BEFORE THE NATIONAL GREEN TRIBUNAL (SZ) CHENNAI

MEMORANDUM OF APPLICATION
(Under Section 18(1) read with Sections 16 (h) of National Green Tribunal Act, 2010)

Appeal No.14 of 2022

M. Yuvadeeban ...Appellant

Vs.

Department of Fisheries & Ors. ...Respondents

INDEX

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(1421/11)

Through
Yogeshwaran. A
Counsel for Appellant

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AFFIDAVIT DATED 27.11.2022 FILED BY THE APPELLANT PURSUANT TO THE ORDER DATED 14.11.2022

I, M. Yuvadeeban s/o Margaret Lawrence, aged about 26 years, residing at B2, Ramaniyam Marvel, Seshadripuram, 1st main road, Velacherry, Chennai 42, do hereby solemly affirm and sincerely state as follows:

1. I am the Appellant herein and am aware of the facts and circumstances of the case and am competent to affirm to the contents of this affidavit.
2. I submit that during the course of the hearing on 14.11.2022, it was submitted that the presence of inter alia, the admitted seagrass beds in the estuary and the fact that the coast is admittedly a turtle nesting ground, entitles it to protection of the law as a CRZ 1A area, where harbours are not permitted to be established.
3. This Hon’ble Court directed the appellant to file a note on the impact of the construction of training walls on nesting of the olive ridley turtles.

Training walls and impact on turtle nesting

4. The project involves the construction of two training walls, dredging, removal of the sand bar and permanent opening of the estuary mouth. The fact that

erosion would occur on the Northern side (Alamparai kuppam) side is an admitted fact in reports of the project proponent.

Alamparaikuppam

5. In the rejoinder filed by the appellant, detailed submissions have been made on this aspect and relevant pages from the EIA, feasibility reports and time series google earth imagery have been filed. The coast to the north of the training wall will experience severe erosion on account of net loss of sediment and given the fact that the shoreline north of the estuary mouth already faces erosion which is managed naturally – the coast is in a state of dynamic equilibrium, which is impaired irreversibly when interfered with by hard structures such as breakwaters, groynes etc.
6. The respondents do not dispute the fact that the coast on the Alamparai side will undergo severe erosion on account of the training walls to be constructed. The solution of three groyne fields proposed in the counter affidavit is adding insult to injury – it will exacerbate the problem and cause erosion of the shoreline to the north and result in construction of more groynes and seawalls – permanently destroying the coast. It is the mindless construction of groynes and seawalls by the fisheries department and public works department which caused the destruction of our coast – this Hon'ble Tribunal in its orders in OA No.4 of 2013, has finally put a stop to it.
7. Irrefutable evidence of Turtle nesting on the Alamparai side :
    1. Report of the DFO to APCCF dated 11.04.2022 provides a table with 73 nests in 2021-2022.
    2. See data from Tree foundation (which works for the forest department) from 2010 – 2022 @ page 694 (rejoinder – File D)
    3. Photos of turtle nesting on the Alamparai coast with GPS locations @ page 741 – 782 (rejoinder – File D)
    4. Google earth imagery with turtle nests on the Alamparai coast in 2021-2022 @ page 783 (rejoinder – File D)
8. Due to the construction of the training walls, the beach will get eroded and these turtle nesting grounds will be destroyed. This is impermissible in law.

Azhagankuppam

9. On the Southern side (Azhagankuppam side), there will be a net accretion of sand, causing a build-up of sediment in the immediate vicinity of the southern training wall.
10. The Azhagankuppam coast is an admitted turtle nesting ground:
    1. GO Ms.146 dated 27.09.2016 mentions Azhagankuppam
    2. Report of the Conservator of Forests , Villupuram to the PCCF dated 18.04.2022 clearly states that during 2021-2022 at Azhagankuppam village 33 nests have been identified and 3717 eggs have been collected. The report also states that the location where the retaining walls (training wall) are to be constructed and dredging (digging) is a habitat of olive ridley turtles. Forest range officer's report dated 12.04.2022 also provides the above information.
    3. Map submitted by the forest department of nest locations shows nests on the sand bar – clear proof that the sand bar itself is a nesting ground. The sand bar is wide and does not shift during the turtle nesting season.
11. The respondents, including the forest department, without any pleading or evidence, submitted that the fact that accretion of sand would occur on the Southern side (Azhagankuppam side), would help turtle nesting as turtles would have a wider beach to nest. This contention is devoid of logic and merit.
12. Firstly, the training wall itself is proposed to constructed on the sand bar, which is identified as a turtle nesting ground by the forest department. The construction of the training wall, removal of the sand bar to open up the mouth would destroy this turtle nesting ground. This is impermissible in law.
13. Secondly, Turtles do not land up in larger numbers to a specific spot because more sand is available. The coast on the Azhagankuppam side is already an active turtle nesting ground with a wide beach. The accretion in no way would "improve" the turtle nesting grounds.
14. Turtles are born with magnetite particles in their brain, which imprints location as soon as they emerge. Using the earth's magnetic field as a guide, turtles

return to the beaches where they were born. Therefore, the contention that more sand and a wider beach will be available and hence more turtles will come ashore to nest lacks substance. Studies on turtle's magnetic orientations are annexed as **Annexure A-73**.

15. Thirdly, accretion of sand on the southern side would alter the profile of the beach and affect turtle nesting. Studies have shown that beaches formed by non-natural processes are not conducive for turtle nesting.
16. A study titled "Effects of Beach Nourishment on Sea Turtles: Review and Research Initiatives" by D. Andrew Crain et al states, "A review of the literature on sea turtles and beach nourishment found certain problems repeatedly identified. For nesting females, characteristics induced by nourishment can cause (1) beach compaction, which can decrease nesting success, alter nest-chamber geometry, and alter nest concealment, and (2) escarpments, which can block turtles from reaching nesting areas. For eggs and hatchlings, nourishment can decrease survivorship and affect development by altering beach characteristics such as sand compaction, gaseous environment, hydric environment, contaminant levels, nutrient availability, and thermal environment. Also, nests can be covered with excess sand if nourishment is implemented in areas with incubating eggs" Copy annexed as **Annexure A-74**.
17. A study titled "The Nest Environment and the Embryonic Development of Sea Turtles" by Ralph A. Ackerman states, "In particular, renourished beaches appear to be harder than natural beaches and a vertical erosional scarp often forms on the surface zone of the beach" Copy annexed as **Annexure A-75**.
18. It is submitted that beaches formed due to accretion are not natural beaches – their profile is very different from a beach formed by natural process – they are similar to a beach formed by nourishment.
19. The argument raised by the respondents is devoid of merit and no "benefit" occurs to the Azhagankuppam side due to the training walls in so far as turtle nesting is concerned.
20. Further, the respondents are silent about the impact of increased motorised boat traffic in the area on turtle mortality. The leading causes for turtle

mortality when they migrate and approach nesting grounds are propeller hits from boats and death due to entanglement in nets. This is an acknowledged fact. A study titled "Incidental Capture and Mortality of Olive Ridley Turtles (*Lepidochelys olivacea*) in Commercial Trawl Fisheries in Coastal Waters of Orissa", India by G. V. Gopi et al states, "This study concludes that more than 70% of turtle captures in shrimp trawl fisheries in Orissa occurred within 5 km from shore. These were in generally shallow waters, less than 10 fathoms. A steep increase occurred in the mortality rate when the duration of the trawl was extended beyond 2 hours. Strandings were higher in zones where there is heavy marine fishing and high sea turtle abundance." Copy annexed as **Annexure A-76**.

21. A study titled Threats to sea turtles on the Rameswaram – Dhanushkhodi Coast by S. Krishnapillai states" "Sea turtle populations in this area have already been depleted due to their over-exploitation for trade and from accidental drowning in fishing gear of gill nets and trawlers (Bhupathy and Saravanan, 2002). Boat propellers can also cause damage to the flippers and shells of sea turtles." The study further states, "Introduction of mechanisation in fisheries resulted in the accidental catch of turtles in gillnets, which became a major threat to their populations." Copy annexed as **Annexure A-77**.
22. It is reiterated that the impact of fishing vessels on turtles has not even been discussed in the EIA reports submitted for the present project.

Bird diversity of Yedayanthittu estuary

23. The E-bird checklist showing 165 species of birds observed at the estuary. A note by Dr. Shantaram has already been filed on the importance of shallow estuaries to birdlife. The list of Globally threatened species of birds at Yedaiyanthittu estuary (https://www.birdsofindia.org/IUCN-Red-List) :
    1. Black-headed Ibis
    2. k Pallid harrier
    3. Painted stork
    4. Spot-billed Pelican
    5. Oriental darter
    6. Grey-tailed tattler

7. Eurasian curlew
8. Great knot
9. Black tailed Godwit
10. Curlew Sandpiper
11. Lesser Flamingo

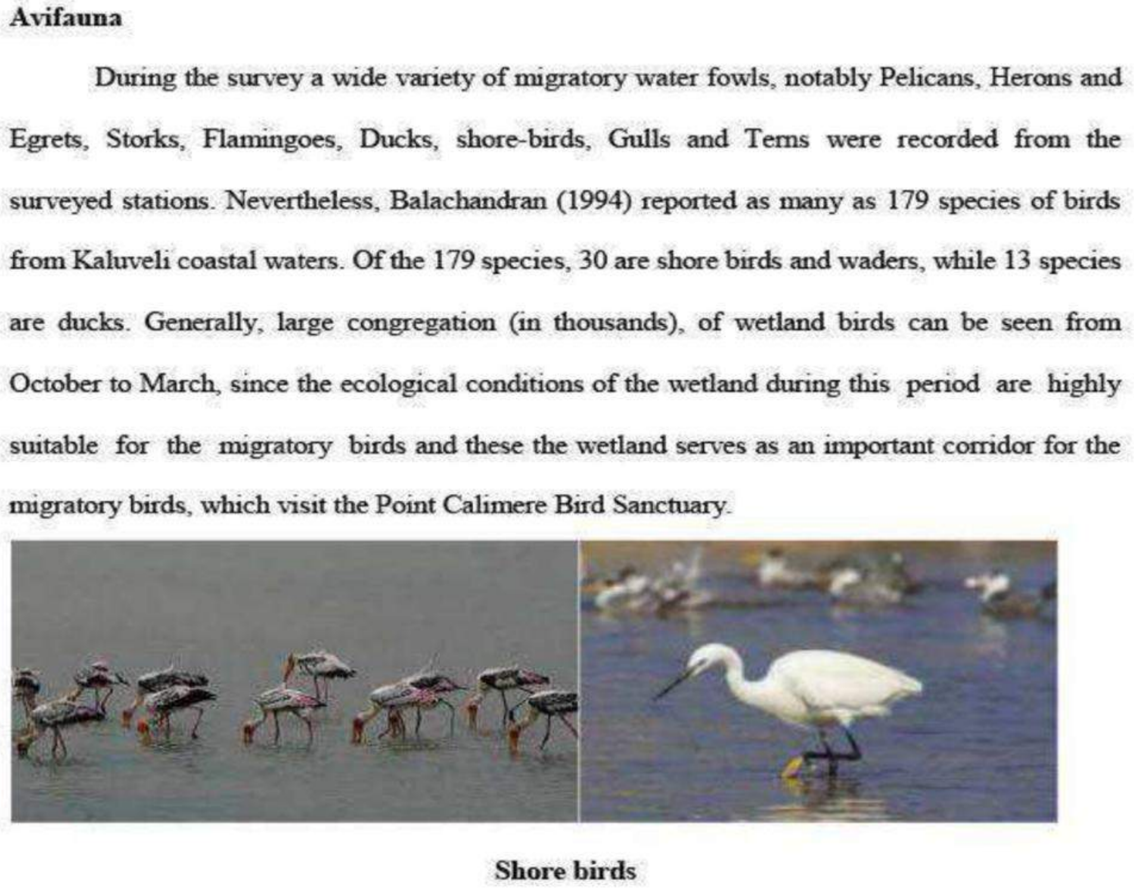
24. 68 species of migratory birds at Yedaiyanthittu estuary are listed under Convention on migratory species as well.

    1. Brown Shrike
    2. Black-headed Gull
    3. Rosy Starling
    4. Purple Heron
    5. Common Kestrel
    6. Green Sandpiper
    7. Brown-headed Gull
    8. Blyth's reed warbler
    9. Pintail Snipe
    10. Oriental Honey Buzzard
    11. Pallid Harrier
    12. Lesser Black backed Gull
    13. Pacific Golden Plover
    14. Common Sandpiper
    15. Pied Cuckoo
    16. Grey Tailed Tattler
    17. Barn Swallow
    18. Osprey
    19. Eurasian Marsh Harrier
    20. Spotted Redshank
    21. Eastern Yellow Wagtail
    22. Greylag Goose
    23. Northern Shoveller
    24. Eurasian Wigeon
    25. Northern Pintail

26. Green Winged Teal
27. Whimbrel
28. Curlew
29. Common Snipe
30. Wood Sandpiper
31. Common Redshank
32. Peregrine falcon
33. Garganey
34. Dunlin
35. Asian Brown Flycatcher
36. Blyth's Pipit
37. Lesser Sand plover
38. Greater sand plover
39. Kentish Plover
40. Caspian tern
41. Montagu's Harrier
42. Great Knot
43. Slender Billed Gull
44. White winged tern
45. Sandwich tern
46. Ruddy Shelduck
47. Greater Flamingo
48. Lesser Flamingo
49. Pied Avocet
50. Black tailed Godwit
51. Pallas Gull
52. Whiskered Tern
53. White Stork
54. Green Warbler
55. Black Bellied Plover
56. Little Ringed Plover
57. Ruff

58. Curlew Sandpiper
59. Temminck's Stint
60. Little Stint
61. Terek Sandpiper
62. Common Greenshank
63. Marsh Sandpiper
64. Little tern
65. Common tern
66. Western Yellow wagtail
67. Richard's Pipit
68. Paddyfield Pipit

25. It is submitted that Asian Waterbird Census (AWC) is an integral part of the global waterbird monitoring programme, the International Waterbird Census (IWC), coordinated by Wetlands International. The AWC was initiated in 1987 in the Indian subcontinent and since has grown rapidly to cover major region of Asia, from Afghanistan eastwards to Japan, Southeast Asia and Australasia. The census, thus covers the entire East Asian – Australasian Flyway and a large part of the Central Asian Flyway. Data from the annual census (January 2022) carried out by them was requested from its Tamilnadu State coordinator and is filed herewith as **Annexure A-78**.
26. Data on bird diversity was also requested from Birdcount India, a coalition of several organisations working on conservation and citizen science and the lists of species given by them for the Yedayanthittu estuary as well as the Alamparai fort area of the estuary are annexed as **Annexure A-79**.
27. It is submitted that the report of the Annamalai university submitted by the project proponent for the purpose of obtaining the impugned clearance, at page 73 of the report records that during the survey wide variety of migratory water fowls were observed at the survey stations. Extract below.



Avifauna

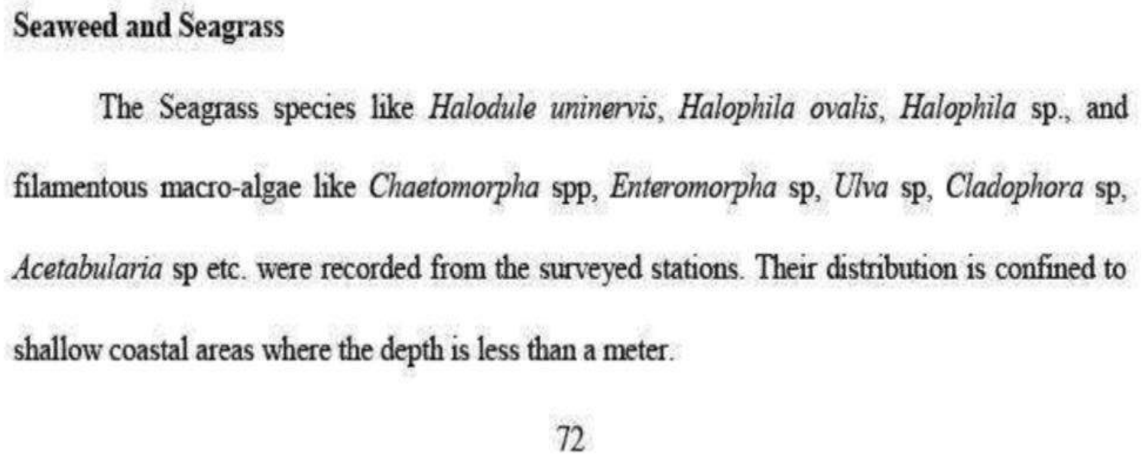
During the survey a wide variety of migratory water fowls, notably Pelicans, Herons and Egrets, Storks, Flamingoes, Ducks, shore-birds, Gulls and Terns were recorded from the surveyed stations. Nevertheless, Balachandran (1994) reported as many as 179 species of birds from Kaluveli coastal waters. Of the 179 species, 30 are shore birds and waders, while 13 species are ducks. Generally, large congregation (in thousands), of wetland birds can be seen from October to March, since the ecological conditions of the wetland during this period are highly suitable for the migratory birds and these the wetland serves as an important corridor for the migratory birds, which visit the Point Calimere Bird Sanctuary.

Shore birds

28. It is submitted that the importance of the Yedayanthittu estuary are for birdlife cannot be doubted and it is important to protect the estuary from any disturbance.

Seagrass beds

29. The estuary is covered in seagrass beds. The presence of seagrass beds in the estuary is recorded in several published literature, copies of which have been filed by the appellant in file B.
30. The report of the Annamalai university submitted by the project proponent to the SEIAA states at page 72 under the head "Other ecologically sensitive groups" also records the presence of seagrass at the survey stations. Extract below:



Seaweed and Seagrass

The Seagrass species like *Halodule uninervis*, *Halophila ovalis*, *Halophila* sp., and filamentous macro-algae like *Chaetomorpha* spp, *Enteromorpha* sp, *Ulva* sp, *Cladophora* sp, *Acetabularia* sp etc. were recorded from the surveyed stations. Their distribution is confined to shallow coastal areas where the depth is less than a meter.

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The location of the survey stations is at page 5 of the report, figure 1. The latitude and longitude provided in Table 1 is marked in the image provided in figure 1. It shows that the survey stations covered the area from the estuary mouth to the areas well past the harbour locations.

Fig. 1. Map showing the stations in Kaluveli Backwaters

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31. It is submitted that the appellant has pleaded in the appeal as well as the additional affidavit, rejoinder about the presence of seagrass beds in the estuary and that the sites ought to be protected as CRZ 1 A.
32. In order to further obviate any doubt about the presence of seagrass beds in the estuary, the Azhagankuppam harbour site was visited on 20.11.2022 and photos and videos of seagrass beds right at the site where the project proponent commenced dumping of sand and reclamation. The area around this site was also surveyed and seagrass beds were recorded. A video clipping is uploaded at this link : https://drive.google.com/file/d/1l-4jhPSwyKpkhn5poUV3V4E9OlinZyWg/view?usp=share_link . A photo of the seagrass beds adjacent to the Azhagankuppam site is pasted below for reference, photos and videos marked as **Annexure A 80**.

