mass nesting site on the coast of Odisha, 200 km south of Gahirmatha), the findings might not depict the situation in Gahirmatha accurately.

In the case of Gahirmatha, the nesting beach differs significantly from that of Rushikulya. The estuary of the Brahmani-Baitarani River is much larger compared to the Rushikulya River, depositing substantially greater amounts of sediment into the ocean and resulting in a significantly larger shallow seabed (Mishra et al., 2019). Additionally, the freshwater inflow from the Brahmani-Baitarani River system is considerably greater than that of the Rushikulya River, leading to relatively lower salinity levels across the study area. Studies so far provide baseline information about turtle aggregations, but there is a need to follow up on such works in other areas with differing environmental conditions. Therefore, this study aims to build up on the already available information from other sites and bridge the existing knowledge gap about the dynamic nature and the driving factors of turtle aggregations from Gahirmatha, which is significantly different in terms of environmental as well as oceanographical conditions compared to Rushikulya.

1.6 Study Objectives

The study focused on the following two objectives:

1. To estimate the spatial extent and the dynamic nature of the olive ridley offshore aggregation (reproductive patch) along the Gahirmatha coast.

Questions:

- What is the spatial extent of nearshore aggregation of olive ridley sea turtles along the Gahirmatha coast?
- How does the dynamic nature of the nearshore aggregation of olive ridley sea turtles evolve over the breeding season, in terms of distribution and density?

2. To understand the factors influencing the offshore aggregation of olive ridley sea turtles along the Gahirmatha coast.

Question:

- What are the key ecological and environmental factors influencing the offshore aggregation of olive ridley sea turtles along the Gahirmatha coast, and how do these factors contribute to the observed patterns and dynamics of the aggregation.

2. Study Area:

Odisha, located on the eastern coast of India, features a coastline that extends approximately 480 km, stretching between the states of Andhra Pradesh to the south and West Bengal to the north. In 1974, H. Robert Bustard identified Gahirmatha as a significant rookery for olive ridleys during a crocodile survey for the Food and Agriculture Organization (FAO). Bustard noted that Gahirmatha might be the largest rookery for any sea turtle species globally and a crucial habitat for the endangered olive ridley turtles (Bustard, 1976). Consequently, based on his recommendations, the rookery was incorporated into the Bhitarkanika Sanctuary in April 1975.

However, the sanctuary did not protect the turtles in the offshore waters, leading to a rising mortality rate of breeding adults over the subsequent two decades due to indiscriminate fishing practices, which significantly increased turtle mortality (James et al., 1989). To address this issue, in September 1997, the waters surrounding Bhitarkanika were designated as the “Gahirmatha Marine Wildlife Sanctuary”, aiming to protect the olive ridley sea turtles in both their nesting habitats and nearshore waters.

The Gahirmatha Marine Wildlife Sanctuary is situated in the northeastern part of Odisha (80°45' E and 20°17' N). The sanctuary is bounded by the Bay of Bengal to the east and the coastline to the west. The Gahirmatha coastline extends approximately 35 km from Dhamra to the Barueni river mouth. This beach forms the coastal boundary of the 141-square-kilometer Bhitarkanika Wildlife Sanctuary in the Cuttack district. The Wheeler Islands and the Paradeep Port mark the northern and southern boundaries, respectively.

The core area of the park spans approximately 725 square km, while the buffer area covers about 709 square km. The core area includes an 11-kilometer strip extending into the sea from the Ekakula coastline in the northeast to the Barunei mouth in the south, and a 10-kilometer strip from the Barunei mouth to the Mahanadi mouth. These areas are subject to total restrictions throughout the year.

Following the fragmentation of the beach in 1989 due to a cyclonic storm, the mass nesting beach was reduced to a 3-kilometer sand spit. This spit has further fragmented since 1997 into two sand spits, each approximately 1.5 km in length. In recent times, mass nesting has been confined to a 2-kilometer stretch of beach on Abdul Kalam Island. However, this island is experiencing severe erosion, resulting in a rapid decline in suitable nesting areas. A decade ago, the mainland beach extended only till Ekakula, but due to sediment deposition, the beach has now extended almost 5 km, nearly connecting to Abdul Kalam Island, with only a 500-meter separation remaining. This newly formed beach, which is 100-300 m wide, lacks vegetation. Given the severe erosion impacting the availability of nesting areas on Abdul Kalam Island, this newly extended coastline has the potential to become the next mass nesting site for olive ridley sea turtles.

Fig 1. Map of the Odisha coastline showing all three mass nesting beaches

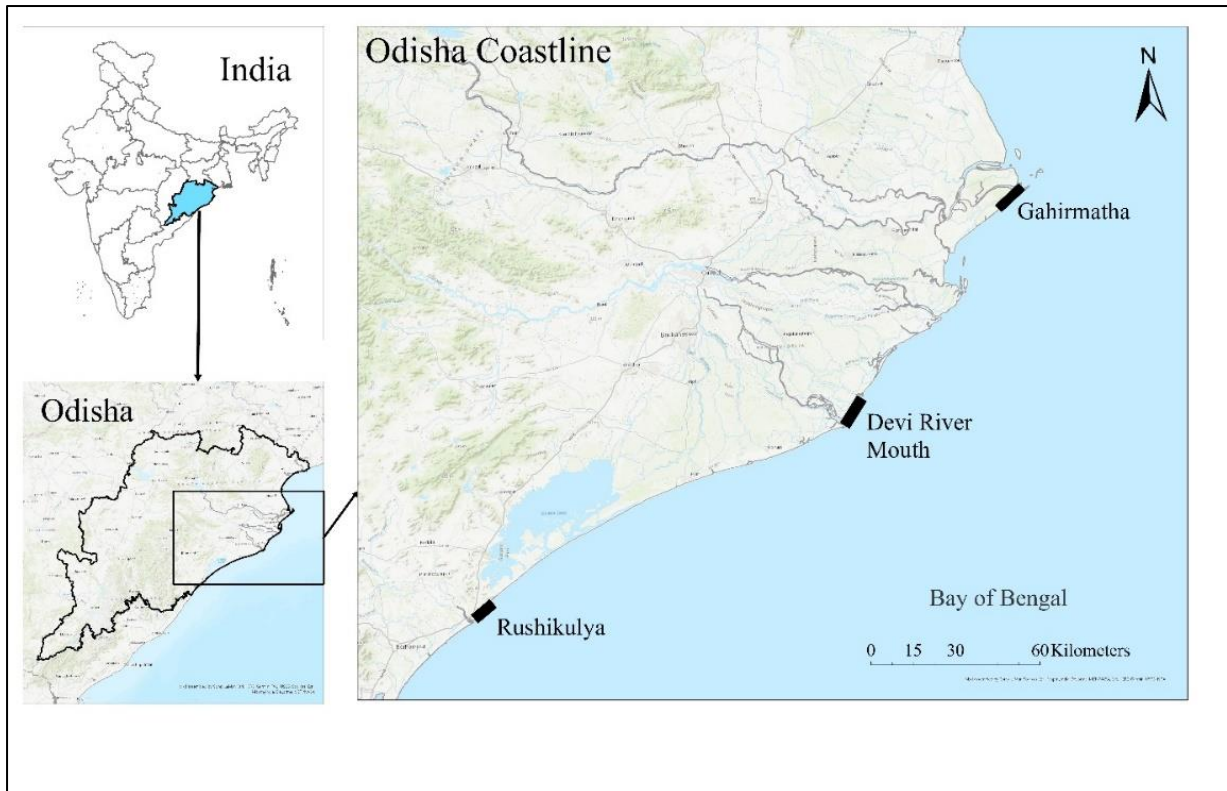
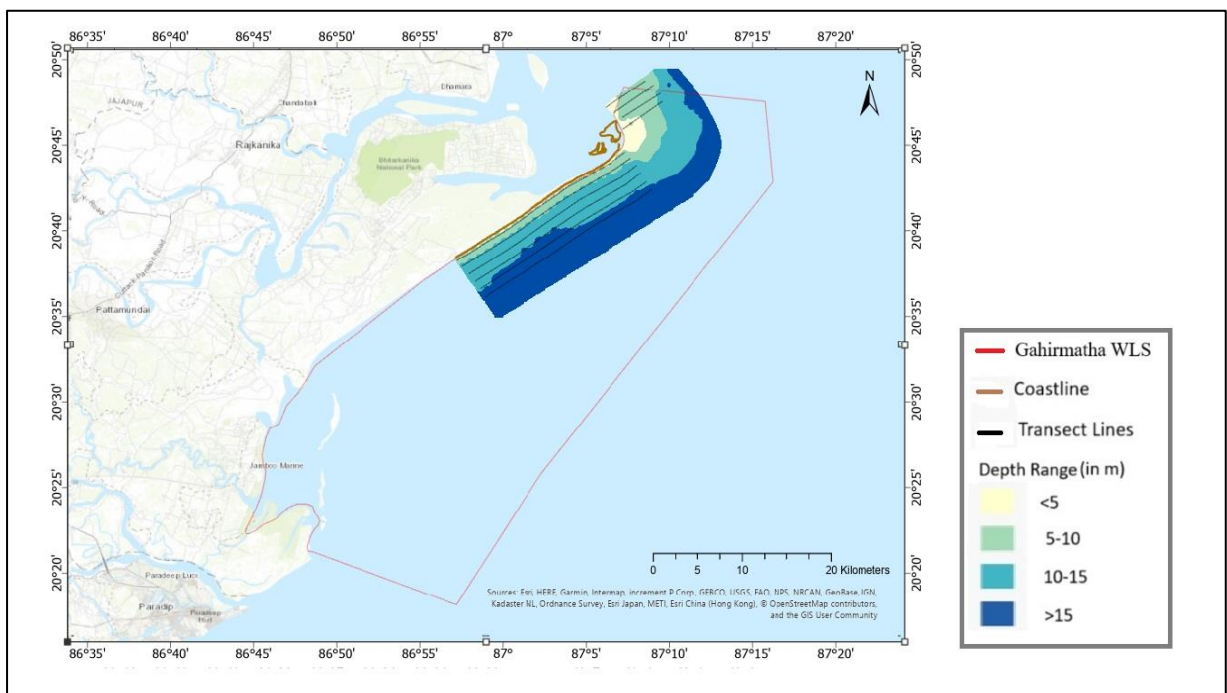