33. It is submitted that due to tides, videos of the other sites could not be made on that day but the presence of seagrass beds throughout the estuary, as recorded by the project proponent's own study is not a fact in dispute.
34. It is submitted that the proposed project is not permitted in this biodiverse, ecologically sensitive area and the impugned clearance has been obtained by supressing these crucial facts.

It is therefore prayed that this Hon'ble Tribunal may be pleased to record these submissions and allow the appeal as prayed and thus render justice.

M. Yuvay

Solemnly affirmed and signed his name

This the 29th day of November, 2022

At Chennai

BEFORE ME

Chethana.V
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ADVOCATE : CHENNAI

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Sea Turtles: Navigating with Magnetism

Young sea turtles use the Earth's magnetic field as a source of navigational information during their epic transoceanic migrations and while homing. A new study using satellite telemetry has now demonstrated for the first time that adult turtles also navigate using the Earth's magnetic field.

Kenneth J. Lohmann

The ability of sea turtles to navigate across vast expanses of seemingly featureless ocean has long fascinated biologists. As hatchlings, turtles that have never before been in the ocean establish unerring courses toward the open sea and then maintain them after swimming beyond sight of land. Young juvenile turtles follow complex migratory pathways that often lead across entire ocean basins and back. Later, as adults, turtles migrate from feeding grounds to specific mating and nesting areas, after which many return to individual feeding sites. The itinerant lifestyle of sea turtles is thus inextricably linked to an ability to navigate through the open sea.

Studies with young sea turtles have suggested that a significant part of a turtle's navigational skill involves magnetoreception — the ability to detect the Earth's magnetic field. The Earth's field is one of several cues that guide newly hatched turtles as they migrate offshore for the first time [1]. Farther out to sea, magnetic fields unique to different geographic areas function as navigational markers that elicit changes in swimming direction at crucial points in the migratory route where the turtles might otherwise stray off course [1,2]. Older juveniles learn the magnetic topography of the area where they live and develop 'magnetic maps' which permit navigation toward specific target areas [3]. The large size of adults, however, has made the navigation of mature turtles difficult to study, and whether nesting females use mechanisms similar to those of younger turtles has been difficult to determine. A study published recently in *Current Biology* [4] has confirmed for the first time that adult turtles, like hatchlings and juveniles, use the Earth's magnetic field to guide their movements.

Scientific interest in sea turtle navigation began about fifty years ago with the writings and musings of the American zoologist Archie Carr, who was among the first to study sea turtles [5,6]. Carr, who died in 1987, lived to see many secrets of sea turtle biology revealed, but one that remained mysterious was how turtles navigate. Frustrated by the lack of progress in this area, Carr wrote near the end of his life that the lack of a credible theory to account for sea turtle navigation was "an insult to science" [7].

The honor of science was eventually redeemed when newly hatched loggerhead sea turtles were found to have a well-developed ability to sense the Earth's magnetic field [1,8]. Initial studies revealed that hatchlings have a magnetic compass sense, which enables them to maintain headings relative to the Earth's field as they migrate offshore [8]. In addition to providing directional information, the Earth's field also provides a potential source of positional information. The intensity (strength) of the field and the inclination or tilt of the field lines both vary predictably across the globe, so that each region of the ocean typically has a unique magnetic field associated with it [9]. Subsequent studies showed that hatchlings can detect both magnetic field intensity [10] and magnetic inclination angle [11]. Moreover, when exposed to regional magnetic fields that exist in widely separated locations along their migratory route, turtles that had never before been in the ocean responded by swimming in directions that would, in each case, facilitate movement along the migratory pathway [2,9].

The discovery that young turtles can distinguish among the 'magnetic signatures' of different oceanic regions led to the hypothesis that older turtles can use this ability to locate specific feeding and nesting sites [10,12]. The idea was that juvenile and adult turtles, as they gain experience with their habitat, might learn the magnetic topography of the areas where they live and eventually develop 'magnetic maps' that can be used in navigating to particular locations. The existence of such magnetic positioning systems was soon confirmed experimentally in juvenile green turtles (*Chelonia mydas*, Figure 1) [3].

Although much progress has been made toward understanding how hatchling and juvenile turtles guide themselves, navigational mechanisms and strategies in some species change as animals mature [13]. Determining whether adult and juvenile turtles navigate in similar ways has proven difficult, however, because adults weigh more than 100 kg and are much too large for the controlled laboratory experiments that have proven so powerful in unraveling the navigational mechanisms of younger turtles.

All of which brings us to the new study by Luschi *et al.* [4]. In an ambitious experiment, the authors captured adult female green turtles that had come ashore on a remote island in the Indian Ocean to lay their eggs. The turtles were taken by boat to locations 100–120 km away and released into the ocean with satellite transmitters attached to their carapaces, so that the paths of the turtles could be monitored as they returned to the island. Three groups of turtles were tested. Turtles in one group had magnets attached to their heads just prior to release. The magnets produced fields much stronger than that of the Earth and were intended to prevent the turtles from using magnetism as they swam back to the nesting beach. A second group of turtles had magnets attached to them during transport but removed prior to release. The intent was to determine if strong fields applied during transport disrupted homing, either by preventing the turtles from sensing magnetic information as they were being carried to the release site or by producing a long-lasting effect on the magnetic receptors. Finally, a third group of turtles served as controls and had non-magnetic brass disks attached to their heads.

Luschi *et al.* [4] observed that the paths of turtles in all three groups were somewhat convoluted, but nearly all turtles eventually returned to the island. Oceanic currents presumably contributed to the indirect paths by constantly displacing the turtles from their attempted courses. When movements caused by currents were subtracted out, however, a clear pattern emerged: control turtles swam more directly toward the island than did either of the two groups of turtles that had been exposed to the magnets.

These results provide the first evidence that adult turtles use magnetic cues when homing to their nesting beaches. In addition, the study highlights the power of new techniques for analyzing the tracks of marine animals by resolving the paths into components attributable to ocean currents and those attributable to the animal itself [14]. Without this new approach, disentangling the effect of magnets from that of currents and other factors would have been difficult or impossible.

Although the magnets clearly affected homing, the exact part of the turtles' navigational system that was affected cannot be determined. One possibility is that the magnets disrupted a magnetic map sense like that known to exist in juvenile green turtles [3]. Alternatively or additionally, the effect might have been on a magnetic compass [8,15].

An unexpected finding was that magnets adversely affected navigation regardless of whether turtles were exposed to them while homing or only exposed during transport to the release site. Two interpretations of the latter finding are possible. One is that turtles can use their magnetic sense to derive some general information on the direction of displacement during transport. Alternatively, the application of strong magnets might produce an effect on magnetoreceptors that persists well beyond the time that the magnets are removed.

Figure 1. An adult green turtle on a tropical reef.
(Photo by Ursula Keuper-Bennett and Peter Bennett.)

The findings of the new study [4] may lead to a reconsideration of an earlier experiment in which magnets were attached to the heads of green turtles migrating to Brazil from Ascension Island, a small island in the south Atlantic [16]. Turtles leaving the island carrying magnets followed westward courses similar to those of control turtles, leading to the conclusion that magnets had no effect on open-sea navigation. An interesting caveat, however, is that satellite transmitters, which themselves produce magnetic fields and thus have the potential to disrupt magnetoreception, were placed on the heads of several control turtles. By contrast, all transmitters in the new study [4] were placed on the carapace and away from the head. If results of the earlier study are analyzed using only turtles with transmitters placed as in the new study, then a statistical difference exists between the latitudes at which the control and magnet groups reached the Brazilian coast [16]. Thus, with hindsight, the earlier study may also provide evidence consistent with the hypothesis that adult turtles exploit magnetic cues in navigation.

The results of both studies highlight an additional consideration: adult sea turtles, like all other animals studied to date, are likely to exploit multiple cues in navigation [7,9]. Although magnets impaired navigational performance in the new study and perhaps in the earlier one [16], the magnets did not, in either case, prevent the turtles from eventually reaching their goals. This implies that, when magnetic cues are disrupted, the turtles can fall back on other sources of information such as celestial compasses [17], wave direction [18], or olfactory cues [12], in much the same way that blind and blindfolded people are often able to use non-visual cues to guide themselves. Flexible use of multiple sources of information is likely in turtles, inasmuch as it occurs in homing pigeons [19] and in numerous other animals [20]. Regardless, however, the finding that adult sea turtles exploit magnetic cues in homing is a significant step forward in our understanding of these remarkable ocean navigators.

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Magnetic Orientation and Navigation in Marine Turtles, Lobsters, and Molluscs: Concepts and Conundrums[1]

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SYNOPSIS. **The Earth's magnetic field provides a pervasive source of directional information used by phylogenetically diverse marine animals. Behavioral experiments with sea turtles, spiny lobsters, and sea slugs have revealed that all have a magnetic compass sense, despite vast differences in the environment each inhabits and the spatial scale over which each moves. For two of these animals, the Earth's field also serves as a source of positional information. Hatchling loggerhead sea turtles from Florida responded to the magnetic fields found in three widely separated regions of the Atlantic Ocean by swimming in directions that would, in each case, facilitate movement along the migratory route. Thus, for young loggerheads, regional magnetic fields function as navigational markers and elicit changes in swimming direction at crucial geographic boundaries. Older turtles, as well as spiny lobsters, apparently acquire a "magnetic map" that enables them to use magnetic topography to determine their position relative to specific goals. Relatively little is known about the neural mechanisms that underlie magnetic orientation and navigation. A promising model system is the marine mollusc *Tritonia diomedea*, which possesses both a magnetic compass and a relatively simple nervous system. Six neurons in the brain of *T. diomedea* have been identified that respond to changes in magnetic fields. At least some of these appear to be ciliary motor neurons that generate or modulate the final behavioral output of the orientation circuitry. These findings represent an encouraging step toward a holistic understanding of the cells and circuitry that underlie magnetic orientation behavior in one model organism.**

INTRODUCTION

Perceived through human senses, the environment beneath the ocean's surface is often a murky, disorienting, and nearly featureless realm. Relative to air, visibility in the sea is greatly diminished by turbidity and the increased scattering of light. Visual landmarks are seldom present, and except under unusually clear conditions in shallow areas, celestial cues such as skylight polarization patterns, or the position of the sun and stars, cannot be perceived (Shashar *et al.*, 2004). To humans, the idea of holding a consistent heading under such conditions, let alone navigating with precision from one distant location to another, appears impossible without specialized equipment. Yet more than 70 percent of the Earth's surface is covered by ocean, and numerous marine animals move about from place to place during both day and night, often with remarkable precision and over long distances.

For anyone who has been diving in deep waters, it is tempting to conclude that there are fewer orientation cues available in the ocean than on land. However, although our own senses are not optimized to detect stimuli in the marine environment, it does not follow that animals that have evolved in the sea have the same limitations, or that environmental cues imperceptible to us are not readily detected by other species. Studies have revealed diverse and sometimes unexpected sensory abilities in marine animals. For example, hatchling sea turtles exploit ocean waves as an orientation cue and determine wave propagation direction by detecting sequences of accelerations (Lohmann and Lohmann, 1992; Lohmann *et al.*, 1995*b*). Sharks have an acute electric sense with which they can detect prey (Kalmijn, 1971), dolphins can detect characteristics of objects from a distance using ultrasonic echolocation (Harley *et al.*, 2003), and crabs perceive water depth by sensing water pressure (Fraser and Macdonald, 1994). Thus, the challenge of investigating orientation and navigation in the ocean is to attempt to perceive the marine environment not through our own sensory systems, but through the sensory modalities of the animals that live there.

Among a number of sensory cues potentially available in the ocean, the Earth's magnetic field is a particularly pervasive environmental feature (Skiles, 1985). In contrast with most other cues, the field is present night and day, is largely unaffected by weather and season, and exists in all parts of the ocean, from shallowest to deepest. Thus, it is perhaps not surprising that a number of ocean animals have evolved the ability to derive useful directional and/or positional information from the Earth's magnetic field (Wiltschko and Wiltschko, 1995*a*). Here we highlight recent findings about the magnetic orientation, navigation, and neuroethology of three well-studied but phylogenetically diverse marine animals: the loggerhead sea turtle *Caretta caretta*, the spiny lobster *Panulirus argus*, and the sea slug *Tritonia diomedea*. Despite vast differences in behavior, habitat, and the distances over which each travels, all of these animals depend at least partly on the Earth's magnetic field to guide their movements.

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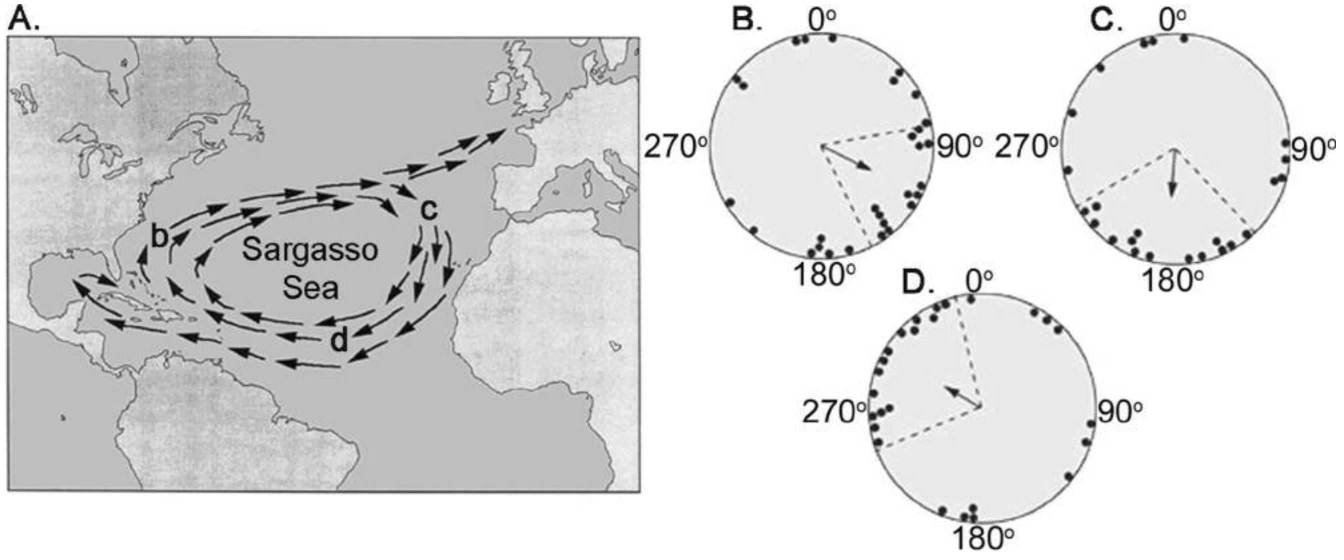

FIG. 1. A. The circum-Atlantic migration of young loggerhead turtles. Dark arrows on the map represent generalized currents of the North Atlantic Gyre. **B–D.** The orientation of hatchling turtles tested in magnetic fields from the three locations marked by letters on the map. Each dot within the orientation circles represents the average swimming direction of an individual hatchling. The arrow within each circle represents the mean heading of the group and the dashed lines represent the 95% confidence interval for the mean. Adapted from Lohmann *et al.* (2001).

DIRECTIONAL AND POSTIONAL INFORMATION IN THE EARTH'S MAGNETIC FIELD

At least two different types of information can potentially be derived from the Earth's magnetic field. Directional or compass information enables an animal to maintain a consistent heading in a particular direction such as north or east. Positional, or "map" information as it is sometimes called, assists an animal in assessing its geographic position, so that it can move in an appropriate direction along a migratory route or toward a specific destination such as a home area.

Magnetic compasses are known to exist in diverse animals (Wiltschko and Wiltschko, 1995*a*), and the list of marine animals known to possess such compasses now includes sharks (Kalmijn, 1978), spiny lobsters (Lohmann *et al.*, 1995*a*), sea turtles (Lohmann, 1991; Lohmann and Lohmann, 1993), isopods (Ugolini and Pezzani, 1995), and salmon (Quinn *et al.*, 1981). Much less is known about the use of magnetic positional or map information. During the past decade, however, evidence has accumulated that at least two marine animals, sea turtles and spiny lobsters, are able to derive positional information from the Earth's field.

Hatchling sea turtles and regional magnetic fields

Young loggerhead sea turtles (*Caretta caretta*) perform one of the longest and most spectacular marine migrations. Hatchlings along beaches of the east coast of Florida, U.S.A., emerge from nests, scramble across the beach to the sea, and migrate offshore to the Gulf Stream and North Atlantic gyre, the circular current system that encircles the Sargasso Sea (Fig. 1a; Carr, 1986; Lohmann and Lohmann, 2003; Musick and Limpus, 1997). Young loggerheads evidently remain for at least several years in the gyre system, during which time many cross to the eastern side of the Atlantic Ocean (Bolten *et al.*, 1993, 1998) before returning to the waters of the southeastern United States to take up residence in coastal feeding grounds (Carr, 1987; Sears *et al.*, 1995; Musick and Limpus, 1997).

The waters of the North Atlantic gyre provide a favorable, food-rich environment for young turtles, but straying beyond the latitudinal extremes of the gyre is often fatal. As the northern edge of the gyre approaches Portugal, the east-flowing current divides. The northern branch continues past Great Britain and the water temperature decreases rapidly. Loggerheads swept north in this current soon die from the cold (Carr, 1986, 1987; Hays and Marsh, 1997). Similarly, turtles that venture south of the gyre may be swept into the South Atlantic current system and transported far from their normal range. An ability to recognize the latitudinal extremes of the gyre, and to respond by orienting in an appropriate direction, might therefore have considerable adaptive value.

How might a young turtle with no previous experience in the ocean determine when it is approaching the northern and southern boundaries of the gyre? Several features of the Earth's magnetic field vary in a predictable way across the surface of the Earth and might, in principle, be used in position-finding (Skiles, 1985; Lohmann *et al.*, 1999). For example, at each location on the globe, the geomagnetic field lines intersect the Earth's surface at a specific angle of inclination. Because inclination angle varies with latitude, an animal able to distinguish between different field inclinations might be able to approximate its latitude (Skiles, 1985; Lohmann *et al.*, 1999). Experiments have revealed that hatchling loggerheads can indeed distinguish between different inclination angles (Lohmann and Lohmann, 1994). They can also distinguish between different field intensities corresponding to those that they encounter in different locations along their migratory route (Lohmann and Lohmann, 1996). Thus, hatchling loggerheads evidently emerge from their nests already capable of detecting two different magnetic field elements that vary across the Earth's surface and might provide positional information useful in guiding a long-distance migration.

To investigate further whether loggerheads can exploit positional information inherent in the Earth's magnetic field, hatchlings were subjected to fields replicating those found in three widely separated locations along the perimeter of the North Atlantic Gyre (Fig. 1a; Lohmann *et al.*, 2001). Turtles tested in a magnetic field replicating one that exists offshore near northern Florida swam east-southeast (Fig. 1b). Those exposed to a field like one found near the northeastern edge of the gyre swam approximately south (Fig. 1c). Turtles exposed to a field replicating one found near the southernmost part of the gyre swam west-northwest (Fig. 1d). Thus, the results demonstrate that loggerhead turtles can distinguish among magnetic fields that exist in widely separated oceanic regions.

In addition, the orientation behavior elicited by each of the three fields is consistent with the interpretation that these responses have functional significance in the migration. Near northern Florida, orientation toward the east-southeast would lead turtles away from the coast and farther into the Gulf Stream. The Gulf Stream veers eastward soon after passing Florida. When it does, turtles positioned safely away from the gyre perimeter are presumably less likely to stray into fatally cold water that lies to the north. In the northeastern region of the gyre, the Gulf Stream divides. Southward orientation in this area is likely to help turtles remain in the gyre and avoid the North Atlantic Drift, the north-flowing current that can carry turtles into the cold oceanic regions of Great Britain and Scandinavia (Carr, 1986, 1987; Hays and Marsh, 1997). Near the southernmost boundary of the gyre, orientation to the west-northwest is consistent with the migratory route of the turtles. Such orientation may prevent turtles from straying too far south and may also help them remain in favorable currents that facilitate movement back toward the North American coast, where most Florida loggerheads spend their late juvenile years (Musick and Limpus, 1997).

Thus, specific magnetic fields characteristic of widely separated oceanic regions elicit orientation responses that are likely to help turtles remain safely within the gyre and progress along the migratory route. The results imply that young loggerheads in effect exploit such fields as navigational markers.

Magnetic navigation of spiny lobsters

The finding that young sea turtles use regional magnetic fields as navigational markers demonstrates that animals can exploit positional information in the Earth's field during long-distance migrations. Recent results, however, suggest that magnetic field information can also be used in position-finding by marine animals that move over much smaller distances.

The Caribbean spiny lobster, *Panulirus argus*, lives on hard bottoms and coral reefs throughout the waters of the Caribbean and the southeastern United States. *P. argus* is a nocturnal forager and spends the day protected within crevices and holes (Herrnkind, 1980). During nightly foraging trips, lobsters often travel significant distances from the den, and at the end of the trip return either to the same den or another one nearby (Herrnkind and McLean, 1971; Herrnkind, 1980). Tag and recapture studies have shown that lobsters are capable of homing after being displaced several kilometers from a capture site (Creaser and Travis, 1950).

Spiny lobsters have a magnetic compass sense (Lohmann *et al.*, 1995*a*), but the apparent ability of these animals to return to specific areas after experimental displacements suggests that they also have an ability to determine their position relative to a geographic target area. Animals are said to be capable of "true navigation" if, after displacement to a location where they have never been, they can determine their position relative to a goal without relying on familiar surroundings, cues that emanate from the destination, or information collected during the outward journey (Phillips *et al.*, 1995; Phillips, 1996). Until recently, those few animals shown to possess true navigation were all vertebrates (Phillips *et al.*, 1995; Phillips, 1996). In contrast, those few invertebrates that had been carefully studied had been found to return to specific sites by using path integration, landmark recognition, compass orientation, and other mechanisms that cannot compensate for displacement into unfamiliar territory (Wehner, 1996; Wehner *et al.*, 1996; Wehner, 1998; Collett and Collett, 2000; Collett *et al.*, 2002; Graham and Collett, 2002).

Recent experiments, however, have clouded the tidy dichotomy that was once thought to exist between vertebrate and invertebrate navigational abilities. Spiny lobsters were found to orient reliably toward capture sites when displaced to unfamiliar sites over distances of 12–37 km, even when deprived of all known orientation cues *en route* (Fig. 2a; Boles and Lohmann, 2003). Thus, lobsters are the first invertebrates known to fulfill the criteria of true navigation.

Little is known about the sensory cues and mechanisms that underlie true navigation. To test the hypothesis that lobsters derive positional information from the Earth's magnetic field, lobsters were exposed to fields replicating those that exist at specific locations in their environment. Lobsters tested in a field that exists north of the capture site oriented southward, whereas those tested in a field like one that exists south of the capture site oriented northward (Fig. 2b; Boles and Lohmann, 2003). These results provide strong evidence that spiny lobsters possess a magnetic positioning system that is capable of helping them navigate to specific geographic areas. Thus, true navigation in lobsters, and perhaps in other animals, may be based at

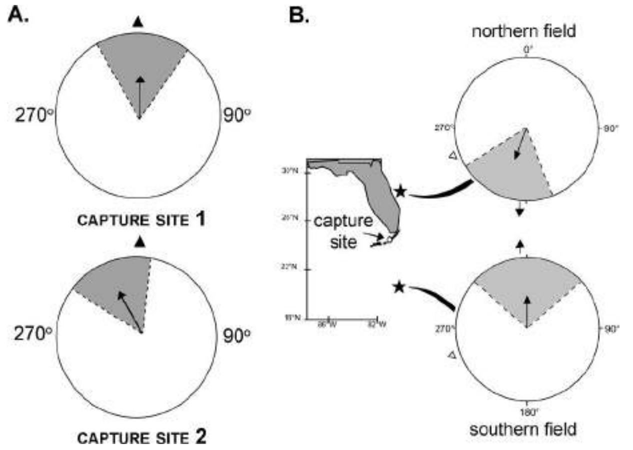

FIG. 2. A. The orientation of displaced spiny lobsters. Lobsters were captured from one of two sites (capture sites 1 and 2, indicated by CS1 and CS2) and their orientation behavior tested at one of two test sites (TS1 and TS2). Lobsters captured at CS1 were tested at TS1 only. Animals from CS1 were tested at TS1 and TS2. In each orientation diagram, each dot represents the mean heading of one lobster, the arrow represents the mean heading of the group and the dashed lines represent the 95% confidence interval for the mean angle. Dark arrows outside each circle indicate the heading from the test site to the capture site. In all cases, the lobsters oriented in a direction that coincided approximately with the bearing to the capture site. **B.** The orientation of lobsters tested in magnetic fields replicating the fields that exist at two distant locations (marked by stars on the map). Lobsters were captured at CS2 on Figure 2A, a location indicated by the tip of the arrow in Figure 2B, and then transported to TS 1 on Figure 2A (the small open circle on Fig. 2B). Lobsters tested in a field characteristic of a location north of the test site oriented approximately southward, whereas those exposed to a field that exists south of the test site oriented northward. The dark arrows on the outside of each orientation diagram indicate the direction in which lobsters would be expected to orient if homing from each fictive location. The open triangle outside each orientation diagram indicates the actual direction to the capture site from the test site. In each case, lobsters responded as if they had been displaced to the locations marked by the stars rather than by orienting in the direction that was actually towards the capture site. From Boles and Lohmann (2003).

least partly on a magnetic map sense. Indeed recent experiments with sea turtles have suggested that, as these animals mature, they become capable of true navigation (Avens *et al.*, 2003; Avens and Lohmann, 2004) and acquire a magnetic map similar to the one used by lobsters (Lohmann *et al.*, 2004).

NEURAL MECHANISMS OF MAGNETIC ORIENTATION IN *TRITONIA DIOMEDEA*

Despite our growing understanding of how animals use the Earth's magnetic field, little is known about the neural mechanisms that underlie magnetic orientation behavior (Deutschlander *et al.*, 1999; Lohmann and Johnsen, 2000). One factor that has complicated such analyses is that most magnetic orientation research has focused on vertebrate animals (Phillips, 1986; Beason and Semm, 1987; Lohmann, 1991; Wiltschko and Wiltschko, 1991, 1995*a*; Able and Able, 1995). Although several vertebrates have proven to be excellent subjects for behavioral experiments, the complexity of the vertebrate nervous system makes cellular-level investigations of neural circuitry challenging.

One animal model system that appears particularly promising for studies of the neural circuitry underlying magnetic orientation behavior is *Tritonia diomedea*, a nudibranch mollusc. Behavioral experiments have demonstrated that this animal orients to the Earth's magnetic field (Lohmann and Willows, 1987) in the lab, and field displacement experiments suggest that they use magnetic orientation to guide themselves between shallow and deeper areas (Willows, 1999). In addition, the central nervous system is relatively simple, consisting of approximately 7,000 neurons in six fused ganglia (Boyle *et al.*, 1983). Many of these neurons can be identified individually on the basis of color, size, and location within the central ganglia (Fig. 3a). Moreover, the nervous system is readily accessible for electrophysiological recordings both in semi-intact and isolated brain preparations (Willows *et al.*, 1973).

Intracellular electrophysiological recordings have demonstrated that three bilaterally symmetric pairs of identifiable neurons respond with altered electrical activity to changes in earth-strength magnetic fields (Lohmann *et al.*, 1991; Wang *et al.*, 2003, 2004). Two of these pairs, known as the Pd5 and Pd6 neurons, are excited by changes in direction of the ambient magnetic field (Lohmann *et al.*, 1997; Popescu and Willows, 1999; Wang *et al.*, 2003). The third pair, known as the Pd7 neurons, is inhibited by the same magnetic stimuli that excite Pd5 and Pd6 (Wang *et al.*, 2004). All six of the magnetically responsive cells (LPd5, RPd5, LPd6, RPd6, LPd7, and RPd7) presumably function in the neural circuitry underlying magnetic orientation behavior.

The function of the Pd5 and Pd6 neurons

Recent anatomical, electrophysiological, and immunochemical analyses have provided insight into the roles that some of these neurons are likely to play (Popescu and Willows, 1999; Wang *et al.*, 2003; Cain *et al.*, in review). Both Pd5 and Pd6 have neurites that branch extensively within the pedal ganglia, as well as peripheral branches (axons) of the primary neurite that enter ipsilateral pedal nerves (Lohmann *et al.*, 1991; Wang *et al.*, 2003). These peripheral axons appear to innervate parts of the ipsilateral foot epithelium (Fig. 3b; Wang *et al.*, 2003; Cain *et al.*, in review). Action potentials carried by these axons propagate from the CNS to the peripheral tissues (Wang *et al.*, 2003; Cain *et al.*, in review).

Pd5 and Pd6 are large cells (often >400 μm) and appear white under epi-illumination. Both of these features are characteristic of neurons that produce peptide neurotransmitters (Snow, 1982). A previously unknown group of three neuropeptides (TPeps) has been isolated from the cell bodies of Pd5 and Pd6 using HPLC (Fig. 4a; Lloyd *et al.*, 1996). These peptides localize to the foot tissues innervated by the nerves containing axons of Pd5 and/or Pd6 (Fig. 4b; Willows *et al.*, 1997). Moreover, these peptides are found in

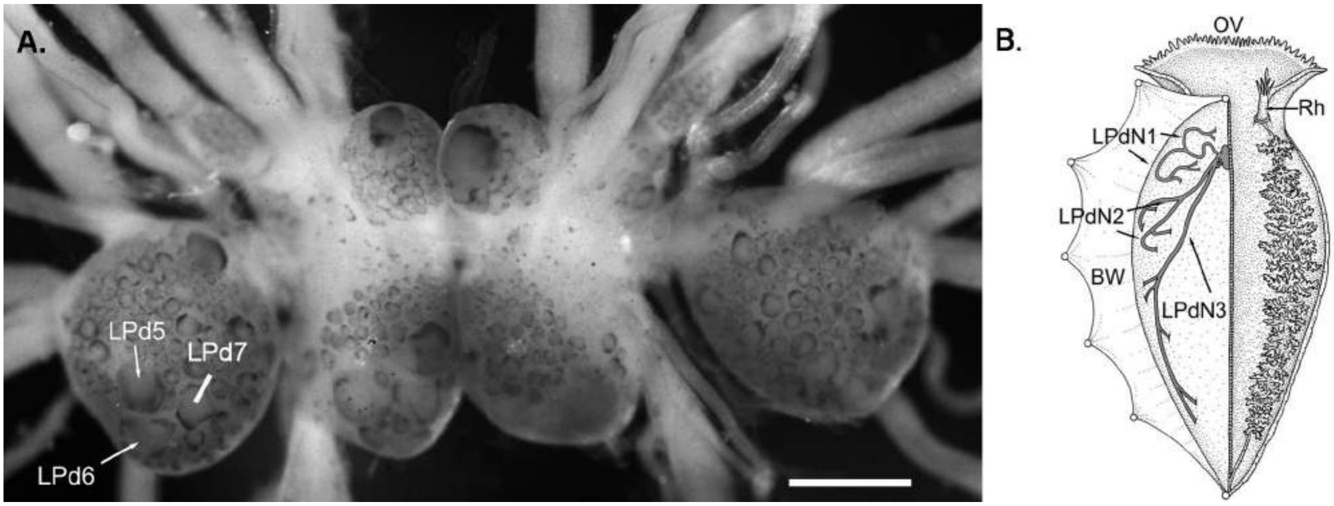

FIG. 3. A. The dorsal surface of the fused central ganglia of *T. diomedea*. Many large, individually identifiable neurons are visible on the surface of the brain. Three of these cells, LPd5, LPd6, and LPd7, are labeled. Scale bar = 1 mm. **B.** Schematic representation of the innervation patterns of the left pedal nerves 1, 2, and 3. LPdN1 and LPdN2 contain axons from LPd6. LPdN2 and LPdN3 contain axons from LPd5. All three nerves innervate the lateral body wall (BW) and the ciliated pedal epithelium. OV = oral veil, Rh = rhinophore.

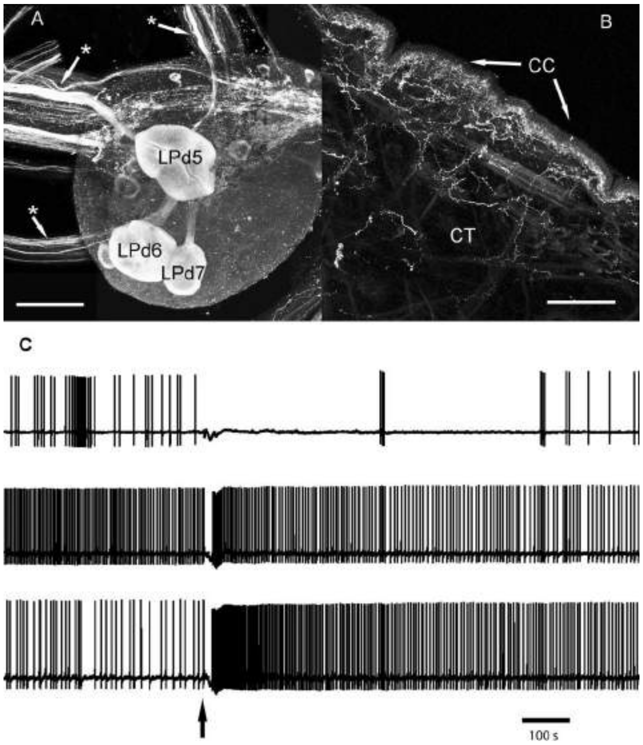

FIG. 4. A. TPep labeling of the CNS. The left pedal ganglion contains TPep-immunoreactive cell bodies and neurites. Immunoreactive axons are visible in the pedal nerves (*). Scale bar = 500 μm. **B.** TPep labeling of the foot. The ciliated foot epithelium (the tissue was sectioned transverse to the ciliated surface) contains TPep-immunoreactive processes throughout the connective tissue (CT) with dense labeling near the proximal surface of the ciliated cells (CC). Scale bar = 60 μm. **C.** Simultaneous recordings of the LPd5, LPd6, and LPd7 before, during, and after a swim bout. The black arrow indicates when the swim stimulus was applied to the animal.

dense-cored synaptic vesicles within neurites throughout the foot epithelium (Cain *et al.*, in review).

These findings indicate that the Pd5 and Pd6 are peptidergic, efferent neurons that are likely to function in generating or modulating the motor output of the magnetic orientation circuitry. Although the precise role of these cells has not been determined, three major types of effector cells in the periphery of *Tritonia* might plausibly be affected by TPeps released from the Pd5 and Pd6 cells: muscles, cilia, and mucus glands.

The muscles of the foot generate dorsal and ventral flexions during the escape swim and also help turn the animal during mucociliary crawling (Willows *et al.*, 1973). At the onset of swimming, both the Pd5 and the Pd6 neurons burst briefly, but then remain inactive for the duration of the swim (Fig. 4c). This pattern of activity implies that these cells are not directly involved in producing the dorsal and ventral flexions that comprise swimming. Similarly, neither intracellular stimulation of Pd5 or Pd6 nor direct application of TPeps to isolated foot patches results in discernable muscle contraction (Willows *et al.*, 1973; S.D.C., unpublished). Thus, at present, no evidence exists to suggest that the Pd5 or Pd6 neurons control muscle contraction.

The Pd5 and Pd6 cells do, however, appear to control or modulate the activity of ciliated cells (Popescu and Willows, 1999; Wang *et al.*, 2003; Cain *et al.*, in review). A dense field of cilia covers the pedal epithelium and propels the animal forward during muco-ciliary crawling, the primary mode of locomotion in this animal (Audesirk, 1978*a*, *b*). Application of TPeps to isolated foot patches or to isolated ciliated cells results in increased ciliary activity (Willows *et al.*, 1997). In addition, increases in electrical activity in the Pd5 cells are correlated with increases in muco-ciliary transport across the foot (Popescu and Willows, 1999). These finding suggest that the role of the Pd5 and Pd6 neurons is cilio-motor in nature.

The precise mechanism by which TPeps increase ciliary beating and ciliary transport rate is not known. Both processes are tightly coupled to mucus secretion, as mucus provides the viscous environment in which the cilia beat (Denny, 1981). Thus, whereas one possibility is that TPeps act directly on cilia to increase their beat frequency, another is that Pd5 and Pd6 influence crawling by altering the amount or types of mucus being secreted. The two possibilities are not mutually exclusive, and clear evidence for either has not yet been obtained.

The function of the Pd7 neurons

Despite some morphological similarities between the Pd7 neurons and the Pd5/Pd6 (*i.e.,* large size, whitish cell body, location in the pedal ganglia), the function of the Pd7 cells may differ from that of the other two pairs of magnetically responsive neurons (Figs. 3a and 4a; Wang *et al.*, 2004). Unlike the Pd5 and Pd6 neurons, the Pd7 cells are inhibited by rotations of the ambient magnetic field. The neurites of Pd7 extend to the cerebral ganglia and one large axon projects from the brain to the anterior tissues through cerebral nerve 3. Action potentials in the Pd7 neuron propagate from the central ganglia toward the periphery (Wang *et al.*, 2004). The target cells to which the Pd7 project have not yet been determined, but the nerves that contain Pd7 axons innervate areas near the mouth, oral veil, and rhinophores (Willows *et al.*, 1973).