Fig 2. Map of the Gahirmatha Marine Wildlife Sanctuary with bathymetric profile till 8 km from coast



3. Methodology:

3.1 Study Design

All Marine turtles ascend to the water's surface for basking and breathing. Boat-based line transect methodology was employed to enumerate individual turtles surfacing for respiration or basking and mating pairs observed on the water surface.. The surveys were conducted between January 2024 and March 2024. A total of 10 transects, comprising 6 parallel and 4 in perpendicular orientations relative to the coast, were surveyed during the study period (Fig 2). Each of the 6 parallel transects extended over a distance of 21 km, commencing from the Dhamra river mouth and terminating at Satavaya village. The first transect ran adjacent to the shoreline (approximately 200-300 m offshore), with subsequent transects positioned at 1 km intervals. Consequently, these 6 parallel transects encompassed an area extending up to 5 km offshore. Conversely, each of the 4 perpendicular transects spanned a length of 5 km and was positioned directly in front of Abdul Kalam Island, the site of mass nesting events. The entire set of 10 transects was replicated three times during the study duration, which was divided into two distinct periods. The first period, from January to mid-February, was designated as the Pre-Nesting Season. The second period, from mid-February to March, was designated as the Nesting Season. These periods were demarcated based on a visible decline in sightings of mating pairs, indicating the end of the courtship period and the beginning of the nesting period. Moreover, these perpendicular transects maintained a consistent spacing of 1 km between each other. All transects were delineated using Google Earth software and navigated using handheld Garmin GPS device during the field surveys.

For this study, parallel transects were deemed suited to investigate the spatial distribution patterns of olive ridley turtles and their potential association with environmental covariates.

Parallel transects, extending over a broader area, were particularly suited for this objective, as outlined by Kumar (2015). This approach allows us to assess whether turtle distribution is random or influenced by environmental factors across the entire study area. In contrast, the study by Rao et al. (2023) in Rushikulya utilized a focused, long-term monitoring design with perpendicular transects within a pre-defined area known for turtle aggregations. Their primary aim was to monitor changes in density and distribution of the aggregation over time. Our study prioritizes a broader spatial assessment using parallel transects to elucidate whether environmental factors play a role in shaping turtle distribution patterns. In the case of the transects in front of the mass nesting beach, due to the shallow water depth and the irregularity of wave action in the vicinity of the mass nesting beach, perpendicular transects were deemed more suitable than parallel transects.

A fishing boat with a 9 hp engine was used for sampling the transects, maintaining a speed of 8-9 km per hour to minimize double counting of turtles. Sampling was limited to a 5 km offshore area based on previous research (Pandav et al. 1998; Ram, 2000). Additionally, opportunistic surveys were conducted beyond this area to check for turtle aggregation. Surveys were conducted only when the Beaufort Sea state was ≤ 2 , as higher conditions can affect turtle detection (Ram, 2000). Typically, two transects were surveyed per day, spaced three km apart to avoid repeat counts. Surveys were done between 8:00 am and 2:00 pm for better visibility and turtle detectability. Transects were completed within 7-10 days, with the next replicate conducted after 7-8 days.

Individual turtles or mating pairs observed within the semi-circular area in front of the boat were counted. A team comprising three individuals (two observers and one recorder) conducted the sampling. Each observer was assigned to monitor either the right or left side of the boat,

while the recorder operated the handheld GPS device and documented the sighting data. Key information, including time, odometer reading, sighting distance, sighting angle, identification of single turtles or mating pairs, and the number of turtles observed were recorded for each sighting event. Sighting angle and distance were assessed visually, as the use of range finders and compasses was impractical given the sampling environment. While visual estimation introduced some degree of error, efforts were made to mitigate the same by providing training to observers on accurate distance estimation within a 150-meter range. Additionally, to facilitate angle estimation, the boat was equipped with tape markings at 10-degree intervals, with the bow positioned at 90 degrees. In certain areas, where a large number of turtles are encountered, it was not possible to estimate the actual sighting distance and angle for each individual. In such cases, a count of the surfacing turtles was made, and a range of the sighting distance and angle was recorded. Later each individual was assigned a distance and angle within the range, which was randomly generated in Excel.

3.2 Distance Sampling

The densities of turtles were estimated through line transect analysis using the software Distance (version 7.5). Primarily the distance sampling accounts for the proportion of animals that were missed during the survey by using a detection function generated from the records of the distances of those seen, and then estimates abundance. Different probability density functions of the perpendicular distance were modelled using different key functions and adjustments within the Distance software. For single turtles, observations within 15 m were excluded from the analysis to enhance model fit. Whereas, for the mating pairs, left truncation was performed at 20m. Model selection was based on two primary criteria: the Akaike Information Criterion (AIC) and goodness-of-fit (GOF) tests.

3.3 Density Surface Modelling (DSM)

To generate reliable design-based extrapolations of turtle densities, counts of surfacing turtles (aggregated for every 1 km of the transect) were modelled as a function of spatially explicit habitat covariates using generalized additive models (GAM) (Hastie & Tibshirani, 1990; Miller et al., 2013). The effective area of each segment, derived from modelling the distance-based detection function, was incorporated as an offset term in a joint modelling process known as density surface modelling (DSM). This analysis was conducted in R (version 4.2.2) utilizing the `dsm` package (Miller et al., 2013).

First, the entire transect was divided into 1 km segments, and the counts of individual surfacing turtles recorded along the segmented transects were modelled as a function of covariates collected at the segment level at 1 km intervals. The objective of the modelling was to predict the abundance of turtles over space by understanding the factors that influence turtle abundance. Data for five covariates were collected at the segment level: water depth (`depth`), water salinity (`saln`), distance to the mass nesting beach (`mbdist`), distance to the coastline (`cdist`), and distance to the river mouth (`rmdist`). Models were fitted using a forward-backward covariate selection approach, where each forward step was followed by a backward step to remove any variables that were no longer significant (Pearce & Ferrier, 2000). Model sets were compared using the Akaike Information Criterion (AIC), generalized cross-validation (GCV) scores, and the percentage of deviance explained. A prediction grid was created to understand how the turtles are distributed spatially, consisting of 201 grids of 1 km² each. Finally, a surface of estimated turtle abundance across the entire prediction grid was created using the best-fit GAM model.

4. Results:

4.1. Variation in Turtle Sightings and Detection Distances

During the entirety of the study period, the 10 transects surveyed for estimating surfacing turtle density were sampled 30 times totalling 438 km of effort. During the pre-nesting season, a total of 16 transects were sampled, combining a total effort of 272 km. Whereas, in nesting season, a total of 14 transects were sampled, combining a total effort of 166 km. The number of turtles observed in different transects varied significantly based on their distance from the coastline as well as the season of sampling (Table 1). A total of 1026 surfacing turtles were observed during the study period, which comprised 860 single turtles and 83 mating pairs.

Table 1. Turtle sightings along different transects across pre-nesting and nesting season

Season	Transect ID										Total (MP)
	PA1	PA2	PA3	PA4	PA5	PA6	PE1	PE2	PE3	PE4	
Pre-Nesting	41	132	88	47	26	45	51	32	17	6	485(67)
Nesting	19	81	36	37	27	17	186	80	41	17	541(16)
Total	60	213	124	84	53	62	237	112	58	23	1026(83)

Turtle sightings were comparatively less in January and progressively increased towards the end of the study period. There was no effect of sea-state on the sighting distance of turtles, suggesting detectability stayed almost similar between sea-state ranging from 0-2 (Fig 3). The sighting distance of turtles differed between single turtles and mating pairs. The average sighting distance for single turtles was 64.95 m (\pm 34.11 SD, n = 860), whereas the average sighting distance for mating pairs was 107.89 m (\pm 42.75 SD, n = 83). Most of the turtles were sighted at the distance range of 30-80 m, following which the numbers were reduced due to a reduction in detection probability (Fig 4). The sighting distance range was slightly reduced during nesting season when the turtle aggregation was denser and most of the turtles were sighted relatively closer to the survey vessel (Fig 4).