Although the function of the Pd7 neurons is not known, one possibility is that these cells control or modulate some subtle aspect of turning or locomotion that occurs during magnetic orientation behavior. For example, the cells might play a role in controlling movements of the oral veil, rhinophores, or other anterior structures as the animal alters or maintains its heading.

An alternative possibility is that the Pd7 neurons function in suppressing behavior that might otherwise impede orientation or locomotion. It is noteworthy that, during the period immediately after an escape swim when *Tritonia* normally crawls vigorously (Audesirk and Audesirk, 1980), spiking in the Pd7 neurons is greatly reduced relative to pre-swim levels (Fig. 4c). In contrast, spiking in the Pd5 and Pd6 increases after an escape swim (Fig. 4c). An interesting speculation is that the Pd7 neurons might modulate cilia that line the esophagus and are involved in feeding, and that feeding is suppressed during magnetic orientation and after swimming. At present, however, no evidence exists to support or refute this scenario, and additional research will be needed to determine the function of the Pd7 cells.

In summary, a reasonable working hypothesis is that the Pd5 and Pd6 neurons are involved in controlling or modulating the motor output of the magnetic orientation circuitry. These neurons appear likely to influence the ciliary beat rate of the foot epithelium and may therefore play a role in helping the animal align itself with a particular magnetic direction, crawl along a particular heading, or both. The function of the Pd7 neurons is less clear, but a possible role in suppressing behavior incompatible with orientation or locomotion is presently suspected.

As the search for neurons involved in the magnetic orientation circuitry expands, some logical targets for future investigation are neurons presynaptic to the Pd5, Pd6, and Pd7. Among these are neurons that have previously been identified as part of the *Tritonia* swim central pattern generator (DSIs, VSIs, C2), which also appear to mediate post-swim crawling by influencing Pd5 and Pd6 (Popescu and Frost, 2002). Therefore, this set of neurons might represent a multifunctional swim/crawl network as proposed by Popescu and Frost (2002). The relative simplicity of the *Tritonia* nervous system provides reason to hope that careful, sustained investigation will eventually lead to a thorough understanding of the neural circuitry underlying magnetic orientation behavior in this neuroethological model animal.

NEUROETHOLOGY OF MAGNETIC ORIENTATION BEHAVIOR

Aside from the neurobiological work done in *Tritonia* relatively few studies have attempted to investigate the neural mechanisms that underlie magnetic orientation behavior. Some initial progress has been reported with electrophysiological approaches in birds (Semm and Demaine, 1986; Beason and Semm, 1987; Semm and Beason, 1990; Semm and Schneider, 1991), mole rats (Marthold *et al.,* 1997; Nemec *et al.*, 2001), and fish (Walker *et al.*, 1997). Nevertheless, much of what is known or assumed about the neural basis of magnetic orientation behavior has been inferred from behavioral experiments. The reliance on behavioral studies is understandable, given that primary magnetoreceptors have not yet been identified with certainty in any animal. Yet behavioral experiments can ultimately provide only limited insight into the myriad complex and often non-intuitive ways in which nervous systems detect sensory information, process it, and integrate it with other neural input to generate motor responses.

In parallel with behavioral experiments, several theoretical models of magnetoreception have been proposed to explain how animals might detect magnetic fields (Kalmijn, 1978; Kirschvink and Gould, 1981; Schulten and Windemuth, 1986; Ritz *et al.*, 2000, 2002). These models have been invaluable in guiding investigations of possible transduction mechanisms. At the same time, receptor mechanisms (whatever they may be) represent only one small part of the neural processes that comprise magnetoreception. Surprisingly, none of the models proposed so far have considered the crucial role that higher-order processing typically plays in circuits involving sensory information. In all other sensory systems, signal processing results in significant alterations in the neural information that is passed along at each step of a circuit (Kandel *et al.*, 1997). As a result, the neural activity that actually reaches neurons responsible for initiating or modulating behavior often bears little resemblance to the activity of receptor cells. Moreover, higher-order processing often acts as a filter that discards aspects of the sensory world that are not directly relevant to the task which must be performed.

Whereas higher-order mechanisms in vision and hearing have been studied extensively (Kandel *et al.*, 1997), such mechanisms have received little attention in the context of magnetoreception. Nevertheless, the clear lesson to be drawn from other sensory systems is that filtering and feature extraction are often at least as important as receptor responses in shaping the motor outputs that comprise behavior. Thus, identifying areas of the brain that process magnetic field information, determining the role of centers known to be "responsive" to field stimuli, and studying how motor responses are generated are all as important as identifying receptor cells. Only by expanding studies to include higher order processing can the neural mechanisms that underlie magnetoreception and magnetic orientation behavior be fully understood.

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Research News

Geomagnetic Landmarks Give Turtles Sense of Where They Are, Where to Go

How sea turtles navigate across vast expanses of featureless ocean to reach feeding and breeding sites has long been a mystery. Now, clues are surfacing to indicate turtles rely partly upon invisible landmarks created by the Earth's magnetic field.

July 30, 2004

How turtles navigate across vast expanses of seemingly featureless ocean to reach distant feeding and breeding sites has long been a mystery of the seas. Now, clues are surfacing to indicate sea turtles rely at least partly upon an invisible map of landmarks created by the Earth's magnetic field.

While technological global positioning systems process signals from satellites, the turtles' system draws upon variations in Earth's magnetic field, which give each geographic area a distinctive magnetic pattern. New research shows that sea turtles can apparently detect and distinguish among the magnetic fields in different locations, enabling them to compile a "magnetic map" for navigating to specific feeding and nesting areas.

The findings, reported in the April 29, 2004, issue of *Nature*, may enhance conservation efforts to protect endangered turtle species and suggest new methods of human navigation, according to the researchers. The study was led by University of North Carolina marine biologists Kenneth and Catherine Lohmann along the Atlantic coast of Florida and was supported by a $413,000 grant from the National Science Foundation.

As newly hatched turtles leave the beach and enter the sea for the first time, they use the earth's magnetic field and the direction of ocean waves as crude compasses to guide them offshore into deeper waters favorable for growth and development. The young turtles, however, use the field primarily as a source of directional information for maintaining a heading.

"Older turtles," Lohmann said, "learn to use magnetic-field information in a far more sophisticated way, as a kind of map that can be used to pinpoint specific areas. It's as if turtles have their own GPS based on magnetism."

According to Michael Greenfield, a director with NSF's Animal Behavior Program, "Older turtles would need a more accurate map, as they must do more than simply orient seaward and enter a current. They have to find a specific beach on which to land, mate, and -- for females -- lay eggs. This all demands considerable accuracy in orientation."

The Lohmanns' research suggests that mature turtles can distinguish very minor differences in the magnetic field found in different locations, and then make the appropriate course corrections while still far out to sea, he said.

"The discrimination of magnetic field characteristics that would be required to do this is truly mind-boggling," said Greenfield, "but this work indicates that the turtles can do it."

To determine if turtles, at several years old, possess a magnetic map detailed enough to direct them toward a specific site, the Lohmanns and their colleagues built a special cube-shaped magnetic coil system approximately the size of a two-story house to surround a circular plastic pool. The coil could reproduce the magnetic fields that exist in different locations along the southeastern U.S. coast. Green sea turtles (*Chelonia mydas*) captured from a nearby coastal feeding ground were placed in the pool and observed as they adjusted their swimming direction upon exposure to various magnetic fields.

When the turtles were exposed to a magnetic field characteristic of a coastal area about 209 miles north of their homes, they invariably swam southward. In contrast, turtles exposed to a field that exists an equivalent distance to the south responded by swimming northward.

The findings showed that turtles can distinguish between the magnetic fields that characterize different geographic locations. Moreover, turtles responded to the magnetic fields by orienting themselves in a direction that would have led them towards the capture site had they been where each magnetic field naturally occurs.

It is not yet understood how turtles detect magnetism, nor exactly how they derive a navigational map from it. Maybe they combine magnetic cues with coastline features. Maybe they derive location coordinates from a set of two magnetic factors, such as intensity and inclination. Maybe they sense slight variations in the rate of change in the magnetic field, much like a hiker reads tightly spaced lines on a topographic map to discern a distinctive canyon.

"No one knows for sure how any animal senses magnetic fields," Kenneth Lohmann said. "Crystals of magnetite (the same mineral used in compass needles) have been detected in turtle heads, but there is not yet clear evidence for a link between the magnetite and the nervous system."

As these are endangered species, he said, invasive methods of physiological study are not appropriate.

Understanding how magnetic fields influence turtle travel could help biologists assess how migratory marine life can be affected by human activities that create anomalies in the ocean's magnetic fields. Such anomalies can be introduced by underwater electrical cables, oil rigs, sea walls with iron framing and coastal condominiums, Lohmann said. Even the metal-wire cages that protect sea turtle nests from raccoons alter a magnetic field somewhat. "Whether that matters, nobody can say," he said.

Lohmann speculates that hatchling turtles may imprint on the magnetic field of their home beach and, if so, such a phenomenon could be the basis of strategies for species preservation. "It has proven difficult to re-establish sea turtles in areas where they've been eradicated," he said. "If we could somehow get turtles to consider such areas home (perhaps by exposing emerging hatchlings to the magnetic fields of locations where former colonies nested), it may be possible to re-establish some populations."

-- Sean Kearns

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The turtles were placed into cloth harnesses and tethered to limit their travel.
Credit: Ken Lohmann, University of North Carolina, Chapel Hill

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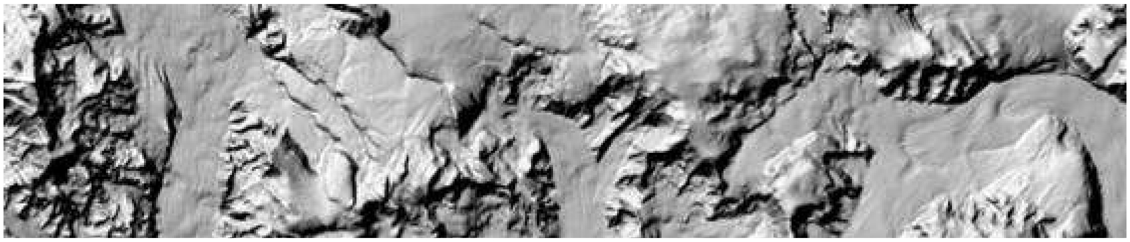

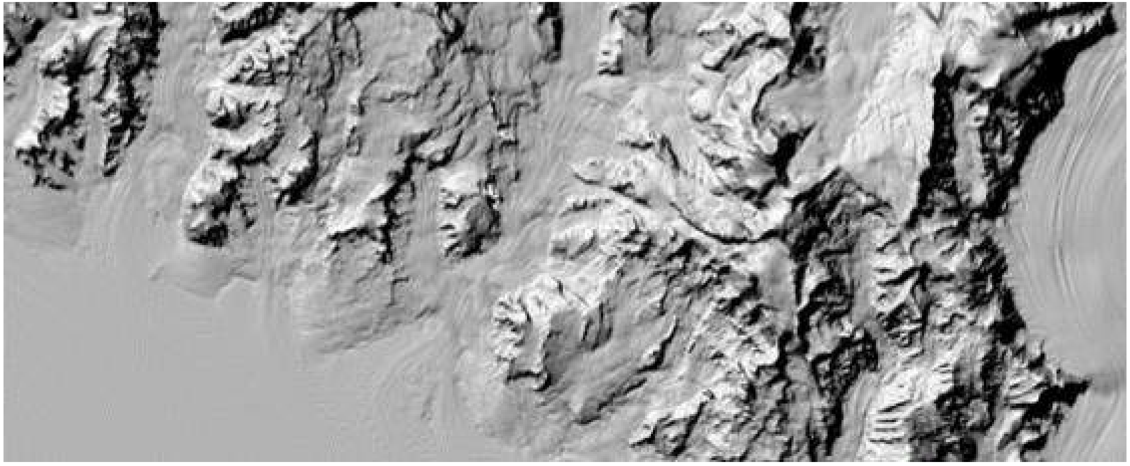

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Effects of Beach Nourishment on Sea Turtles: Review and Research Initiatives

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Abstract

Beach nourishment is an engineering solution to erosion of beaches. As in any restoration project, the goals of beach nourishment are the restoration of habitat to promote survival of plants and animals and to maintain aesthetically pleasing sites for humans. Unfortunately, beach nourishment sometimes alters parameters of the natural beach, decreasing the reproductive success of sea turtles. Engineers have recognized this problem and are working to improve nourishment practices. Biologists must specify problems incurred by sea turtles as a result of beach nourishment so that they may be addressed. A review of the literature on sea turtles and beach nourishment found certain problems repeatedly identified. For nesting females, characteristics induced by nourishment can cause (1) beach compaction, which can decrease nesting success, alter nest-chamber geometry, and alter nest concealment, and (2) escarpments, which can block turtles from reaching nesting areas. For eggs and hatchlings, nourishment can decrease survivorship and affect development by altering beach characteristics such as sand compaction, gaseous environment, hydric environment, contaminant levels, nutrient availability, and thermal environment. Also, nests can be covered with excess sand if nourishment is implemented in areas with incubating eggs. The extent and implication of each problem are discussed, and future research initiatives are proposed.

Beach nourishment is the placement of beach fill as an engineering solution to beach erosion. Virtually all habitats have been altered by human influences, and beaches are included in the list of habitats requiring restoration. In this sense, beach nourishment should be viewed as having great potential to help sea turtle populations by providing nesting habitat that would otherwise be unavailable. Nourishment should not be viewed as a practice necessarily harmful to sea turtles. Although nourishment techniques may pose problems for sea turtles, properly enacted management techniques can alleviate many of these problems (Nelson & Dickerson 1988a). Because halting beach nourishment activities is not a viable option, modifications of current nourishment methods are required. Engineers have begun to consider sea turtles in the design criteria for nourishment projects (Montague 1993), but a thorough review of how the changes induced by nourishment can affect sea turtles is lacking. We review beach nourishment as it relates to life-history stages of sea turtles and offer suggestions for future research initiatives. Many of the studies cited in this review are derived from "gray" literature, and therefore their conclusions must be considered with caution. Nevertheless, a synthesis of current information is necessary. We hope that this review will stimulate collaborations between engineers and biologists. Such endeavors can result in a solution satisfying both the biological requirements of sea turtles and the engineering and economic requirements of humans.

Effects of Beach Nourishment on Nesting Females

Female turtles require certain beach characteristics to nest successfully, and beach nourishment has the potential to change some of these physical characteristics. Adult female turtles survey a nesting beach from the water before emerging to nest (Carr & Ogren 1960; Hendrickson 1982). This behavior apparently is one method by which a turtle assesses the quality of a potential nesting beach. Other methods that sea turtles use to assess beaches are unknown, but Mortimer (1982) noted that sand-grain size is not an important factor in a turtle's choice of nesting beach. Obviously, placement of sand on eroded beaches increases the habitat available for nesting, and the total number of nests and turtle crawls often increase after nourishment (Lund 1986; Witham 1990; Flynn 1992). Therefore, the amount of habitat available to a turtle after beach nourishment is not the problem; it is the quality of that habitat that is often questionable. Unless drastic alterations in beach profile result, it is doubtful that beach nourishment affects beach selection by a nesting female.

After emerging from the sea, a female turtle must crawl up the beach and select a nesting location. Nest placement

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has important consequences for reproductive success: placement can affect a female's reproductive success and fitness through her own survival, the survival of her offspring, and the sex of her offspring (Bjorndal & Bolten 1992). How are nest sites selected, and how can characteristics induced by nourishment alter such selection? Stoneburner and Richardson (1981) hypothesized that nest-site selection by *Caretta caretta* (loggerhead turtle) may be related to thermal gradients in beach sand, but adequate support for this hypothesis has not been generated. No consistent pattern of nest distribution was found in a study of *Chelonia mydas* (green turtle) at Tortuguero, Costa Rica (Bjorndal & Bolten 1992), or in a study of *Dermochelys coriacea* (leatherback turtle) at Saint Croix, U.S. Virgin Islands (Eckert 1987). Because nest-site selection by female turtles is poorly understood, it is difficult to predict any effects that changes induced by nourishment could have on selection of a nest site.

Important physical characteristics of beaches include sand-grain size, grain shape, silt-clay content, sand color, beach compaction, moisture content, mineral content, substrate water potential, and porosity/gas diffusion (Nelson 1992*a*). Beach profile may also be an important characteristic. Alterations of these physical characteristics can make beaches unsuitable for sea turtle activity. Therefore, perhaps the most critical step in an environmentally sound nourishment project is choice of quality fill material (Yanno & Sultzman 1992). Optimal fill material is sand that closely matches the physical qualities of the natural beach (Coastal Engineering Research Center 1984). Replacement sand is obtained from three main sources: inlets, channels, or offshore borrow pits. Offshore borrow pits provide sediments more similar to natural beach sediments, but sources of such sand are becoming scarce and alternative sources are being explored. Sediment types vary in amount of carbonate sand, quartz sand, shell, coral, clay, and silt content. Sediments with high clay or silt content (perhaps greater than 5–10%) must be avoided because beach compaction or concretion can result from the drying of newly laid sediments (Dean 1988).

Increased compaction as a result of nourishment may decrease nesting success by impeding or preventing nest excavation by a female sea turtle (Mann 1977). Nourishment can cause compact beaches by (1) increasing the silt/clay percentage of a beach (W. G. Nelson 1985), (2) changing grain size or shape (W. G. Nelson 1985; Nelson 1985; Nelson & Mayes 1986), (3) altering natural grain layering (Nelson 1985; Nelson & Mayes 1986), and/or (4) use of construction equipment on the beach (W. G. Nelson 1985; Nelson & Mayes 1986). Compaction of a beach has been quantified by two methods: (1) by determining the bulk density of a core sample, which is the ratio of dry soil mass to its total volume (mass of dry sand/total volume of dry sand), and (2) by measuring sediment shear resistance or ability to penetrate the sand. Bulk density is measured from a standard volume core sample extracted from the beach, whereas shear resistance is measured with a cone penetrometer which is thrust into the sand to determine resistance in cone index units (CIUs; same as cone penetrometer index units, CPUs; often converted to pounds per square inch, PSI). Shear resistance would seem to be the better of the two methods for predicting a turtle's ability to dig through the sand, and thus the better measurement. Shear resistance is used to estimate compaction, although factors other than compaction can cause increased shear resistance (Spangler & Handy 1982). For simplicity we will assume that measurements of increased shear resistance indicate compaction, but this may not always be true.