Fig 3. Changes in sighting distance with different sea-states across pre-nesting and nesting seasons with 95% confidence intervals (in grey)

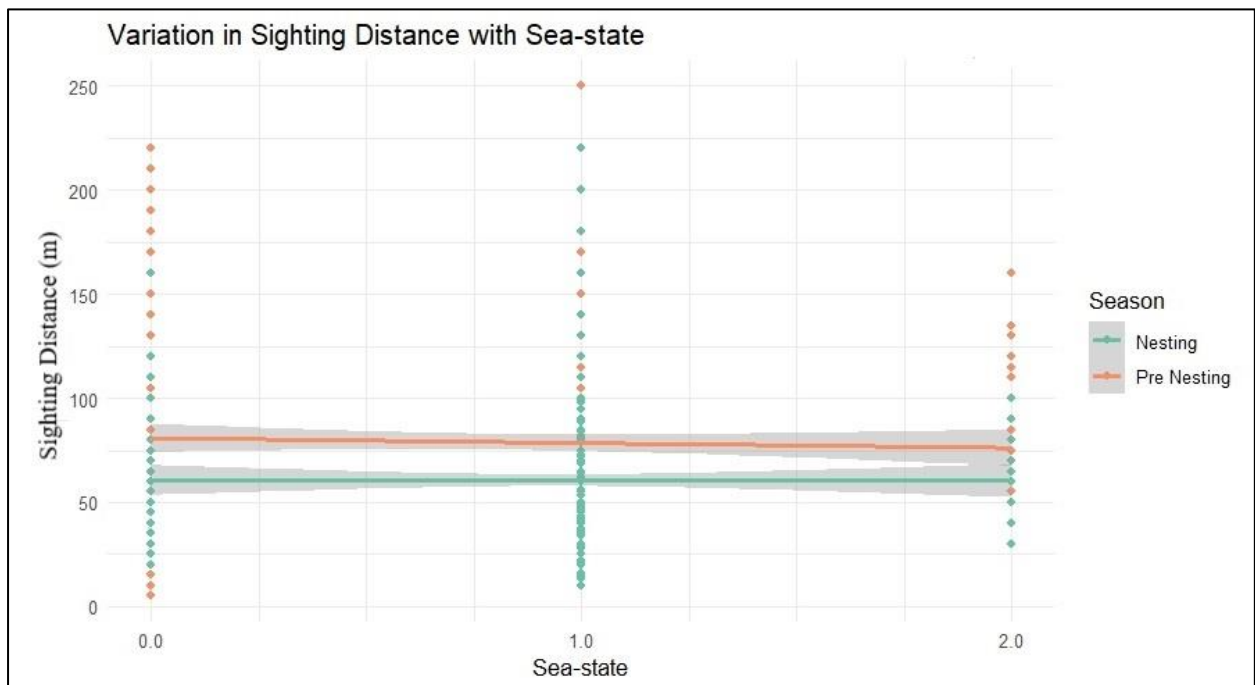
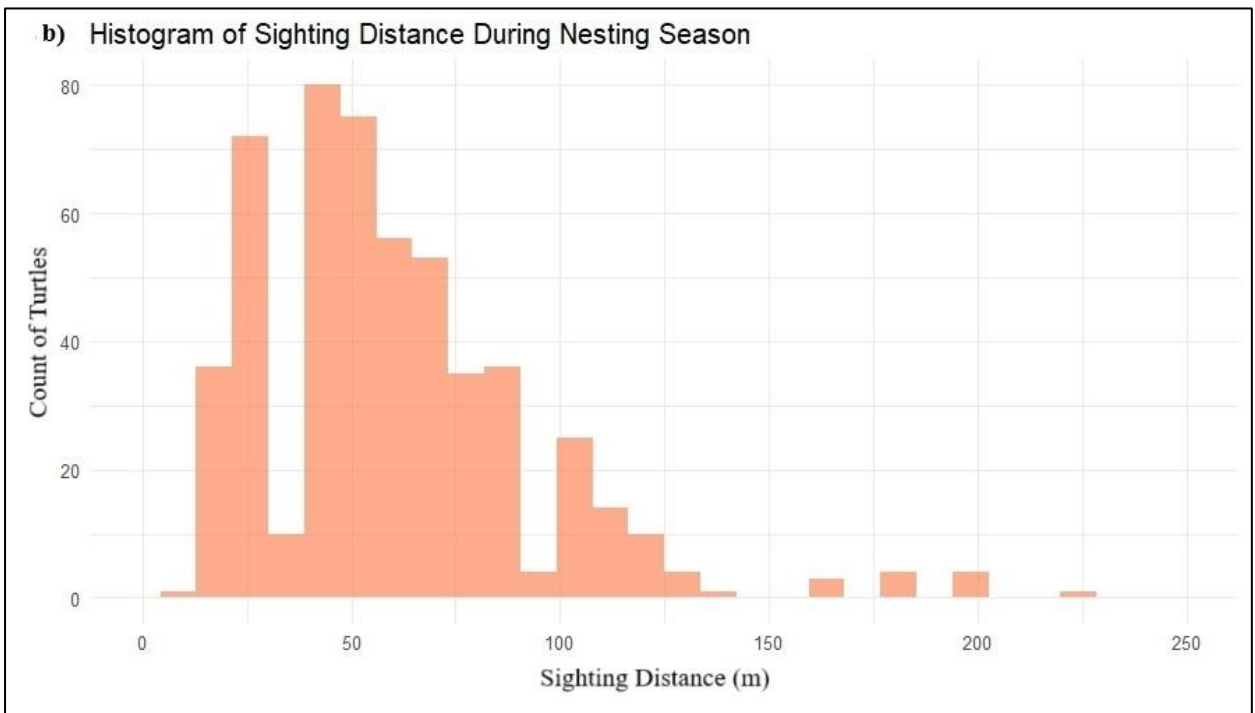
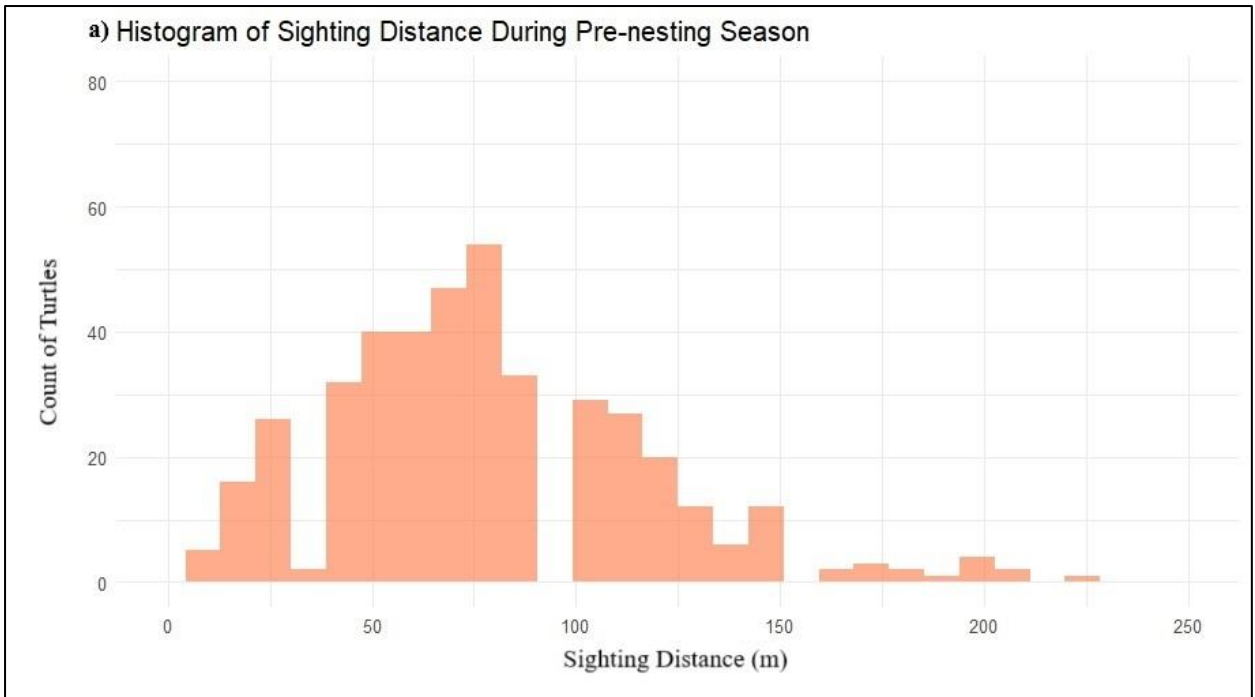


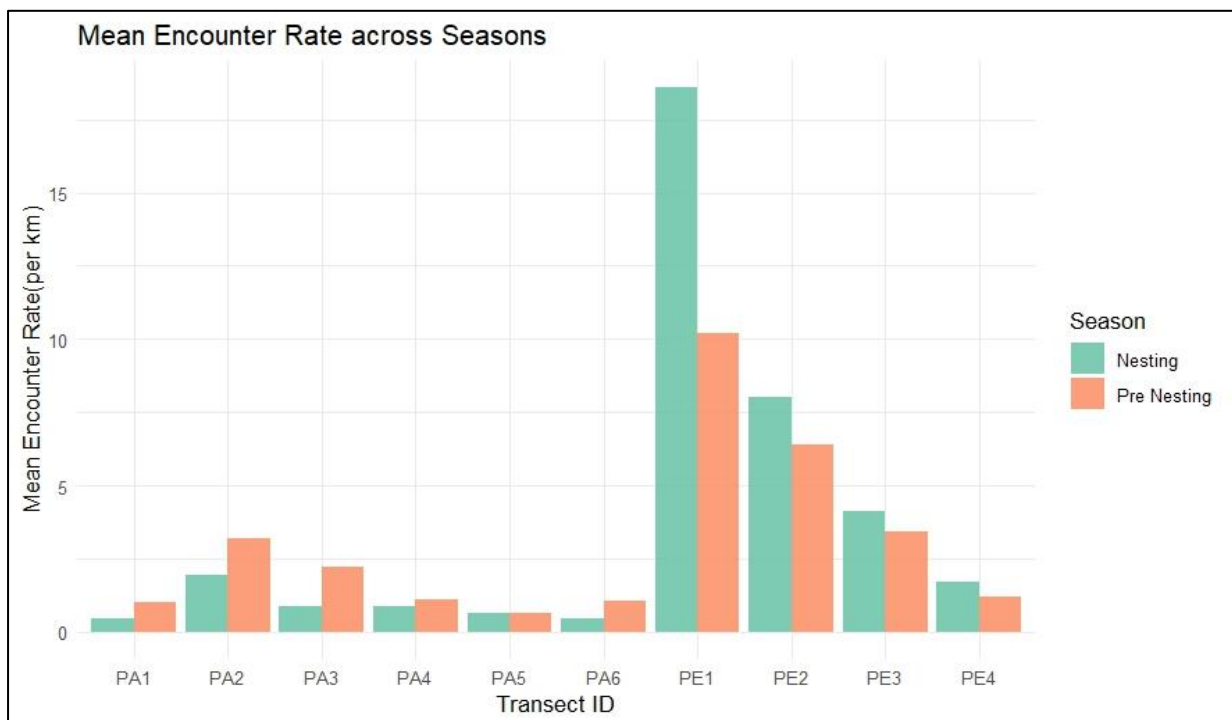
Fig 4. Histogram of sighting distances during a) Pre-nesting season, b) Nesting season



4.2 Surfacing Turtle Encounter Rate Across Seasons

Encounter rates of surfacing turtles were significantly different across all the transects during the study period (Kruskal-Wallis chi-squared = 24.449, df = 9, p-value = 0.003646), with predominantly more sightings along the perpendicular transects than on the parallel transects. Also, turtle sightings were higher closer to the coast, and therefore decreased beyond 2 km (Fig 5). The mean encounter rate of turtles was higher in parallel transects in pre-nesting season and it lowered during the nesting season. Whereas the opposite happened for the perpendicular transects.

Fig 5. Mean encounter rate of turtles across different transects during pre-nesting and nesting seasons



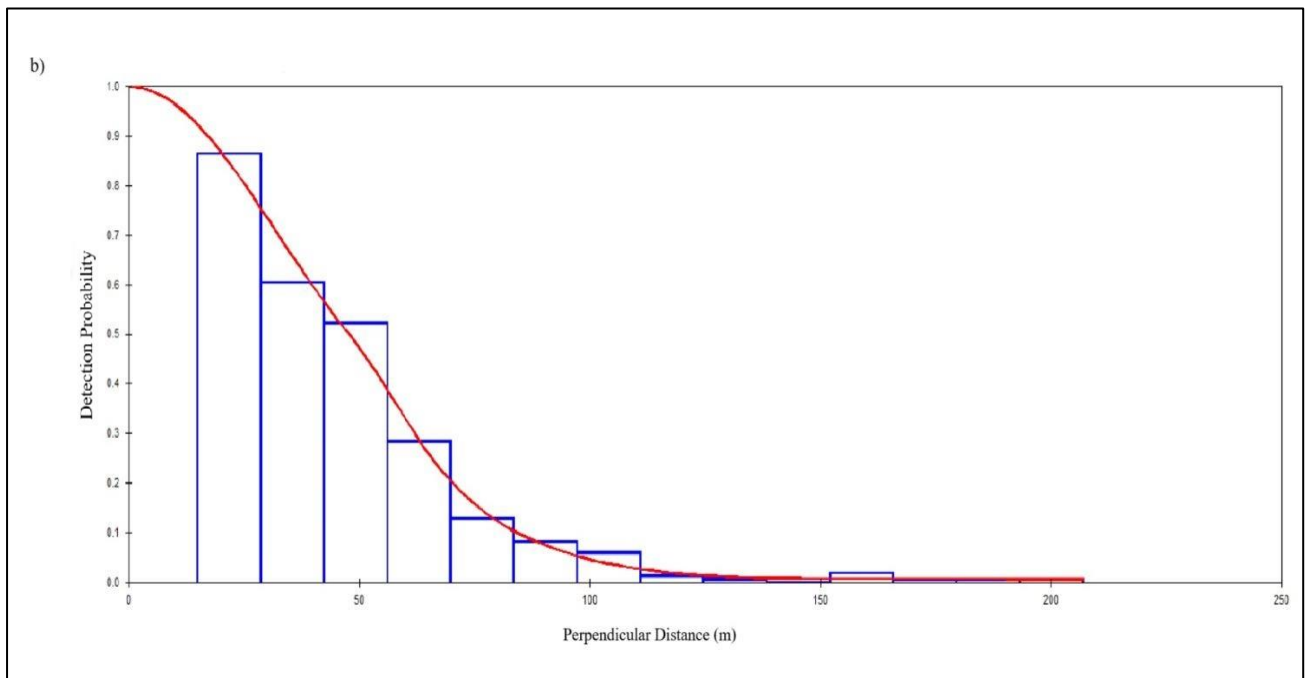
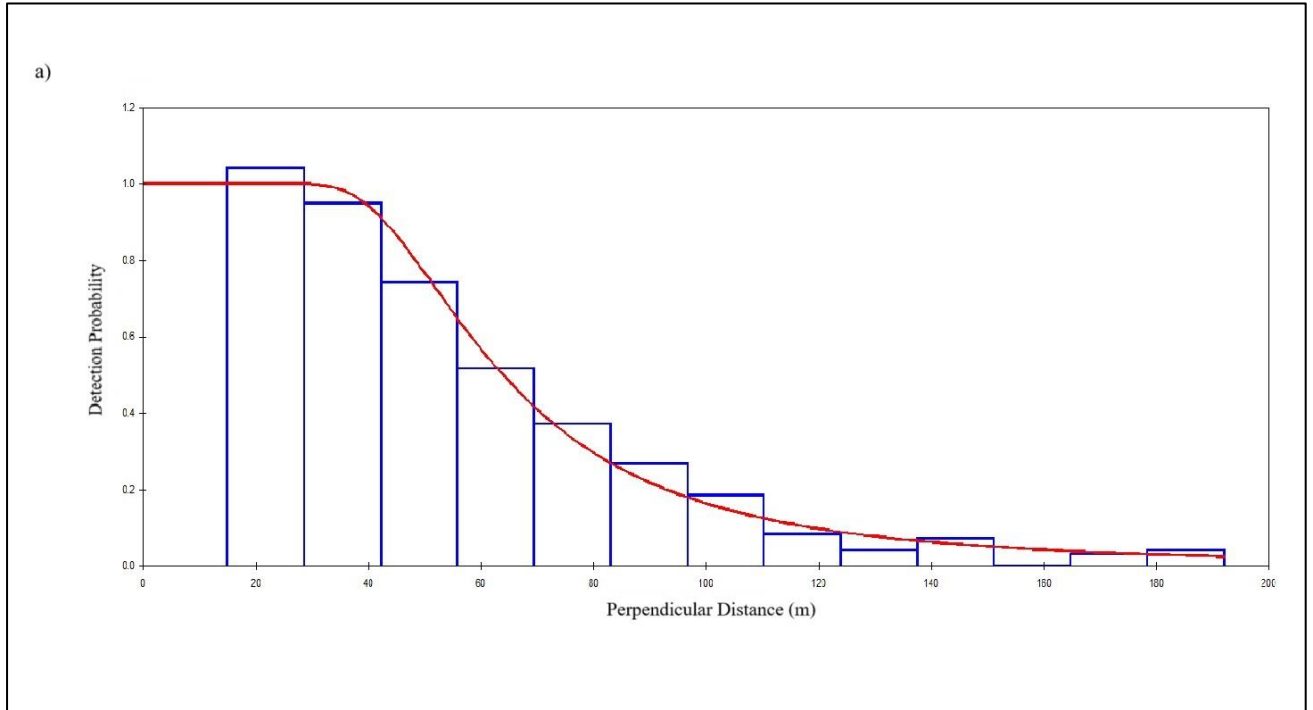
4.3 Surfacing Turtle Density Estimates Across Seasons

While using Distance software to estimate surfacing turtle density, sightings within 15 m were truncated for a better model fit. For the mating pair density estimation, sightings within 20 m were truncated for a better fit. The best-fit model was decided based on the lower AIC value. In all cases, the hazard rate model with cosine adjustment turned out to be the best-fit model (Fig 6). The density estimates increased significantly from the pre-nesting season to the nesting season (Table 2). The estimated surfacing turtle density for the pre-nesting season was 13.09 turtles per sq. km with a CV of 22.4%. The estimated density increased during the nesting season and became 37.85 turtles per sq. km with a CV of 35.7%.