The U.S. Army Corps of Engineers offers guidelines for measurement techniques and analysis of beach compaction using a cone penetrometer (Nelson 1992*b*). The guidelines suggest beach tilling on beaches where the 6" or 12" cone index value exceeds an average of 750 CIU. Beaches with a 12" cone index value between 650 and 750 CIU require further evaluation to determine the need for tilling. These criteria led engineers and management agencies to assume that an optimal compaction for sea turtle nesting exists (Applied Technology and Management, Inc. 1991). The important consideration of compaction measurement is not some optimal value, however, but the natural variance in compaction values and the nesting success on beaches with such values. Reasons for variations in beach compaction are important to uncover.

The designation of 750 CIU as the maximum acceptable compaction value was based on surveys of Atlantic beaches in Florida (Nelson 1987). It has been suggested that Florida's Gulf Coast beaches are naturally more compacted, and that the 750 maximum CIU designation is not applicable to Gulf beaches (Hodgin et al. 1993; Truit & Foote 1993). A study on a Gulf beach of Marco Island, Florida, consistently found compaction levels exceeding 750 CIU on both natural and nourished portions of beach, and turtle nesting occurred on both beach types (Coastal Engineering Consultants, Inc. 1992). Density of turtle nesting is much lower on Florida's Gulf Coast beaches than on the Atlantic Coast beaches, suggesting that sand compaction acts as a natural limitation to sea turtle nesting activities.

Compaction is a problem associated with beach nourishment but does not occur with every nourishment project. Rimkus (1992) inferred that of six natural and six nourished beaches studied, natural beaches were more compacted based on bulk density measurements. Nevertheless, shear resistance is often higher on nourished beaches than on natural beaches in the same area (Nelson & Dickerson 1988*b*, 1989; Moulding & Nelson 1988; Parkinson & Ryder 1992). Apparently due to increased compaction, nesting success [(female nesting emergences/female total emergences) × 100] commonly decreases in the first nesting season after nourishment but returns to normal values in subsequent years (Raymond 1984; Burney & Mattison 1992, 1993; Lebuff & Haverfield 1992; Burney & Margolis 1993). Foote and Sprinkel (1994) noted a negative relationship between compaction and nesting success, but the correlation was not significant. Compacted sand caused by beach nourishment can last from one to seven years, depending on weather and wave conditions (Moulding & Nelson 1988); quality of sediment also determines duration of compaction.

Nelson et al. (1987) prescribe beach tilling to soften compacted sediments after nourishment activity. Tilling appears to reduce compaction (Nelson et al. 1987; Nelson & Dickerson 1988c), but the effect of tilling on sea turtle nesting success and hatching success is not clear. A study of the effectiveness of beach tilling in increasing female nesting success showed no significant difference in mean nesting success on tilled and untilled nourished beaches (data analyzed from Dickerson & Moss 1990). We found no studies addressing the effect of tilling on hatchling emergence. The Recovery Plan for the U.S. Population of Loggerhead Turtles (National Marine Fisheries Services and U.S. Fish and Wildlife Service 1991) recommends that the effectiveness of tilling on softening beaches be fully evaluated to determine the persistence of beach softening, frequency of tilling required, and the best mechanical method for softening. Although this recommendation is still applicable and studies in this area are needed, emphasis should not be placed solely on correcting compaction once it has occurred. Efforts would be best spent studying methods to prevent compaction during beach nourishment (Nelson & Dickerson 1988c).

Other physical characteristics of the beach can be modified as a result of nourishment. Steep escarpments often form as the nourished beach adjusts to its new profile. These escarpments can restrict turtle access to the nesting beach (Davis et al. 1993) and usually result in increased non-nesting emergences (Gahagan and Bryant Associates 1990; Steinitz 1990, 1991; Bagley et al. 1994; Ehrhart et al. 1994). Bagley et al. (1994) and Ehrhart et al. (1994) note increased nesting activity on beaches adjacent to those with escarpments, suggesting that deterred animals were able to nest successfully on nearby beaches. Scarps normally dissipate with time as the beach assumes a natural profile (Steinitz 1991), but they can be smoothed with construction equipment as they form to alleviate problems associated with sea turtles (Nelson 1991).

Proper nest-chamber geometry is fundamental to the success of a nest. In a survey of three nourished and three natural beaches, Fletemeyer (1983) noted that turtles nesting on nourished beaches constructed shallower nests. A recent study of loggerhead nests showed no significant difference in mean nest depth between nests on a nourished and a natural beach, but it did find a significant difference in the variance of the nest depths (Carthy 1994). More research is needed to evaluate the effects of nourishment on nest-chamber geometry and egg incubation.

After depositing her eggs, a female turtle attempts to camouflage her nest to conceal it from predators. Changes imposed by nourishment could inhibit nest concealment and make the nest more prone to predation. Nelson and Dickerson (1987) found no differences in the time spent camouflaging nests on nourished versus natural beaches. Ryder (1991), however, observed that many nesting females on a nourished beach failed to cover the nest with a disguising mound of sand, whereas females on a control beach had no such problem. Raccoon predation was much higher (9%) on the nourished beach than on the natural beach (0.5%). Ryder attributed increased predation on the nourished beach to a higher raccoon population associated with an adjacent recreational area. A thorough study that avoids pseudoreplication is necessary to determine criteria that affect nest predation.

Effects of Beach Nourishment on Eggs and Hatchlings

Physical and chemical changes induced by nourishment could have detrimental effects on the survival and future reproductive contribution of developing embryos and emerging hatchlings. Three main abiotic factors that influence the survival of reptilian eggs are temperature, gas diffusion, and available moisture (Packard & Packard 1988). These factors have a tremendous impact on egg survival due to the semipermeable nature of the reptilian egg. During the development of a sea turtle embryo, a mesh of blood vessels, emanating from the embryo's umbilicus, coats the inside of the shell. This vascularization transports gases—(most important, oxygen)—and nutrients that diffuse across the shell to the embryo, permitting normal development and growth.

The availability of gases to the embryo is a result of the physical properties surrounding the nest. Geological and physical factors can alter physical properties of a beach and, thus, the characteristics of gas movement in beaches (Ackerman 1980). As an example, consider the way an embryo obtains oxygen. Diffusion is the primary mechanism of oxygen exchange between the developing embryo and the air (Prange & Ackerman 1974). Therefore, any alteration in the physical characteristics driving oxygen diffusion could inhibit the embryo from obtaining oxygen. Indeed, Ackerman (1981) found that embryonic growth slowed and mortality increased in environments in which gas exchange was reduced below levels occurring on "natural" beaches. Because the oxygen consumption of turtle embryos increases during the latter half of embryonic development (Maloney et al. 1990), embryos in these stages may be particularly sensitive to altered beach characteristics.

The hydric environment surrounding buried eggs is important to the hydric, thermal, respiratory, and osmotic properties that affect egg incubation (Ackerman 1991). The hydric environment of a beach depends on the type and size of sand grains and the sorting of these grains on the beach; all three factors can be altered on nourished beaches. Nourished beaches often retain significantly more water than do natural beaches (Ackerman et al. 1991, 1992; Broadwell 1991; Rimkus 1992; Parkinson et al. 1994), probably due to alterations in sediment type and size. This increased water content can drown eggs (Horikoshi 1992) or increase heat capacity, which can buffer temperature changes (Ackerman et al. 1985). McGehee (1990) found that 25% water by weight was optimal for loggerhead eggs. Water content is not an accurate measure of water availability to the egg, however; water potential is the more appropriate measure. Water potential is a measure of the energy required to overcome forces of adhesion, cohesion, and ionic attraction that bind molecules of water to soil particles. Water potential and absolute moisture content are related in a nonlinear fashion, but it is water potential that actually dictates the diffusion of water across the eggshell. Each sediment type has a different water potential and, thus, the results of McGehee (1990) cannot be extrapolated to other sediments. The water potential of beach sediments should be measured before and after nourishment to assure that alterations in available moisture do not occur. In a survey of 15 beaches in Florida, Ackerman et al. (1992) noted that although nourished beaches have significantly greater water content than natural beaches, there is little difference in water potential between nourished and natural beaches.

Most minerals essential for embryonic growth are in the egg prior to oviposition (Palmer & Guillette 1991). It is possible, however, that externally derived minerals are required during embryonic development; research in such areas is lacking. If nourishment sand differs in amounts of these critical minerals, altered development may occur.

Environmental contaminants have the potential to alter the hatching success of sea turtles and the health and sex of hatchlings. These contaminants can be packaged maternally in egg yolk or albumen prior to eggshell formation or can be passed across the eggshell during egg incubation. Of interest to this study are the sediment-borne contaminants. Canals, harbors, channels, and inlets are sinks for contaminants, and if material from such sources is used in nourishment projects, adverse effects on sea turtle survival could result. Contaminants are linked to decreased survivorship in the eggs of *Chelydra serpentina* (snapping turtle) (Bishop et al. 1991) and *Alligator mississippiensis* (American alligator) (Woodward et al. 1993). Some contaminants such as polychlorinated biphenyls (PCBs) and DDT metabolites (DDD, DDE, and DDT) also have estrogenic effects that can cause abnormal gonadal development in reptiles (Bull et al. 1988). Many of these hormonal-modifying contaminants can move across the eggshell (Bergeron et al. 1994), resulting in the embryo being exposed to contaminants in the surrounding substrate. PCB and DDT metabolites have been detected in eggs of loggerhead turtles (Clark & Krynitsky 1980, 1985) and green turtles (Thompson et al. 1974; Clark & Krynitsky 1980). The effects of the contaminant concentrations reported in these studies are unknown.

A natural thermal regime during egg incubation is necessary for normal metabolic activities and sex determination. In sea turtles, sex is determined by temperature during the second trimester of egg incubation, with high temperatures primarily producing females and low temperatures producing males (Mrosovsky & Yntema 1980). Thus, the thermal climate of the beach determines the sex ratio of hatchlings produced. Abnormal sex ratios can be expected if a nourished beach differs from the natural beach in thermal parameters. Several studies have quantified the sex ratios produced in natural beaches (Mrosovsky et al. 1984; Mrosovsky 1988; Horikoshi 1992). Such studies have been limited due to the lethal techniques used to sex hatchlings, and no studies have determined the ratios produced in nourished beaches. A new technique has the potential to determine the sex of hatchlings noninvasively by hormone analysis of allantoic fluids in the egg (Crain et al. 1994).

Changes induced by nourishment can cause abnormal thermal conditions by altering sand color and heat capacity. Nourishment can directly alter thermal conditions by changing the sand color of a beach: darker sands absorb more radiation than lighter sands, and darker beaches would be expected to be warmer. Indeed, Ackerman et al. (1992) found warmer temperatures on the darkest nourished beach in a study of twelve beaches. Heat capacity (heat storage) of nourishment sand must also be considered because increased water content increases heat capacity. Because nourished beaches generally have greater water content than natural beaches, changes in beach temperatures may be buffered.

The search for optimal sediments for nourishment projects has led to the use of sediments from various sources. An alternative to sediments that naturally occur along the southeastern United States is aragonite sand commercially mined in the Bahamas (Olsen & Bodge 1991; Bodge & Olsen 1992). Aragonite sand has a lighter color than sands of the southeastern United States, and this lighter color increases the reflectivity of the aragonite sediments. This leads to incubation temperatures 2°C cooler on average than Florida silicate/calcite sand, which causes significantly longer incubation times for eggs in aragonite sand (Lutz et al. 1992, 1993; Schulman et al. 1994). Although alterations in sex ratios due to these cooler temperatures have not been addressed, experimental studies show that temperature alterations of 2°C can produce significantly more males. Nelson and Fletemeyer (1987) noted a higher mean number of pipped dead hatchlings from clutches in aragonite sand, but other studies have found no such problem (Lutz et al. 1992, 1993).

Sediments from inlets and channels are also considered as alternatives to offshore sediments. Material dredged from Sebastian Inlet, Florida, was finer, moister, and more compacted and had a mean temperature of 1°C cooler than did sediments on a control beach (Parkinson et al. 1994).

The timing of beach nourishment activity directly affects the success of sea turtle eggs. Nourishment projects conducted during the period of reproductive activities in the summer and fall can cause decreased sea turtle nesting success and hatching success as a result of outdoor lighting, nighttime beach activity, use of dredging equipment at night, and obstruction of beach by the dredge pipe (Wolff 1988). Also, nests can be covered with excess sand if nourishment occurs after turtle nesting. Such adverse effects can be avoided by conducting beach nourishment operations outside of the turtle nesting season (Pullen & Yancey 1979; Arnold 1992). Unfortunately, winter and spring projects are often less desirable due to unsafe conditions for workers, increased cost for funding agencies, and potentially less stable beach sediment (Bonner 1992; Green 1992). Rule 16B-41 of the Florida Department of Environmental Protection (passed August 23, 1992) restricts nourishment projects in Florida during sea turtle activities (May 15 through October 15) unless (1) "appropriate measures to protect marine turtles and their habitat, such as nest surveys, nest relocation, nest marking, modification of coastal construction and measures to reduce sand compaction are to be used," (2) the Department of Environmental Protection deems the project justified based on economic, safety, public health, and technological reasons, or (3) the habitat is degraded to the point of not supporting successful marine turtle nesting activity. If nourishment is to occur during the nesting season, nests must be relocated; several relocation projects conducted during beach nourishment have been successful (Wolf et al. 1987; Wolf 1989), but relocation should be considered on a site-specific basis (Flynn 1992; Spandoni & Cummings 1992). Nest relocation is obviously preferred to nests being covered by excess sand, but eggs may be damaged during movement (Pritchard 1992) or unknown biological mechanisms may be altered.

Sand compaction can inhibit hatchling emergence by physically impeding the upward crawl of hatchlings. Despite anecdotal accounts of such occurrences, most studies find no adverse effect of nourishment on hatchling emergence (ability of the hatchling to move from the subterranean nest to the sand surface) (Raymond 1984; Gahagan and Bryant Associates 1990; Broadwell 1991, 1992). In fact, Broadwell (1991, 1992) noted that more turtles emerged from nests in nourished areas (90% of eggs laid) than from nests in natural areas (80.2% of eggs laid), which she attributed to the optimal substrate used for nourishment.

Evidence indicates that female sea turtles return to nest on beaches where they hatched (Carr 1986; Bowen et al. 1992). A hatchling that takes minutes to crawl to the ocean and spends years if not decades at sea as passively pelagic flotsam can return to the same region, same beach, or perhaps even the same spot on a beach to nest. Suggested mechanisms for the phenomenon are (1) a magnetic compass such as in carrier pigeons, (2) chemical imprinting such as in Pacific salmon, or (3) a combination of the two. Recent research examining the magnetic compass model shows that hatchlings do have a sense of polar orientation (Lohmann & Lohmann 1994). But no model is yet sufficient to provide a mechanism for natal homing in sea turtles, and chemical messages are possibly involved. The porous nature of sea turtle egg shells exposes the developing embryo to chemical signals from the beach. Thus, the turtle is exposed to potentially orienting chemicals for almost two months as it develops. If chemical signals are involved in hatchling imprinting, beach nourishment could alter the ability of a nesting female to find a particular beach. The behavior of nesting females when natal beaches are altered is unknown, and perhaps the dynamic nature of barrier islands and mainland beaches has promoted plasticity in beach selection. The suggestion that nourishment alters natal homing is offered not to hinder nourishment activities but to promote consideration of nourishment effects on unknown biological mechanisms.

Research Priorities

Both biological and physical parameters must be addressed in any research concerning the effects of nourishment on sea turtles, and the research initiatives we suggest attempt to integrate the two types of parameters. No single recommendation can solve the problems associated with beach nourishment; solutions will be obtained only through collaborative research between coastal engineers and biologists.

(1) Stop conceptualizing nourishment as a single entity. A nourished beach can vary greatly in physical, biological, and chemical characteristics. Too often, researchers extrapolate the results of a single nourishment project to all nourishment projects. Many variables determine the success of a nourishment project with respect to sea turtles, and these variables fall under two major categories: source sand and application technique. If one or more variables is suboptimal, restorationists may encounter problems. Conceptualizing the many facets associated with a successful beach nourishment project is necessary for appropriate assessment.

(2) Utilize standard methodology and incorporate necessary comparisons when assessing the biological effects of beach nourishment. Studies of the biological effects of beach nourishment could benefit from (1) using standardized methodology, (2) comparing pre- and post-nourishment biological parameters, and (3) comparing nourished and natural beaches. Standardized methodology and comprehensive data collection are essential for accurate assessment of all parameters associated with beach nourishment (Witham 1989; Bell 1991) but are especially important in assessing compaction. Also, lack of prenourishment data precludes drawing valid conclusions, and inadequate comparisons often result in pseudoreplications. Adequate assessment of nourishment depends upon pre- and post-nourishment comparisons of total nests, nesting success, and hatching success. Many researchers have begun to collect pre- and post-nourishment information in an effort to better understand the interaction of beach compaction and sea turtle reproductive success (Davis et al. 1993). Also needed are comparisons of many natural and nourished beaches. Annual fluctuations in total nests, nesting success, and hatching success are common, and concurrent comparisons of nourished and nearby natural beaches are necessary to address such fluctuations.

(3) Determine the natural variation in beach compaction and water potential, and how these values relate to sea turtle nesting and hatching success. For any factor of interest, control or normal values are needed to make accurate interpretations of data from manipulated areas. Values of compaction and water potential for natural beaches have been documented, but sufficient data are not available to assess natural variation in these factors. Variation within a given beach is accounted for in most compaction sampling designs, but variation among beaches is seldom considered. There may be significant geographic variation in compaction and water potential. Florida beaches along the Gulf of Mexico appear to be more compacted than beaches of the Atlantic Coast, and certain regions may be characteristically more or less compact than others. If geographic differentiation of these variables exists, maximum acceptable values should be determined on a regional basis. Compaction and water potential should be analyzed with respect to sea turtle nesting success and hatching success. Resulting correlations could be used (1) to help set maximum acceptable compaction and moisture values, (2) to explain natural barriers to nesting, and (3) to optimize conditions at established turtle projects.

(4) Test the effect of tilling on beach sand compaction, sea turtle nesting success, and sea turtle hatching success. Compaction values, nesting success, and hatching success should be assessed before and after tilling due to conflicting results concerning the effects of beach tilling. Results will indicate whether or not tilling can mitigate some of the adverse effects of nourishment.

(5) Determine the effects of incubation in aragonite sand on the sex of hatchlings. Aragonite is being considered as an alternate source of nourishment sand. Studies show that aragonite sediments have cooler temperatures at nest depth than do natural sediments, which could result in skewed sex ratios because sex determination in sea turtles depends on nest incubation temperature. The effects of incubation in aragonite sand on hatchling sex ratio should be determined. Both basic research on the mechanism of how temperature affects sex determination and applied research on assessing differences in aragonite and silicate/calcite sediments are needed.