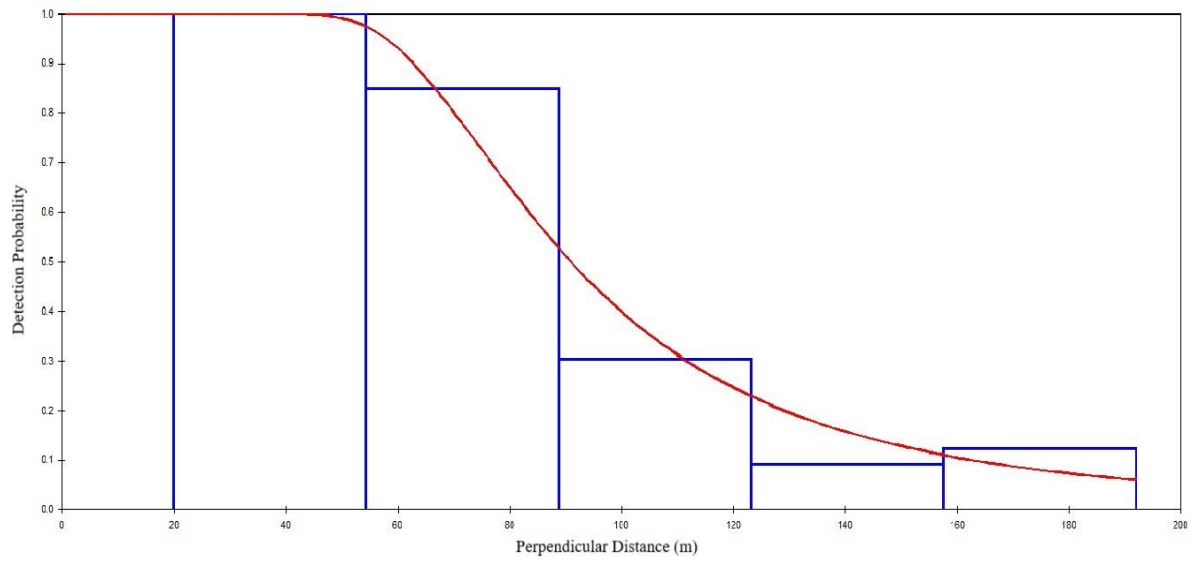
Table 2. Surfacing turtle density across seasons (mating pair density was only analysed for the pre-nesting season, due to very less sightings in the nesting season)

Season	Pre-Nesting	Nesting	Mating Pair
No. of sightings	421	447	63
Detection Model	Hazard Rate/Cosine	Hazard Rate/Cosine	Hazard Rate/Cosine
AIC	3912.80	3891.89	758.51
ESW	59.09	35.57	81.31
Density (turtles/sq. km)	13.09	37.85	1.76
95% CI Range	8.01-21.41	17.5-81.85	0.90-3.46
% CV	22.4	35.7	31.9

Fig 6. Histogram of change in detection probability with increase in perpendicular distance for a) pre-nesting season, b) nesting season, c) mating pairs



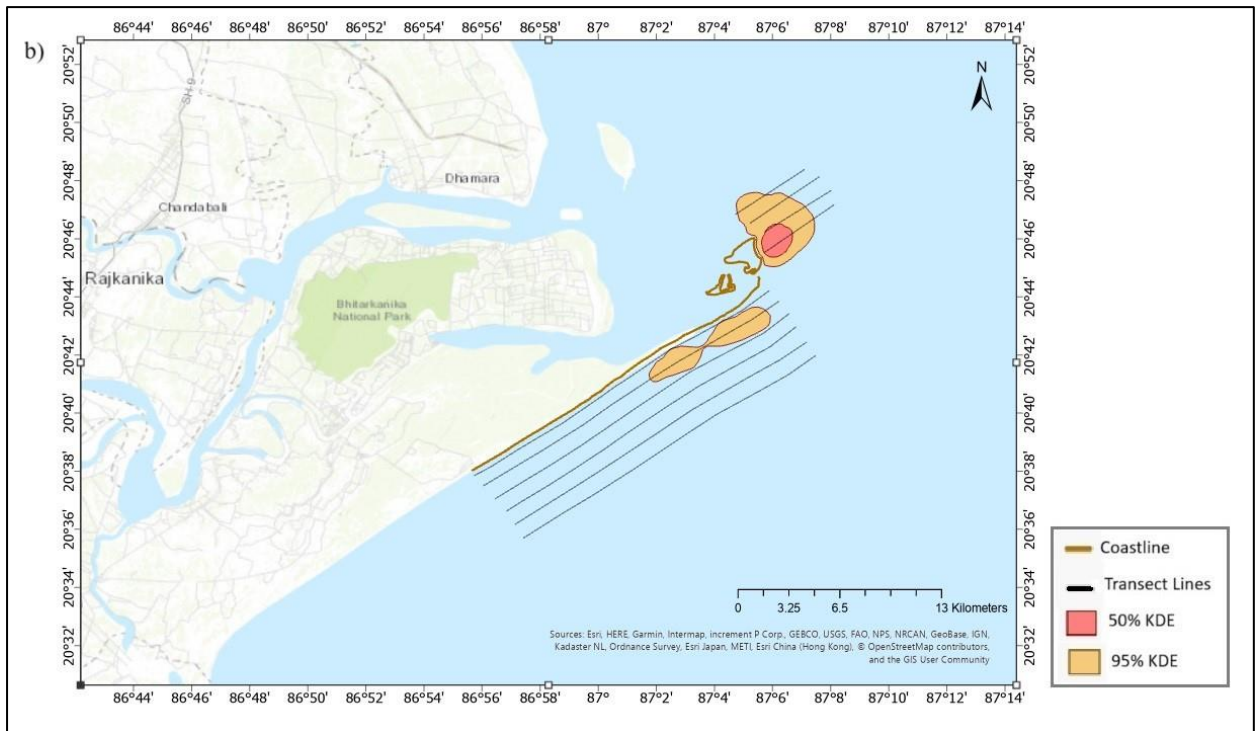
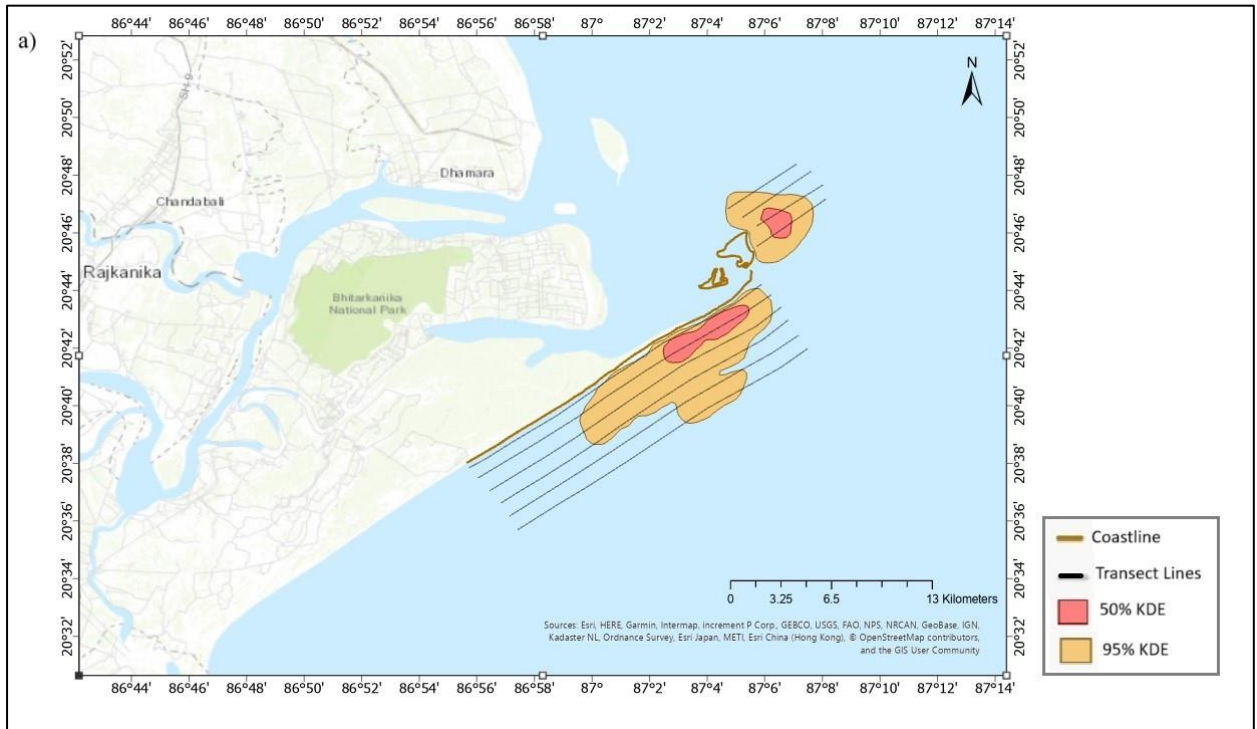
c)



4.4 Spatial Distribution of Surfacing turtles

The general area of use (represented by 95% KDE) and the core area of use (represented by 50% KDE) differed across the seasons. The aggregation shifted towards the mass nesting beach with the progression of the nesting season (Fig 7). During the pre-nesting season, the general area of use was 67.9 sq. km, and the core area of use was 10 sq. km. During the nesting season, the general area of use was reduced to 24.8 sq. km and the core area of use was reduced to only 3.4 sq. km, effectively occupying a very small area directly in front of the mass nesting beach.

Fig 7. Kernel Density Estimate of surfacing turtles during a) pre-nesting season and b) nesting season



4.5 Modelling Surfacing Turtle Densities and Abundance Estimates

The final Generalized Additive Model (GAM) was selected based on the lowest AIC and GCV (Generalized Cross-Validation) values. Based on the two criteria, the best-fit model for the pre-nesting season was able to explain 55.8% of the total deviance. On the other hand, the best-fit model for the nesting season was able to explain 88% of the total deviance in the sighting data of surfacing turtles (Table 3). The predictor variables of distance from the coastline (cdist) and the distance from the mass nesting beach (mbdist) had a significant effect on surfacing turtle densities in both seasons (Fig 8 & Fig 9). Generally, the surfacing turtle densities decreased with an increase in distance from the mass nesting beach as well as the coastline.

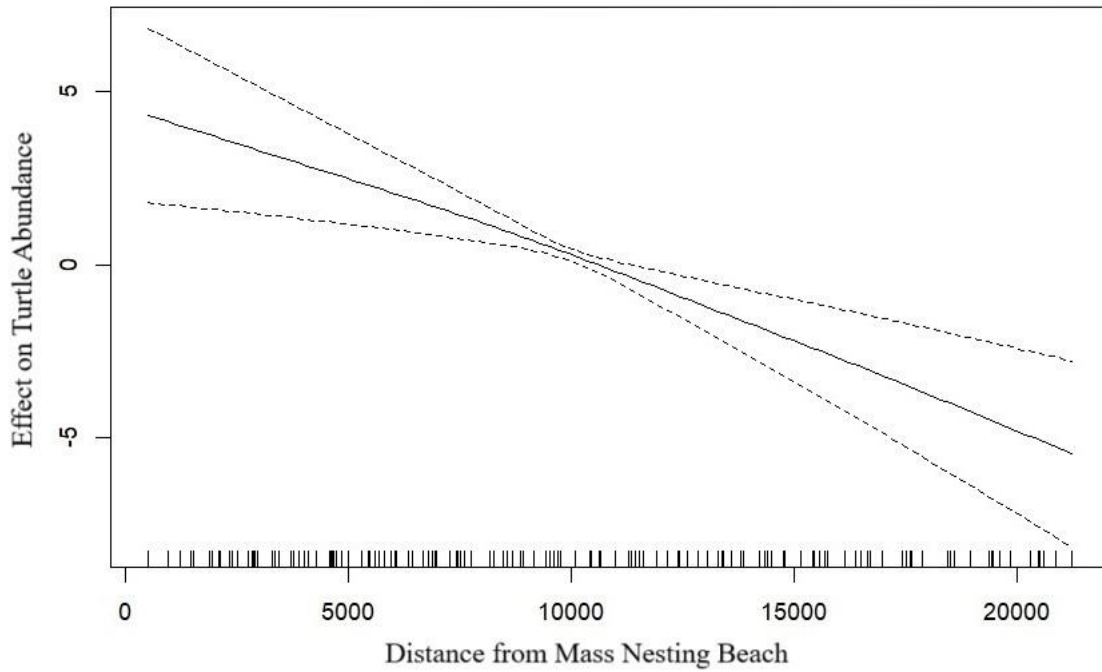
The abundance of surfacing turtles was estimated by extrapolating the point estimate with the area of each grid. The abundance of surfacing turtles for the pre-nesting season is 1356 turtles, with a CV of 21%. However, this number increased to 4412 turtles, with a CV of 10%. A higher abundance of turtles was observed along the coastline and to a lesser extent just in front of the mass nesting beach during the pre-nesting season. However, it changed during the nesting season, and turtle abundance was highly concentrated just in front of the nesting beach.

Table 3. The best fit GAM model and the associated abundance numbers across the seasons

Season	Pre-Nesting	Nesting
Detection Model	Hazard Rate/Cosine	Hazard Rate/Cosine
GAM Model		
Intercept	-12.1833	-11.3354
s(mbdist)	2.146*	9.560*
s(cdist)	4.633*	5.214*
Deviance Explained (%)	55.5	88
GCV Score	242.8	280.47
Point Estimate	1356	4412
% CV	21.37	10.5
95% CI	896-2052	3594-5417

Fig 8. The generalized additive model response curves (solid lines) with 95% confidence intervals (dashed lines) for Pre-nesting Season for a) Distance to Mass Nesting Beach and b) Distance to Coastline

a) Effect of Distance from Mass Nesting Beach on Turtle Abundance during Pre-nesting Season



b) Effect of Distance from Coast on Turtle Abundance during Pre-nesting Season

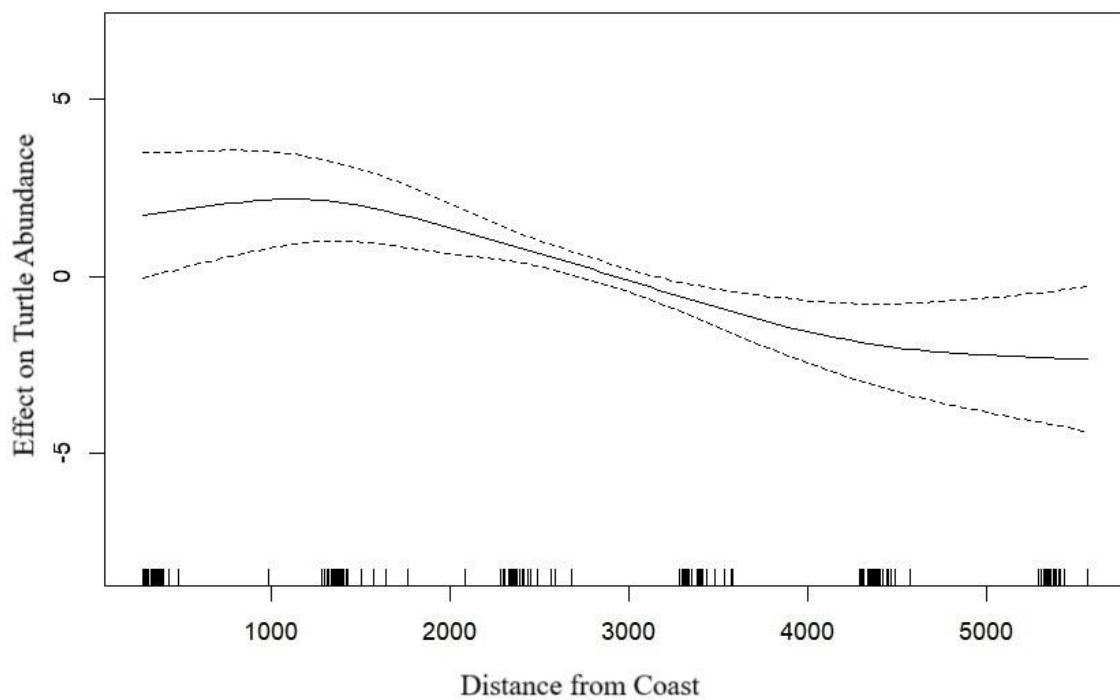
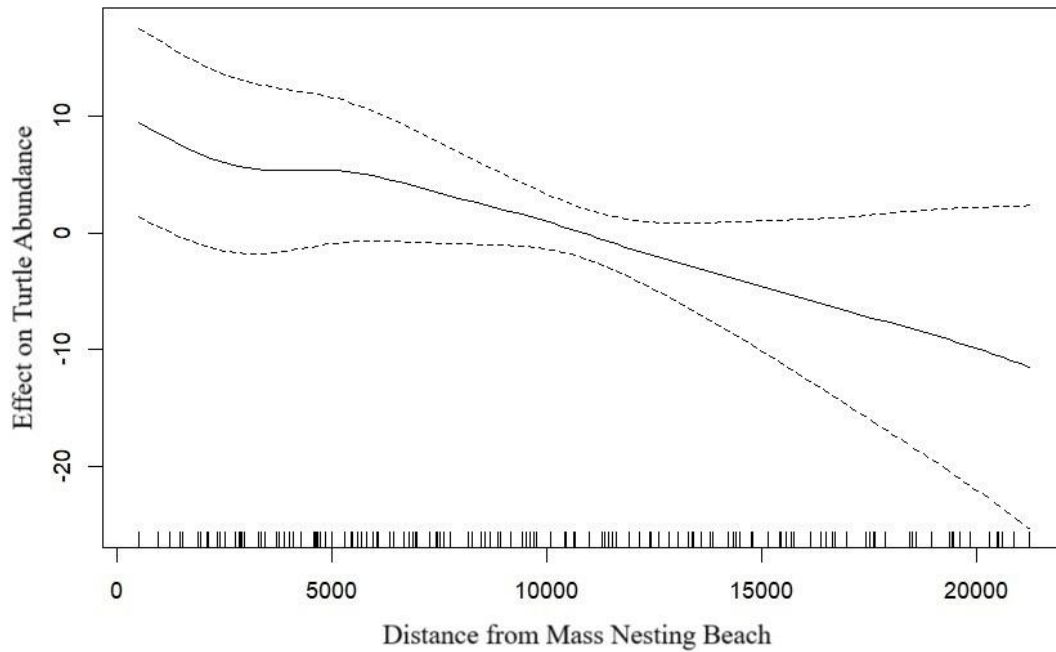