(6) Determine the effects of toxicants on embryo and hatchling survivorship. Canals, harbors, channels, and inlets act as "sinks" for environmental contaminants. When sand for nourishment activities is obtained from such sources, adverse effects can be manifested in sea turtle eggs and hatchlings. First, mobilization of toxicants must be understood. With what efficiency do contaminants move across the egg shell? How does moisture affect this mobilization? How is the contaminant compartmentalized once inside the eggshell (in yolk, albumen, embryo)? The actual effects of the contaminants must also be assessed (for example, increased mortality, immune suppression). Complete assessment would require both descriptive and experimental studies. A surrogate species, such as a freshwater turtle, could be used for experimental research.

(7) Determine nutrient and mineral requirements and mobilization across the eggshell. Water and oxygen pass across the eggshell during egg incubation, but little is known about the transport of minerals and nutrients across the eggshell. If minerals and nutrients pass across the eggshell and are important in embryo survival, beach nourishment has the potential to change survival by altering concentrations of nutrients and minerals. Both basic and applied research are needed to answer these questions.

(8) Determine how nourishment can affect nest chamber architecture. A recent study revealed differences in architecture between nest chambers on a natural and a nourished beach (Carthy 1994). The positioning of eggs in the beach can determine rate of metabolism, sex of individuals, and survival of the embryos. Surveys of nest chamber architecture on natural and recently nourished beaches are needed.

(9) Determine how nourishment can affect nest predation. Many problems confound the assessment of predation on nourished beaches. First, the formula for hatching success should be standardized, and depredated nests should be included in the calculation of hatching success [hatching success = (total eggs hatched/total eggs laid) × 100]. Standardization will allow valid comparisons among beaches. Another problem with predation studies is pseudoreplication. Before research is begun, beaches should be carefully matched to avoid confounding factors such as higher predator density. Basic research is needed to define the beach criteria that determine nest predation rates.

(10) Determine effects of nourishment on hatchling imprinting. Sea turtles have the ability to return to nest on their natal beaches. The mechanism of this natal homing has not been determined. Therefore, determination of the effects of nourishment on hatchling imprinting is an enormous task. Nevertheless, basic and applied research should be undertaken to elucidate the mechanism(s) of natal homing and the potential effects of using sand from various sources.

(11) Publish research in peer-reviewed journals. A review of the literature concerning effects of beach nourishment on sea turtles revealed a paucity of papers in peer-reviewed journals. A subject as important as the effects of beach nourishment on sea turtles merits rigorous research culminating in publication in peer-reviewed journals.

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The Nest Environment And The Embryonic Development Of Sea Turtles

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4 The Nest Environment and the Embryonic Development of Sea Turtles

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CONTENTS

4.1 INTRODUCTION

Sea turtle eggs are deposited in a large clutch in a nest excavated by the female in sandy marine beaches. Incubation requires several months during which time the sea turtle embryo grows from a few cells to a fully formed organism capable of independent existence. During this process energy stored in the egg by the female is transformed into embryonic tissue. The developing embryo is coupled to the nesting beach through the exchange of the O_2, CO_2, H_2O, and heat that is either required or produced by the energy transformation process. The nesting beach is the incubator for sea turtle embryonic development and operates by producing a climate space that is appropriate for embryonic development. Deposition of the egg clutch depends on the ability of the female to select and excavate a suitable nest chamber. Successful incubation of the eggs depends on the presence of suitable conditions in the beach sand. Among these conditions are temperature, humidity or water potential, salinity, and levels of respiratory gases. A microclimate suitable for incubation is generated by interaction among the physical characteristics of the

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material composing the beach, the physical structure of the beach, local climate, and the eggs in the clutch. The microclimate is dynamic and changes with the state of biological activity in the clutch and in the beach. Unfortunately, we know very little about the microclimate of sea turtle eggs during incubation. We know even less about how the physical characteristics of the beach influence the microclimate.

Our understanding of sea turtle embryonic adaptations for development in an egg clutch buried in a nesting beach is not extensive. There is little information available to describe how variation in beach characteristics, hydrology, topography, or local climates influence the environment around eggs. The coupling between eggs and beach is poorly described. No detailed climate space for a reptile egg of any species has been described and, as a result, egg, embryonic, and developmental adaptation are not well understood. This extensive lack of information and insight will not be remedied in this chapter. My focus will be on the environment for incubation and on conceptual ways of examining and describing it while pointing out remaining issues. Unfortunately, the lack of hard information on sea turtle embryonic development and its environment limits the extent to which conceptual synthesis is possible.

4.2 EMBRYONIC DEVELOPMENT

During the course of incubation, the embryo grows inside the egg from a few cells at the beginning to a self-sufficient organism at hatching some 50 to 80 d later. Throughout this process, the egg exchanges heat, H_2O, O_2, and CO_2 with other eggs in the clutch and with the beach surrounding the clutch. The developing embryo is involved in this exchange, because it produces heat and CO_2 and consumes O_2. The embryo may also produce or require H_2O. The osmotic environment of the egg must be influenced to some extent by the exchange of H_2O between the egg and the environment. Because the extraembryonic parts of the egg are interposed between the embryo and the environment, these structures have the potential to act as an agent buffering or even regulating the embryonic milieu. Moreover, the embryo clearly must be developing regulatory processes as it develops so that it is self-sufficient at hatching. These regulatory processes can be expected to mature as development progresses. Thus there is potential for a complex and shifting interaction between the egg and the embryo developing inside. Unfortunately, our knowledge of developmental and regulatory physiology inside the egg is rudimentary for all reptile eggs and especially so for sea turtle eggs and embryos.

Embryonic growth has been described for a number of species. Miller[1] reviewed the embryology of sea turtles and presented a stage-by-stage description. He reports that many measures of embryonic growth can be related to developmental time (incubation period) using 2° and 3° polynomials. Ackerman[2] described the change in embryonic wet mass with time using a logistic equation. In this case, the growth rate is described by a 2° polynomial. How embryonic growth may be influenced by the environment or by exchange with the environment is unknown; however, embryonic growth is unlikely to be independent of the environment.

Embryonic growth is a metabolic process. Fuel, stored in the egg yolk by the female, is moved from the yolk to cells where it is transformed into energy and then used for differentiation and growth. Ackerman[3] measured the O_2 uptake of *Caretta* and *Chelonia* eggs during development. The pattern of change in O_2 uptake with time was sigmoidal, peaking at about the time that hatching occurred and could be described with a logistic curve. Vleck and Hoyt[4] reported data for *Dermochelys* and summarize the available data for reptile eggs in general. Peak O_2 uptakes are a function of initial egg size and, presumably, hatchling mass and increase with about the 0.8 power of initial egg mass. Peak O_2 uptakes for sea turtles are in the range of 90 to 250 ml $O_2 \cdot day^{-1}$. Total O_2 cost of incubation is in the range of 38 to 90 kJ (after converting to energy units) and increases with about the 0.8 power of initial egg mass. Note that the O_2 cost is an estimate of the energy lost due to metabolic inefficiency during development and is not an estimate of the total cost.

4.3 TEMPERATURE

Reptile embryos develop successfully over a range of temperatures.[5-7] Typically, incubation period (I, days) decreases as incubation temperatures (T, °C) increases. The reciprocal of I can be used as a developmental rate (R_d, $days^{-1}$).[7] Ackerman[7] discusses how the relationship between I and T can be described. One descriptor is the range of T over which development occurs with the end points being described as upper and lower lethal temperatures. Another is the position of the curve relating I or R_d to T (the response curve) on the T scale. A third is the slope of the response curve of I or R_d to change in T. Sea turtle eggs are typically incubated at constant temperature in the laboratory where I can be determined with the greatest precision. Eggs in nature do not experience constant temperatures. While diurnal temperature changes in the beach are damped by the depth of the nest, there is still likely to be some diurnal change, and furthermore, nest temperatures may change systematically over the course of incubation (see discussion below). Because there are no experimental or empirical observations, it is not clear whether or not the average of a changing temperature produces the same effects as a constant temperature of the same value. However, because temperature effects are typically nonlinear,[7] we might expect differences.

The thermal tolerance range (TTR) for development of sea turtle embryos incubated at constant temperature appears to fall between about 25 to 27°C and 33 to 35°C and is around 10°C wide. Data for I and T for two sea turtle species are shown in Figure 4.1. The data appear nearly linear as do the summarized data of Miller.[1] However, temperature effects on growth rate are typically nonlinear,[7] and nonlinear curves yield better fits to the data than do linear ones. The Arrhenius equation is often used to describe temperature influences on rate functions[7] and takes the form:

$$R_d = B \cdot e^{(-E/R \cdot T)}$$

where R_d is a rate ($days^{-1}$), the pre-exponential factor (B, $days^{-1}$), represents the position of the curve on the T scale, R ($kJ \cdot mol^{-1} \cdot K^{-1}$) is the gas constant, T (°K) is the incubator temperature, and E ($kJ \cdot mol^{-1}$) is the free energy. The quantity **E**

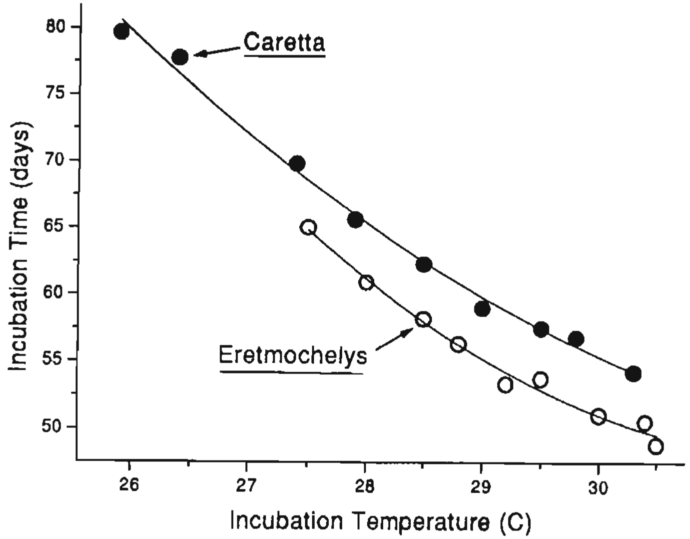

FIGURE 4.1 The influence of incubation temperature on incubation time. Open circles are for the hawksbill turtle, *Eretmochelys imbricata*. The closed circles are for the loggerhead turtle, *Caretta caretta*. Data are taken from the literature cited in the text.

can be used to describe the shape or sensitivity of the response of R_d (or I) to change in T. Q_{10} can also be used to define the shape or sensitivity,

$$Q_{10} = \sqrt{\frac{(T+10)}{T}} \cdot e^{\frac{10 \cdot E}{(R \cdot T \cdot (T+10))}}$$

where T is again in °K. Note that Q_{10} is temperature dependent, whereas E is single valued. Ackerman[7] reported an E of 38 kJ · mol^{-1}, equivalent to a Q_{10} of 1.6. A similar analysis for the *Eretmochelys* data shown in Figure 4.1 yielded an E of 66 kJ · mol^{-1}, equivalent to a Q_{10} of 2.4 between 25 and 35°C. The values for the species are probably not different,[7] indicating that changes in temperature produce similar changes in I. However, the position of the curves appear to be different, with the *Eretmochelys* data displaced below the *Caretta* data. An explanation for this remains to be found, but the difference may be related to beach temperature.

The influence of temperature on sea turtle embryonic sex determination is very interesting and very puzzling. Temperature-dependent sex determination (TSD, also called environmental sex determination, or ESD) among sea turtles operates to produce female hatchlings at warm temperatures and males at cool. Mrosovsky[8] has recently reviewed TSD among sea turtles and Ewert et al.[9] for all turtles. The sensitive period for sex determination appears to occur around the middle third of incubation.[8,10,11] The threshold temperature (or pivotal temperature, T_{piv}) for the transition from production of one sex to the other (i.e., a sex ratio of 1:1) is around 28 to 30°C for all the species for which there are data. The amount of variation within species is not well defined. Figure 4.2 illustrates the influence of constant incubation temperature on hatchling sex ratio for 4 species of sea turtle. The data are taken from Paukstis and Janzen[12] and Mrosovsky et al.[13] A cumulative normal distribution (represented by the line) is fitted to the data. This distribution is often used to describe dose-response relationships.[14] The estimated T_{piv} is 29.0°C with a standard deviation of 1.77°C. Table 4.1 summarizes T_{piv} estimated by linear regression on data for the individual species as well as on the pooled data. There is considerable scatter in the data both within and among the species, but the T_{piv} values are quite similar among the species. The data sets are not of sufficient quality to determine whether or not T_{piv} varies within species. Typically, because of the endangered and threatened status of sea turtles, only small samples with few replicates are collected. If we treat sex determination as a binomially distributed random variable (i.e., either male or female), Figure 4.3 illustrates the random variation which we might expect from samples of size 10, replicated 10 ten times. Here, 10 replicates were drawn for 5 different, evenly spaced probabilities ranging from 0.1 to 0.9 with T_{piv} ($p = 0.5$) set to 29°C. The situation is very much improved for larger sample sizes on the order of 50 eggs. Much of the variation that is seen in sea turtle TSD data is likely to be random. T_{piv} is of interest because it ought to be useful for predicting the beach temperature required to produce a sex ratio of 50%. This assumes that the T_{piv} produced by constant incubator conditions can be extrapolated to the beach where temperature is not constant. Mrosovsky[8] reports that beach temperatures in some locations are around the levels of T_{piv}, but in other locations, such as the Atlantic coast of Florida, average beach temperatures appear to be in excess of T_{piv} during incubation with an excess production of female hatchlings as a result. The life history consequences of imbalances in sex ratios are poorly understood.[8] One problem, as pointed out by Mrosovsky,[8] is that we know little about the long-term variation of beach temperature. This is of particular importance for long-lived animals such as sea turtles. Unfortunately, there are few long-term temperature data available for beaches. I have found a 12-year record for soil temperature at 10 cm near Gainesville, FL. Figure 4.4 illustrates average July soil temperatures. The data for June and August are similar. Although temperatures in beaches at greater depth are likely to be somewhat cooler, we can see that the average temperature near Gainesville is typically well in excess of T_{piv}. This is consistent with the trend for nesting beach temperature noted by Mrosovsky[8] from a much smaller data base: beach temperatures at appropriate depths seem to be in excess of T_{piv} and ought to produce more female than male hatchlings. It is possible if not likely that the Florida beaches have been warm (in excess of T_{piv}) for some time, perhaps in excess of a decade. To understand TSD in this system we need to know what the normal beach temperature is and how it varies, at least over some period of time in excess of the life span of the sea turtles nesting on the beaches. This is a problem, but could potentially be approached by correlating beach temperature with the temperature at some known (and, hopefully, close) location.

Because temperature has such a pervasive influence on the embryonic development of sea turtles, it is important to understand the determinants of clutch temperature. The most important determinant is, of course, beach temperature. The second important determinant is the exchange of heat between the clutch and the beach.

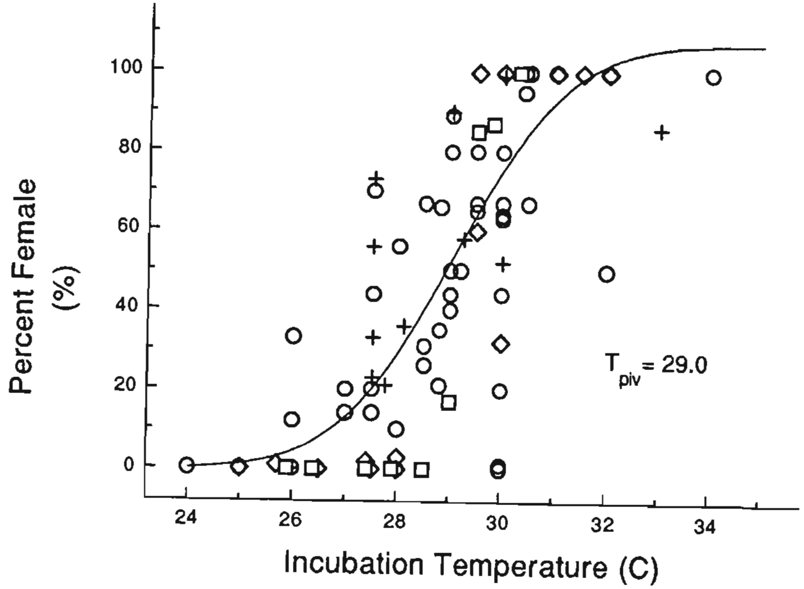

FIGURE 4.2 The influence of constant incubation temperature on hatchling sex ratio of sea turtles. Loggerhead turtles (open circle), ridley turtles (diamond), green turtles (plus), and hawksbill turtles (square) are shown. Data are taken from the literature as described in the text. The line represents a cumulative normal distribution fitted to the data as described in the text.

TABLE 4.1
Pivotal Temperatures (°C) of Several Sea Turtle Species

Species	Pivotal temperature	95% CI	R^2
Chelonia mydas	28.26	1.06	0.52
Caretta caretta	28.74	0.36	0.58
Lepidochelys olivacea	29.13	1.14	0.68
Eretmochelys imbricata	29.32	0.23	0.81
Grouped data	28.74	0.31	0.54

Temperatures were determined using inverse solution of a linear regression equation for sex ratio on temperature at a sex ratio of 50%.

There are extensive records of beach temperature, especially in regard to hatchling sex determination,[13,15-22] but they tend not to be very long term or extensive. Beach temperatures are typically in the range of 26 to 35°C. In some cases beach temperature is relatively constant over the period of incubation, and in others there may be substantial change in beach temperature over incubation.[15] Data for 7 beaches along the Atlantic coast of Florida are shown in Figure 4.5. The data were measured at a depth of 50 cm over a 24-h period, and, because there is little change in temperature at this depth, can be used as estimates of average monthly temperature.[23] Patterns of change in beach temperature surely reflect the physical characteristics of the beach as well as the local boundary layer climate. As a result we can expect considerable variation among beaches. Even distances of a few miles may be sufficient to influence patterns of beach temperature (Figure 4.5). Beach temperature is determined by the exchange of thermal energy at the beach surface with the local boundary climate and by the transmission of heat within the beach. Both the heat balance at the surface of the soil and heat transmission within the soil column are will understood,[24,25] but this knowledge has never been applied to the analysis of beach temperature. Models such as those of Horton et al.[26-28] could be applied to the thermal modeling of the sea turtle nesting beach with the intent of developing more predictive relationships.