Fig 9. The generalized additive model response curves (solid lines) with 95% confidence intervals (dashed lines) for Nesting Season for a) Distance to Mass Nesting Beach and b) Distance to Coastline

a) Effect of Distance from Mass Nesting Beach on Turtle Abundance during Nesting Season



b) Effect of Distance from Coast on Turtle Abundance during Nesting Season

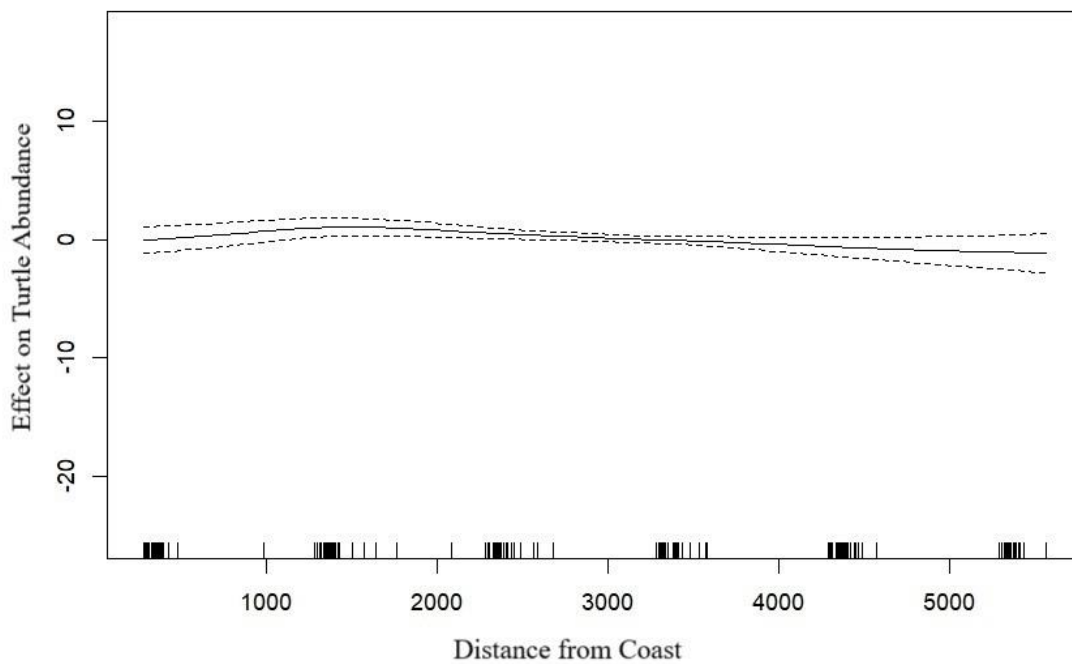
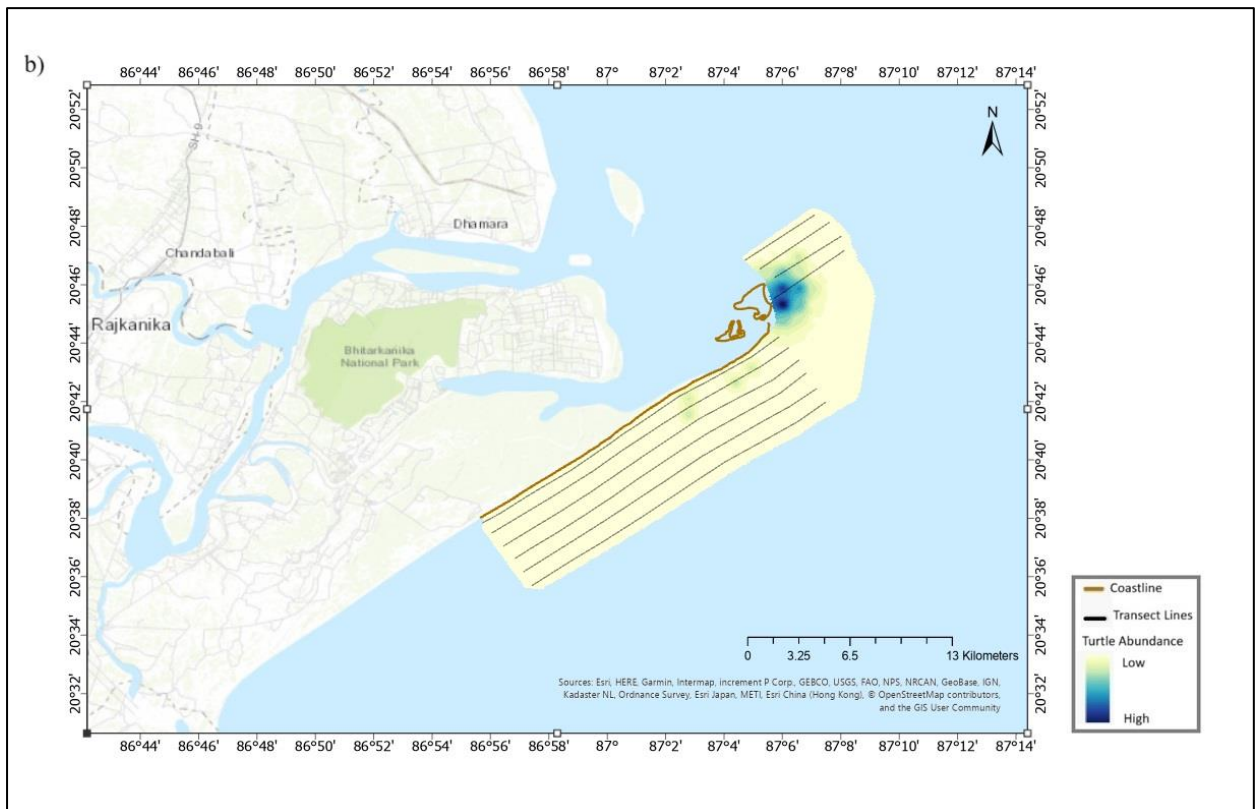
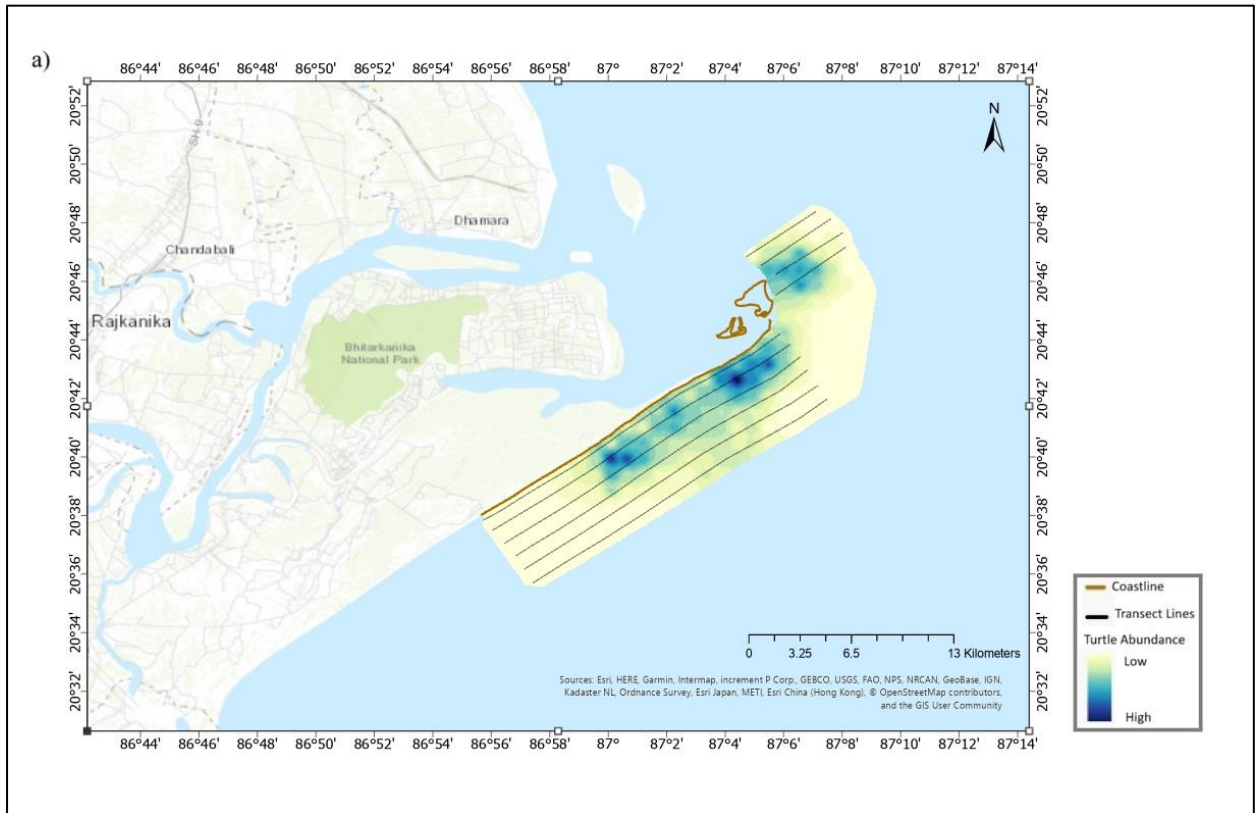


Fig 10. Spatial distribution of predicted turtle abundance by GAM model during a) pre-nesting season and b) nesting season



5. Discussion:

5.1 Dynamic Aggregation Patterns and Seasonal Shifts

The study results indicate that olive ridley turtles were not randomly distributed across the Gahirmatha coastline during the study period. Rather they occurred in large aggregations located in the nearshore waters along the coastline as well as in front of the mass nesting beach. The aggregation was not static and changed in density as well as in the occupied area. The turtle aggregation during the pre-nesting season was much more dispersed and the density estimates were also relatively lower. However, during the nesting season, the aggregation was mostly located in front of the mass nesting beach and the area used by the turtles also reduced significantly. The dynamic nature of the turtle aggregation is consistent with the observations from previous studies (Kalb, 1999; Tripathy, 2013). A past study at Gahirmatha suggested that turtles stayed in the same area (Ram, 2000). However, this might be because the study only looked at mating pairs, not the overall distribution of all the turtles.