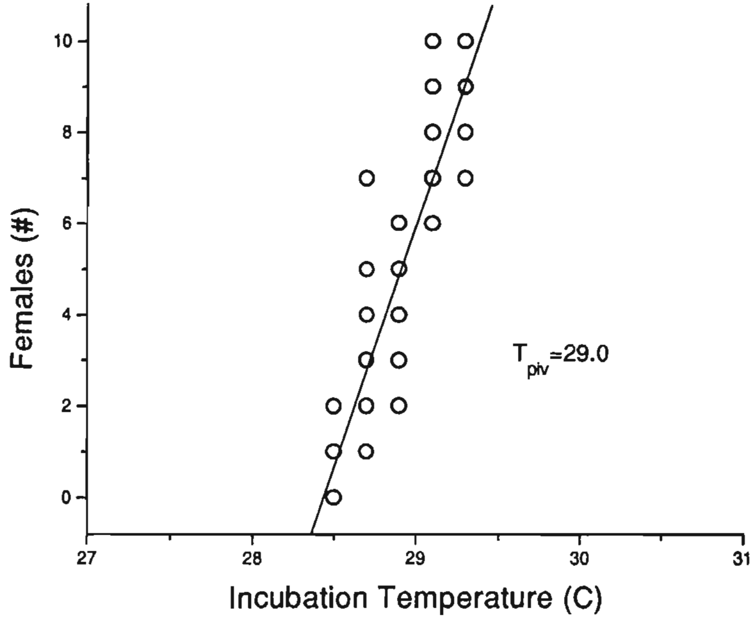

FIGURE 4.3 The number of females resulting from samples from a binomial distribution. Clutch size was 10 eggs and each sample for 5 probabilities between p = 0.1 and p = 0.9 was run ten times. Only different results are shown. The line is a linear regression through the data. At p = 0.5, T_{piv} was 29.0°C.

4.4 WATER

Sea turtle eggs contain a supply of water when they are oviposited. Water is stored in the albumen at the beginning of incubation and is supplemented by water gained through the transformation of yolk.[29] Because there are a number of anatomically and physiologically different compartments inside the eggs, including the embryo and extraembryonic membranes, the yolk sac, the chorioallantoic sac, and the

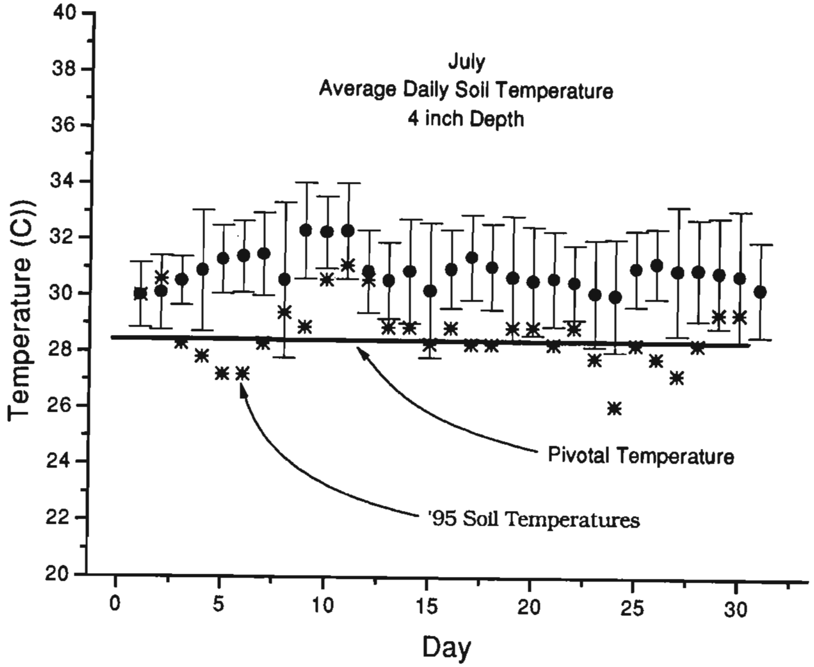

FIGURE 4.4 The average daily temperature at a soil depth of 10 cm in July at Gainesville, FL. The solid line represents pivotal temperature for sea turtles. The asterisks represent average daily temperatures for July 1995.

amniotic sac, water and osmotic balance may be complex. Vleck[30] has reviewed the water economy and osmotic regulation of a number of reptile species, but we know very little above the osmotic events and processes occurring inside the sea turtle egg at any stage of embryonic development. Egg and embryonic osmotic balance are especially interesting because the egg must be open to the exchange of water vapor with the environment in order to exchange respiratory gases. The sea turtle egg is coupled to the environment through the exchange of water vapor and possibly through the exchange of liquid water.[31-33] We know that for some species of reptile, embryonic growth is influenced by egg water exchange[34,35] while for other species, embryonic growth is independent of egg water exchange over some range of exchange rates. Some reptile eggs must take up water in order to produce a viable hatchling.[36] Ackerman et al.[31] suggested that water exchange was likely to be relatively less important for large eggs such as sea turtles than for smaller reptile eggs. We have recently found[65] that the embryonic growth of *Caretta caretta* is independent of egg water exchange over a range of total egg water exchanges of around –10 to +30% of initial egg mass. There also appeared to be little effect on hatchability over this range, which is consistent with the observations of Bustard.[15]

It is clear that hatching success can be correlated with some physical characteristics of the sand environment.[37] Mortimer[38] found that hatching success of Ascension

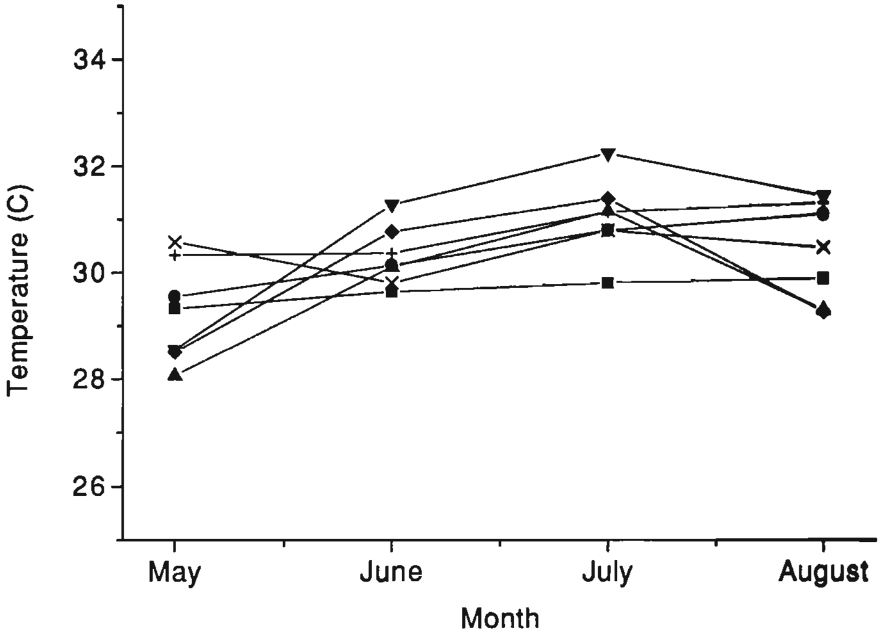

FIGURE 4.5 Average monthly soil temperatures at a 50-cm depth in 8 beaches along the Atlantic coast of Florida between Ft. Pierce Inlet and Boca Raton.

Island *Chelonia mydas* was negatively correlated with sand grain size. However, there appears to be very little data on the water exchange of sea turtle eggs during incubation. It seems to be generally accepted that eggs take up water during early incubation and become more turgid,[15] but the quantity of water exchanged is unclear. There is at least one report[39] indicating that eggs may lose water near the end of incubation, producing a reduction in clutch volume. There is very little available on what happens in between. However, because the water in the sand surrounding the clutch is likely to have a water potential on the order of –5 to –50 kPa and because the water potential inside the egg is on the order of –900 kPa[32,40] there is a net tendency of water to move into the egg during incubation. An added complication for the understanding of egg water exchange is that sea turtle eggs are incubated in large clutches rather than as single eggs. Eggs in the interior of the nest contact each other and the spaces between because the interior of the clutch remains free of sand. As the eggs take up water and swell, these spaces will shrink and disappear. Eggs at the periphery of the nest contact sand over some fraction of their surface as well as other eggs, a rather different physical situation. Moreover, clutches heat up by several degrees during incubation with peak temperature occurring at the center of the clutch.[18,31] Temperature increases of this magnitude will have a significant impact on egg water exchange.[31,33]

The general concepts of egg water exchange can be examined using a steady-state model for the water exchange of a single egg in contact with soil:

$$\dot{M}_{H_2O} = L_p \cdot A \cdot \left(P_{EH_2O} - P_{SH_2O}\right) \qquad (4.1)$$

where $\dot{M}_{H_2O}$ (mg/d) is the rate of water exchange, L_p (mg day^{-1} cm^{-2} kPa^{-1}) is the permeability of the eggshell and shell membranes, A (cm^2) is the area of the eggshell and P_{EH_2O} (kPa) and P_{SH_2O} (kPa) are the vapor pressures of the egg and sand, respectively. The product, $L_p \cdot A$, is often described as the water vapor conductance of the eggshell:

$$G_{H_2O} = L_p \cdot A \qquad (4.2)$$

where G_{H_2O} = mg day^{-1} kPa^{-1}. Egg water exchange as modeled by Equation 4.1 is driven by a vapor pressure (vp) difference between the egg and the surrounding sand which describes the direction of the exchange, while the magnitude of the water exchange is given by the product of the vp difference and the conductance. It is important to note[32] that the permeability represents the sum, in series, of the eggshell permeability (L_p^e) and the soil permeability (L_p^s):

$$1/L_p = 1/L_p^e + 1/L_p^s \qquad (4.3)$$

However, L_p^s for moist sand is orders of magnitude greater than L_p^e. As a result, L_p^e becomes limiting[32] and Equation 4.3 reduces to:

$$1/L_p = 1/L_p^e \qquad (4.4)$$

Thus Equation 4.2 should describe the only important conductance for water vapor exchange of the sea turtle egg. The G_{H_2O} of only *Caretta caretta* appears to have been measured (2175 mg · day^{-1} · kPa^{-1}).[41] This value was close to that expected for other flexible-shelled reptile eggs and about 3 orders of magnitude larger than for a similarly sized bird egg.[41,42] The magnitude of the *Caretta* G_{H_2O} means that the eggs should lose water at a high rate in an environment only slightly drier than the egg itself.[32] One implication seems to be that the environment of sea turtle eggs must be very humid. In any event, the magnitude of the vp difference between the inside and outside of the egg takes on much greater significance for the sea turtle than it does for a bird egg. To my knowledge, no one has reported values for the vp (P_{EH_2O}) of sea turtle eggs. We can assume that the egg vp is equivalent to typical vertebrate tissue vp. Data for other reptile eggs indicate that this assumption is not unreasonable.[35,43] It is possible, however, that P_{EH_2O} changes with incubation time due to osmotic processes occurring inside the egg.[35,43] Moreover, P_{EH_2O} is a function of egg temperature and will change with time as the temperature of the egg changes during development.[7,31]

Sand vp (P_{SH_2O}) at the other end of the vp difference driving egg water exchange is a function of several variables. P_{SH_2O} is determined chiefly by the relationship between the water content and water potential (Ψ) of the sand and is a function of sand water content. Dry sand is comprised of solid sand grains and gas. When water is present, gas is displaced until the water completely fills the gas space. The sand is then considered to be saturated with water. At saturation, the hydraulic pressure in the water is zero with reference to atmospheric pressure. As the water content of the soil decreases from saturation, a negative pressure occurs in the soil water. This pressure is often described as a water potential (Ψ, the potential energy per unit volume, J · m^{-3}) whose dimensions are equivalent to those of pressure (kPa) and can be generated in several ways.[24,44] (1) Ψ is a matric potential if it is due to the capillary effects of surface tension in soil pores or to the binding of water to the surface of soil particles.[45] This is a negative potential. As the soil dries, Ψ becomes increasingly negative. A characteristic curve describes graphically the relationship between sand water content and Ψ of water. (2) An osmotic potential may be present in the water if solutes such as salt are present. This is also a negative potential that is proportional to the concentration of solute present. (3) If the liquid water in the soil is connected hydraulically to a saturated water source (the water table), as is likely to be the case for a nesting beach, then a gravitational potential is also present. This potential is positive and is equivalent to 10 kPa for each meter above the water table. The total potential in sand water is thus the sum of the matric (–), osmotic (–), and gravitational (+) potentials. In terms of water transport in the sand, the matric potentials tends to hold water in while the gravitational potential tends to cause water to drain out. The vp of water in the soil gas phase is generally assumed to be in equilibrium with Ψ. Relative humidity (H_r, %) can be related to water potential (Ψ, 1 kPa = 1 J · kg^{-1}) by:

$$\Psi = (R \cdot T/M_w) \cdot \ln(H_r) \qquad (4.5)$$

where the gas constant R is 8.31 J · mol^{-1} · K^{-1}, the molar mass of water, M_w, is 0.018 kg · mol^{-1} and T is temperature (°K). Characteristic curves for sand from a number of nesting beaches are shown in Figure 4.6. Only a limited range for Ψ is shown because totally dry sand is assumed to have a water potential of –1,000,000 kPa.[45] Sand loses cohesiveness at Ψ greater than –50 to –100 kPa and can no longer support nest excavation. The horizontal section of the characteristic curve represents the presence of bulk water in the sand. The vertical section of curve represents water bound to the surface of the sand particles. Bound water remains after the bulk water has drained from the soil.[45] When bulk water has been removed, leaving only bound water, sand loses its cohesiveness and the individual particles no longer stick together. The sand appears to be dry. When the external pressure exceeds the capillary pressure holding water in the soil, the soil pores empty. When bulk water is present in the soil, Ψ is only weakly dependent on soil water content. This is pronounced for sand (Figure 4.6), where water potential is still above –10 kPa even though most of the water has been lost. I have data for sands from 16 different nesting beaches. All release their bulk liquid water at matric water potentials less negative (lower) than –10 to –15 kPa. In sands, the pores are relatively large and of similar size so that emptying (or filling) occurs abruptly as matric forces are exceeded by drying (or wetting) forces,[45] but the characteristic curves are dependent to some extent on sand grain size. More coarsely textured sands will hold water less tightly than more finely textured sands because the pores are larger in the coarser sands. This means that coarsely grained sands will empty at lower matric water potentials than more finely grained sands.

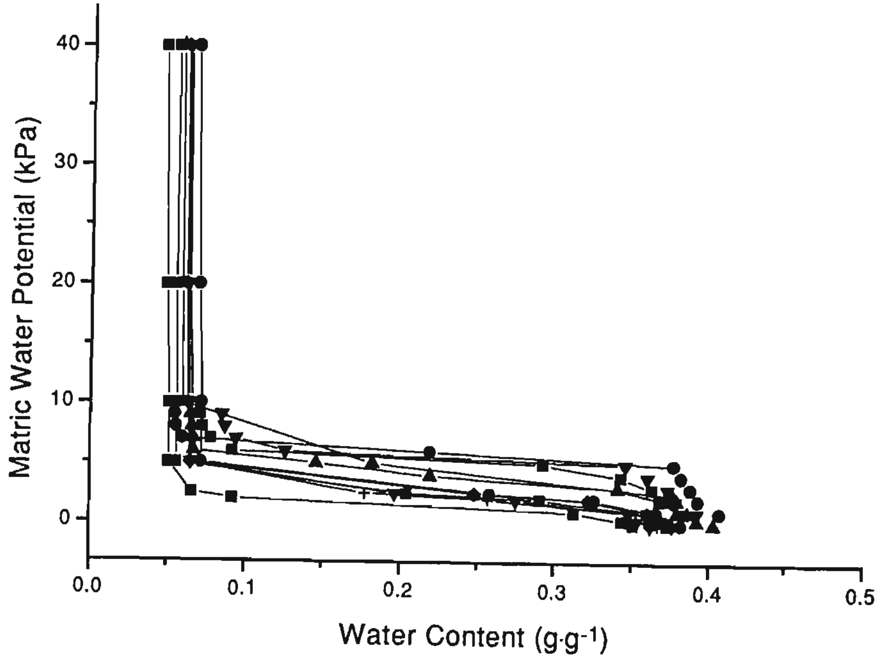

FIGURE 4.6 Characteristic curves for sand taken from a number of beaches along the Atlantic coast of Florida. Details as described in the text.

The vp and Ψ present in the beach sand depends fundamentally on the quantity of water in the sand and its distribution in the beach. The distribution of water in the beach is a result of the balance between water entering and leaving a layer of sand at any depth in the sand depth profile. If the distribution is stable it is because on the average, the same quantity of water enters a layer as leaves it. Sea turtle nesting beaches are characterized by what appear to be relatively stable distributions of beach water that are far from equilibrium and dry out only slowly in the absence of rain.[32] The elements of a water balance for a beach are presented by Ackerman.[32] Nesting beaches are likely to have a source of liquid water (a water table) present not far from the surface (1-5 meters). The water table is close enough to the surface to generate a gravitational potential in the beach. Water will drain downward toward the water table, but slowly because the Ψ difference driving water movement is small (on the order of a few kPa). The chief source of water in the beach is rain. Water injected by rain enters the beach and drains down its gravitational field until it reaches equilibrium with the capillary forces (the matric water potential). Thus at 1 m above the water table the equilibrium matric potential would be −10 kPa, offsetting the 10 kPa gravitational potential and producing a total potential of 0 kPa.

Note that sand with a Ψ of −10 kPa is not dry and still retains 1 to 2% water. The equilibrium condition is approached slowly because the potential differences are usually small, as demonstrated by the *Caretta* nesting beaches in Israel where no rainfall occurs during the nesting season.[32] When drying at the surface occurs after a rainfall, water is lost from the soil to the atmosphere.[24,25,46] As water is lost at the surface, it is drawn up from the underlying sand and the water potential of the sand falls below its equilibrium point. Water is, in turn, pulled up from the free water surface further down in the sand column. Water transport in the soil column produces a characteristic profile in which, after a period of drying, a layer of dry sand comes to overlie a layer of wetter sand. This distribution is familiar to anyone who has worked on a sea turtle nesting beach where a layer of dry sand always overlies moister sand underneath (in the absence of rain). The top, dry soil layer limits water loss to the atmosphere from the wetter layer. Near equilibrium, liquid water may be drawn up at a rate sufficient to balance the water lost across the surface.[24,25,46] The evaporation from the surface is self-limiting. This is because the rate of water vapor transport decreases as the length of the diffusion path increases. It is also because the density of vapor in the pathway decreases substantially after short periods of time.[24,25] The thickness of the dry layer will depend, among other things, on the time since the infiltration of surface water, on the sand structure, and on the depth of the water table. Given sufficient time after surface infiltration, an equilibrium distribution may be reached, but this is likely to require weeks to months.[25] Thus in Israel, with no rain during the nesting season, it appears to take in excess of 3 months to approach equilibrium.[32] The deeper the liquid water surface, the thicker the dry layer is likely to be. It is also likely to be thicker in coarser sand than in finer sands because coarse sands hold water less tightly than finer sands. This phenomenon may account for the observation by Mortimer[38] that hatching success was lower in more coarsely grained Ascension Island beaches. These beaches appeared to be drier than the more finely grained beaches. Most likely, drying fronts had penetrated much more deeply in the coarser beaches, resulting in a much drier environment for the eggs, perhaps dry enough to produce an increase in egg mortality.