5.2 Spatial Distribution of Olive ridley Turtle Aggregation

Information on the spatial distribution of turtle aggregations at Gahirmatha is primarily available for mating pair aggregations. Pandav and Choudhury (2000) reported an aggregation area of 52.5 sq. km, while Ram (2000) estimated it to be 32 sq. km, both using a 100% minimum convex polygon (MCP). However, these estimates are not directly comparable due to methodological differences and the focus on mating pairs alone. While the current study provides the first systematic sampling-based insight into the spatial distribution of olive ridleys along the Gahirmatha coast, encompassing not only mating pairs but individual turtles as well.

Kernel Density Estimation (KDE) was employed to assess the general area utilized by the turtles (95% KDE) and their core usage area (50% KDE). During the pre-nesting season, the 95% KDE indicated a widely dispersed aggregation covering 67.9 sq. km, while the 50% KDE identified a core area of 10 sq. km (Fig 7). The data revealed two primary aggregation zones: a larger area along the coastline from adjacent to the river mouth to Habalikatti beach (approximately 13 km), and a smaller area in front of the mass nesting beach, with a lower density of turtles as shown by the Density Surface Model (Fig 10). The majority of turtles were concentrated within 3 km of the coastline, although some were observed up to 5 km offshore. The distinct separation between these areas is attributed to the formation of a sand spit near the river mouth, which gets submerged during high tide, and the strong tidal influence due to the narrow river mouth opening, potentially deterring turtles from using that region.

Substantial changes in the area of use were observed during the nesting season. The number of turtles in the aggregation increased, while the spatial distribution decreased, as indicated by the DSM model (Fig 10). During this period, turtles predominantly utilized a narrow coastal area, with most aggregating in front of the mass nesting beach. This behaviour, where turtles gather densely near the mass nesting beach just before the arribada, has been documented in several studies (Kalb, 1999; Ram, 2000; Pandav & Choudhury, 2000; Bezy, 2019). A similar study from Rushikulya reported the aggregation area to be 226 sq. km and 94 sq. km (95% KDE) for the pre-nesting and nesting seasons, respectively, in 2008 (Kumar, 2015). This result suggests that the area of use undergoes a significant change as the breeding season progresses, typically reducing as the turtles aggregate closer to the mass nesting beach during the nesting season. Another study from Rushikulya, which investigated nearshore aggregation, found the general area of turtle use over ten years to be 31.82 sq. km (± 3.07), with the core area being 9.53 sq. km (± 3.4) (Rao et al., 2023). This was calculated through the MCP method and is therefore

not directly comparable. Additionally, the survey techniques differed from those used in this study, which covered a substantially smaller area, potentially reflecting in the lower estimates.

The dispersed nature of the turtle aggregation is likely influenced by the behaviour of mated females moving away from the core aggregation area to avoid male harassment (Kumar, 2015). Observations by Pandav and Choudhury (2000) in the Gahirmatha region noted multiple males mounting a single female, indicating male competition. Additionally, males typically spend more time on the surface actively searching for females (Parker et al., 2003), leading them to occupy a larger area.

5.3 Seasonal Variations in Turtle Density

The surfacing turtle density estimates obtained through this study should only be considered as a conservative estimate. Factors like boat speed differing due to variability in sea conditions, not having absolutely accurate measurements for sighting distance and sighting angle, continuous movement of the boat affecting detection, all attributes to potential biases. Thus, the density estimate has a higher CV.

The density estimate of both seasons suggests that only a fraction of the population was present along the Gahirmatha coast during the pre-nesting season (Table 2). The density estimate for the pre-nesting season is comparable to the density of turtles in Rushikulya during a non-arribada season (Kumar, 2015). The density of turtles however increased almost three times during the nesting season, suggesting more and more turtles arrived in the offshore waters as the breeding season progressed. The increase in the number of turtles can also be attributed to

the non-occurrence of arribada in the Rushikulya mass nesting site in 2024. The increase in the density estimate could be a result of more turtle sightings during the latter part of the study period when most of the turtles gathered in front of the mass nesting beach (Kalb, 1999). Moreover, the olive ridleys are known to migrate between the mass nesting sites along the Odisha coastline (Pandav & Choudhury, 2000; Tripathy & Pandav, 2008; Kumar, 2015; Behera et al. 2018), it is possible that a substantial part of the turtles arrived at Gahirmatha from Rushikulya just before the mass nesting. The density estimate obtained from this study is comparatively less when compared to previous studies from the Odisha coastline (Kumar, 2015; Rao et al, 2023). This could be due to the lower number of turtles arriving at the nearshore waters this year, which can be assumed by the count of mass nesting turtles conducted at the Gahirmatha mass nesting beach this year. It is estimated that approximately 150,000 turtles nested this year during mass nesting, which is significantly less than the previous year's estimate of approximately 500,000 turtles (Odisha Forest Department).

5.4 Environmental Factors Influencing Turtle Aggregation

In examining the factors influencing the location of turtle aggregations, distance from the mass nesting beach and the coastline emerged as significant in density surface modelling (Table 3). Contrary to studies conducted in Rushikulya, where depth was a significant factor (Tripathy, 2005; Kumar, 2015), this study found that depth did not significantly explain aggregation locations in Gahirmatha. Previous research reported that turtle aggregations in Rushikulya occur at depths of 15-30 m (Kumar, 2015; Rao et al. 2023), while olive ridleys in the eastern Pacific are observed at depths of 25-35 m (Kalb, 1999). Along the Gahirmatha coast, mating pairs were observed to prefer depths below 20 m (Ram, 2000). However, this study, using DSM modelling, revealed that turtles utilize varying depths across the season. During the pre-nesting season, turtles were dispersed and occupied depths between 5-15 m, with 82% of the turtles

observed in this depth range. In the nesting season, turtles moved to shallower waters in front of the mass nesting beach, with 81% of the turtles occupying depths below 10 m (Fig 8).

Turtles are known to rest on the seabed for prolonged periods (Hochscheid et al. 1999; Hays et al. 2000; Houghton et al. 2002), which aids in energy conservation and faster development of eggs (Plotkin et al., 1991). Different turtle species exhibit specific depth preferences: loggerhead turtles prefer depths of 14 m, while green turtles prefer 17 m (Minamikawa et al., 2000; Hays et al., 2004). Kumar (2015) suggested that olive ridleys achieve neutral buoyancy at depths of 15-20 m, allowing them to remain on the seabed for extended periods. The Gahirmatha coastline has lower salinity compared to Rushikulya, potentially reducing the depth at which turtles achieve neutral buoyancy. Increased freshwater influx lowers buoyancy, facilitating easier dives to the seabed at shallower depths. It also helps the turtle to stay on the seabed for longer periods, without floating up with the currents and flow of the water. This could explain the preferred depth range of 5-15 m for turtles in Gahirmatha, compared to 15-20 m in Rushikulya.

The offshore waters of Gahirmatha are characterized by shallow depths, reaching only 20 m at a distance of 8 km from the coastline. Olive ridley turtles have been documented to favour shallower waters for aggregation, typically within a depth range of 15-30 m (Tripathy, 2013; Kumar, 2015; Rao et al., 2023). Consequently, much of the study area provided an optimal depth range for turtle aggregation. In this context, the spatial distribution of the turtle aggregation was significantly influenced by proximity to both the coastline and the mass nesting beach. Aggregations were generally confined within 3 km of the coast. As the breeding season advanced, the aggregation grew larger, and the core area shifted towards the mass

nesting beach. This observed pattern is consistent with findings from previous studies (Kalb, 1999; Ram, 2000; Pandav & Choudhury, 2000; Bezy, 2019).

5.5 Moving Forward: A Dynamic Approach to olive ridley Turtle Conservation

In conclusion, this study shed light on the dynamic nature of olive ridley turtle aggregations along the Gahirmatha coastline. Unlike random distributions, these turtles formed concentrated aggregations in nearshore waters, with the specific location and density shifting throughout the breeding season. Factors like distance to the nesting beach and the coastline influenced the turtle aggregation locations. Protecting these dynamic aggregation areas is critical for the conservation of this globally significant population. However, it's important to acknowledge that the exact locations of these aggregations can vary between years (Kalb, 1999; Pandav & Choudhury, 2000; Kumar, 2015; Rao et al. 2023). This year's lower nesting numbers indicate that fewer turtles arrived in the nearshore waters, which may have also impacted the size and distribution of the aggregations observed in this study. Long-term studies are necessary to gain a more comprehensive understanding of these variations and which factors might influence them. Given the dynamic nature of these aggregations and the vastness of the Gahirmatha Wildlife Sanctuary, effectively patrolling the entire area for turtle protection is not feasible. Therefore, the forest department's efforts should be strategically focused on the areas which turtles are actually using. Collaborative efforts are needed to identify these areas each season. By implementing rigorous patrolling measures within these concentrated use zones, the forest department can significantly reduce threats like bycatch mortality from fishing activities. Given the limited resources of the forest department, this targeted approach would be more effective in safeguarding the turtles compared to focusing on reducing illegal fishing in the entire sanctuary. Ultimately, a successful conservation strategy requires flexibility and adaptation. By understanding the dynamic use patterns of olive ridley turtles and working collaboratively with

stakeholders, an effective conservation plan can be developed to protect this remarkable species and its critical habitat.

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