Reports of water content profiles in sea turtle nesting beaches are not extensive. Ackerman[32] presented a profile for an Israeli beach taken near *Caretta* nests. Figure 4.7 presents the average water content in five beaches along the Atlantic coast of Florida.[40] The profiles appear as described above with a dry layer at the surface, an intermediate layer with increased water content, and wet layer at the intersection of the soil column with the water table. The moist intermediate layer is characterized by an essentially constant water content throughout its depth. The water content was around 4 to 6% (by mass) and was far from the saturation values of around 35 to 45%. It is in this layer that sea turtle eggs are placed. The most important difference between the Florida and Israeli beaches is in the frequency of rainfall. In Florida, rain often occurs daily and weekly during the nesting season. The result is that the water content of Florida beaches is higher throughout the season, while the water content in Israel starts out high (but lower than in Florida) and decreases during the nesting season as gravitational drainage occurs. Moreover, a drying front forms in both locations, but is much deeper in the Israeli beach (15 to 20 cm) than in the Florida beaches (5 to 10 cm). In both locations, the dry sand at the surface has a Ψ

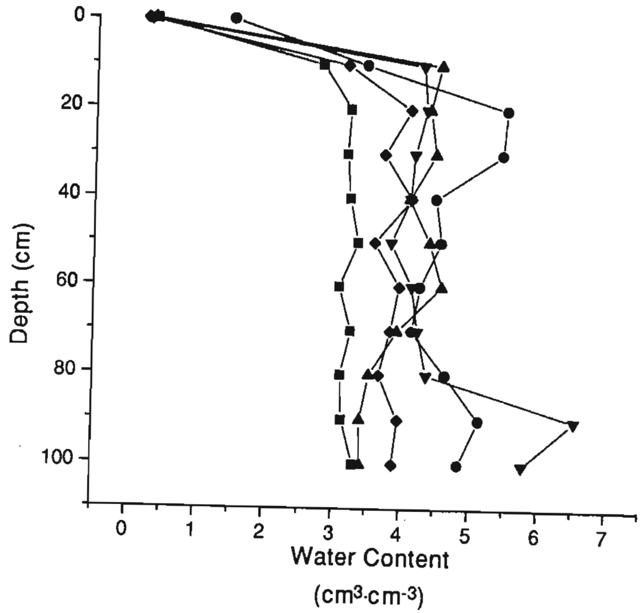

FIGURE 4.7 Water content profile for 5 beaches along the Atlantic coast of Florida. The beach surface is at 0-cm depth. Water table is typically in excess of 1 m.

of around –100,000 kPa or more while the matric Ψ in the intermediate layer is around –5 to –10 kPa. The drying front where the transition from dry sand to moist sand occurs is around 5 cm wide and has a Ψ gradient on the order of 10,000 to 20,000 kPa · cm^{-1}. The presence of salt in the water will increase Ψ somewhat. Mortimer[38] and Rimkus et al.[40] report low levels of salt in beach water producing osmotic potentials on the order of –10 to –60 kPa. These represent very low salt concentrations because seawater has a water potential of around –2000 kPa. Rainfall is likely to flush salt from beach water rapidly. Rimkus et al.,[40] studying the effect of beach renourishment on beach water, found that beaches renourished with sand in a seawater slurry lost all their salt in two weeks or less. Average total Ψ (matric plus osmotic potential) is shown for some Florida beaches in Figure 4.8. Total Ψ is likely to be higher in locations such as Israel, where there is much less rainfall.[20]

It appears that the Ψ and therefore the water vp in the sand around the sea turtle clutch is relatively constant throughout the typical incubation period. If we assume a sand temperature of 30°C and take a typical Ψ to be around –30 kPa, then the water vp in the sand is around 4.232 kPa. If the osmotic concentration of the egg is typical of vertebrate tissue, then the water vp of the egg is around 4.207 kPa. The water vp difference across the eggshell is around 0.025 kPa. Substituting this value and the value for G_{H_2O} (2175 mg · day^{-1} · kPa^{-1}) into Equation 1, we find that a typical egg would take up around 54 mg day^{-1} of water vapor. Over 60 d, this is around 3.3 g or about 6.5% of the mass of a 50-g *Caretta* egg. This water uptake should be considered the maximum quantity possible because the eggs are incubated in clutches rather than singly and because the clutch heats up. Eggs at the periphery of the clutch will be closer to this value than eggs at the center of the clutch. Indeed, eggs toward the center will heat up sufficiently to reverse the direction of water vapor transport. An increase in egg temperature of 0.1°C is sufficient to bring egg water vp to the same level as sand water vp. Pearson[47] analyzed the effect of clutch position and heating on egg water exchange. His model indicated that eggs at the periphery of the nest should experience a net water uptake and eggs at the center of the nest a net water loss during incubation. Water loss for the central eggs occurred near the end of incubation. The observation[39] of a decrease in egg volume near the end of incubation is consistent with the Pearson[47] analysis.

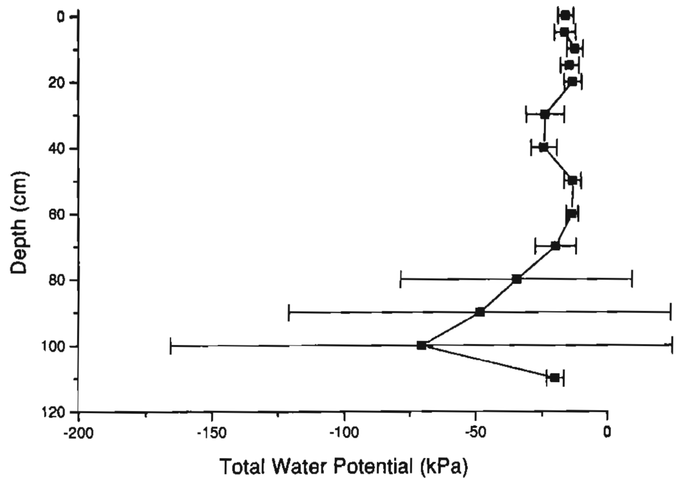

FIGURE 4.8 Total water potential (matric plus osmotic) as a function of depth for beaches along the Atlantic coast of Florida. Data are averaged for 7 beaches. The increased variation at depths greater than 80 cm is due to proximity to the water table which had a salinity typical of seawater.

4.5 GAS EXCHANGE

Sea turtle egg clutches are deposited in a medium, the nesting beach, which limits respiratory exchange because O_2 and CO_2 are free to move only through the gas-filled fraction of soil. This fraction is usually much less than half of the volume present. Gas exchange in the clutch is limited for the same reason. Most of the clutch is composed of the eggs themselves, and respiratory gases can only move through the gas spaces among them. Respiratory gas exchange in these two circumstances can occur by convection or diffusion. Convection in the beach can be induced by temperature variation, changes in atmospheric pressure, or displacement of soil air by water table movement. The magnitude of convection due to these sources is thought to be very small.[45] Prange and Ackerman[48] found little or no effect of water table movement (due to tidal pumping) on the gas exchange of *Chelonia mydas* clutches, but Maloney et al.[19] speculated that tidal pumping may be important. Diffusion of respiratory gases is likely to be the principle means of gas exchange of sea turtle eggs. Net diffusion of any gas can only occur when there is a concentration difference for the gas. This means that, in order to supply the O_2 or get rid of the CO_2 associated with developmental metabolism, concentration differences must set up between the center and edge of the egg clutch and between the edge of the egg clutch and the surrounding sand. As egg and clutch metabolism change with time during incubation, so too should the concentration differences which occur to supply the respiratory needs of the clutch. Ackerman[49] measured P_{O_2} and P_{CO_2} in the sand surrounding the clutch and inside the clutch of *C. mydas* and *Caretta caretta* nests in Costa Rica and Florida. P_{O_2} decreased in the center of the clutch from near atmospheric levels at the beginning of incubation to around 12 to 14 kPa near the end of incubation, while P_{CO_2} increased to around 4 to 6 kPa near the end of incubation. Maloney et al.[19] reported similar patterns of change, but smaller magnitudes in *Caretta* nests in Queensland. Ackerman[49] used a one-dimensional, spherical diffusion model to quantitatively describe gas change by sea turtle clutches, treating the medium (the beach) as if it were infinite. Among other things, this implies that clutch gas exchange is independent of the beach surface. However, Maloney et al.[19] concluded that the model used by Ackerman[49] was not adequate to describe clutch gas exchange in their location. In the situation described by Maloney et al.,[19] the surface may well have influenced clutch gas exchange. This would mean that gas exchange through the top of the nest would have a disproportionate influence on nest gases. The model[49] can be modified easily to deal with this by adding dimensions. An explanation for the observation of Maloney et al.[19] may lie in the relationship between the gas diffusivity of the sand, its water content, and the distribution of water in the sand above the clutch (as described earlier). The gas diffusivity of sand (D_g) can be approximated by the relationship:[45]

$$D_g \cong 1/2 \cdot \phi_g \cdot D_o \tag{4.6}$$

where D_o is the gas diffusivity in air and ϕ_g is the fraction of the sand that is air (taking into account the water present). More accurate estimators are available if required.[24] As described above, a dry layer of considerable thickness is usually found at the beach surface. This layer will have a D_o greater than the moist underlying layers where the water content is on the order of 2 to 10%. Egg clutches incubating in drier climate will tend to be closer to the dry layer (i.e., the dry layer will penetrate into the beach more deeply) than egg clutches incubating in wetter climates. The increased thickness of the dry layer should (at some point) increase the contribution of gas exchange through the top of the nest to overall nest gas exchange. For locations where extensive surface drying may occur, such as Israel or Queensland, a radial (one-dimensional) gas exchange model might not account well for clutch gas exchange, and a two-dimensional model might be more suitable. It is also worth considering the influence of nest crowding on clutch gas exchange. The model used by Ackerman[49] assumed that each nest in the beach was independent of all other nests; that is, that nests were not "breathing" each other's gases. When nests are crowded together, as, for example, may occur in hatchery situations, the gas exchange of nests will not be independent of each other. It is not clear what crowding means quantitatively, but if nests are within a meter or less of each other then it is likely that the influence of one nest on another must be taken into account. As crowding increases, then clutch gas exchange through the top or bottom of the nest becomes progressively more important than gas exchange through the sides, and a two-dimensional planar model may become more applicable.

Clutch gas is important because it establishes the background concentrations of respiratory gases in which the individual egg must exchange the gases necessary to support the metabolic activity of the developing embryo. Gas exchange between the clutch gases and blood in the chorioallantoic capillaries of the egg occurs across the eggshell and associated eggshell membranes. This gas exchange process has been reviewed by Deeming and Thompson[42] for reptile eggs, but has not been extensively studied. Ackerman and Prange[50] reported the O_2 diffusion coefficient for *Chelonia mydas* eggshell and outer shell membrane to be around 5×10^{-5} $cm^3\,s^{-1}\,cm^{-2}\,kPa^{-1}$, a magnitude about twice that of a similarly sized chicken egg. Because the O_2 uptake of the sea turtle egg is only about 20% that of the chicken egg, the O_2 difference across the eggshell and membrane must be much smaller than for the chicken egg. An interesting aspect of this is that the diffusivity of the sea turtle shell must be a function of its water content. When the egg is oviposited, the shell is flooded with fluid. This fluid, if allowed to remain in the shell, would present such a large resistance to O_2 transport (given the shell thickness) that the embryo would run out of O_2 well before the end of incubation. Therefore, the shell must be dried out in some may; furthermore, as water is taken up by the egg during incubation, that water cannot be allowed to accumulate in the eggshell. The relationship between egg gas exchange and egg water exchange is unexplored.

4.6 ALTERED BEACHES

Among other problems faced by sea turtles is the disappearance of nesting beaches, due either to submergence (sea level changes) or to erosional processes. Recent projections based on estimates of climate warming indicate that ocean level may rise by about 1 ft by 2100 (and more thereafter, if nothing changes), submerging many beaches. Beaches are dynamic geological structures with finite life spans, moving in time and space; moreover, sea level has changed many times over the geological life span of sea turtle species. The problem, however, is that the predicted sea level change may occur quite rapidly. This will accelerate beach dynamics. An added complication is that beaches are valuable economic entities. As a consequence there is strong political interest in replacing or maintaining beaches when they begin to disappear. The state of Florida in the U.S., a major nesting site for loggerhead turtles (*Caretta caretta*) as well as for leatherback (*Dermochelys coraceia*) and green (*Chelonia mydas*) turtles, suffers from major erosion of its primary sea turtle nesting beaches. Around 40% of the Atlantic coast beaches are experiencing erosion and 33% are eroding at a critical rate.[51] Because of the economic value of beaches to Florida, the eroded beaches are usually restored to something resembling a natural condition using artificial renourishment techniques. Beach renourishment often involves locating a suitable source of sand offshore of the eroded beach, pumping the sand in a seawater slurry onto the eroded beach to supplement the natural sand present, and shaping the beach platform mechanically. Because renourishment has no influence on the nearshore processes which eroded the beach in the first instance (or on sea level increases), it generally has to be repeated at intervals. It is clear that the process of renourishment produces a beach that is different in some ways from natural beaches. In particular, renourished beaches appear to be harder than natural beaches and a vertical, erosional scarp often forms in the surface zone of the beach. It has been argued that this is due to compaction of the new beach material.[52-57] The continued use by sea turtles of the renourished beaches for egg incubation has generated concern that beach renourishment might adversely influence sea turtle reproduction. This is of some concern because, as we have discussed above, it is known that the incubation climate critically influences embryonic development in sea turtles and other reptiles. Moreover, beach hardening may well impact nest excavation and structure as well as emergence from the nest of hatchlings. However, there is little information available on how renourishment might change the climate for development in the beach.

Rimkus et al.[40] examined the hydric properties of eight renourished and seven natural beaches along the Atlantic coast of Florida in order to provide adequate replication for analyzing treatment effects. Although the distribution of water in both types of beach were similar, renourished beaches appear to retain more water than natural beaches. The field capacity[25,46] of renourished beaches was greater than that of natural beaches. The difference in water retention (i.e., increased water content) is consistent with a difference in the characteristic curves of renourished and natural sand. Renourished sand appears to hold slightly (but significantly) more water at the Ψ occurring in the sand. The difference in water retention may be attributable to differences in the sorting of sand composing the beach. The natural process of beach formation results in extensive sorting of the sand both by layers and within layers.[59] The orientation of the layer is determined by the wave wash on the beach and is typically inclined. Renourished beaches are unlikely to be sorted in the same way because they are not constructed in the same way.

Renourished beaches had a lower bulk density and were less compact than natural beaches.[40] This finding was not consistent with earlier work where the reverse was reported.[52-57] However, the earlier findings were not based on measurements of bulk density; rather, increased compaction was inferred from measurements of beach shear resistance using cone penetrometers.[60] Increases in shear resistance can be due to increases in compaction, but they may also be due to other factors such as sand particle shape and surface characteristics and to interactions (e.g., chemical) between particles.[61] Scarp formation can be attributed to an increase in the shear resistance[61] rather than to beach compaction and thus the presence of scarps does not confirm that a beach is compacted. Another explanation needs to be sought. A measure of beach shear resistance can also be described as a measure of beach hardening or strength. Shear resistance describes the ability of a soil, in this case, beach sand, to resist sliding along internal surfaces. In addition to the external force operating on the object, the object exerts a normal force on the surface over which it is tending to move. For a beach, the normal force would be the weight of sand (overburden) pressing down at the point of movement. The force required to just cause the surfaces to slide along each other (the point at which the material fails) is called the shearing stress (τ_f) and is related to the angle of stress of the normal force (σ) and the friction angle (ϕ) by the equation:

$$\tau_f = \sigma \cdot \tan \phi \tag{4.7}$$

For soils, ϕ is defined as the angle of internal friction. This angle represents the sum of the sliding friction (ϕ_s) and the effect of interlocking by the particles (θ):

$$\phi = \phi_s + \theta \tag{4.8}$$

The contributions of ϕ_s and θ can be separated experimentally. Sliding friction is characteristic of a particular soil and has to do with the nature of the surfaces which are in contact. Interlocking describes the tendency for particles to move out of each other's path as shear (failure) occurs and is strongly influenced by the distribution of particle sizes present (gradation) and density (compaction). Equations 4.7 and 4.8 demonstrate how beach shear resistance (τ_f) could change when only ϕ_s increases with no change in compaction or if compaction changes with no change in the type of particles in the beach (ϕ_s). Thus, the measurement of increased beach shear resistance does not necessarily establish that the beach is also compacted. Measurement of increased shear resistance in renourished beaches would indicate beach compaction, only when the particles on the renourished beach were identical to those on a reference beach. The relationship between shearing strength (τ_f) and the normal force (σ) is describe by the Coulombe equation:

$$\tau_f = c + \sigma \cdot \tan \phi \tag{4.9}$$

where an additional variable, cohesion (c), has been added to Equation 4.7. This relationship can be determined in the laboratory. However, another factor must also be considered. The new material used to renourish beaches may interact chemically through organic molecules bound to the surface. This could also result in increased shear resistance and should be evaluated. The scarps observed on renourished beaches in the tidal wash zone of the beach can be of considerable height and can be dangerous to humans, while limiting sea turtle access to the beach. Increased shear strength acts to increase the stability of slopes[61] with the result that scarps should be more stable on renourished beaches which exhibit increased shear resistance. Vertical cuts, such as scarps on beaches, are common in gullying or erosional situations. The height of the scarp (H_c) can be calculated from the angle of internal friction (ϕ) and the cohesion (c). To a first-order approximation, the greater the ϕ the greater the height (H_c) of the scarp that can develop:

$$H_c = 2 \cdot c/\gamma \cdot \tan (45 + \phi/2) \tag{4.10}$$

where γ is the unit weight of sand. Thus the magnitude of scarp formation on a renourished beach could serve as an index to changes in shear resistance of the beach if compaction were measured in some independent way.

The influence of beach renourishment on sea turtle reproduction or egg incubation has not been studied extensively. However, because the hydric, thermal, and respiratory properties of soil are a function of soil wetness, it might be expected that the microclimate of renourished beaches is different from that of natural beaches.[40] Whether or not and to what extent this difference might impact egg incubation can only be conjectured at this point and must ultimately be assessed empirically. Egg water exchange is driven by the difference in Ψ between the interior of the egg and the beach.[32] Observed differences[40] indicate that it is likely that the water potentials of renourished and natural beaches are so similar that the hydric climate in renourished and natural beaches are identical. The matric Ψ are in the range of –5 to –15 kPa for both types of beach.[40] If the total Ψ of the beach is the sum of the Ψ due to salt and the matric Ψ, then the value is around –20 to –40 kPa for both renourished and natural beaches. Because the driving force for water exchange between eggs and beach is likely to be around 800 kPa,[32] small differences between the two beach types are unlikely to be quantitatively important. However, the increased wetness is likely to alter the thermal and respiratory exchange of the eggs in the clutch. The differences in observed water content[40] between renourished and natural beaches could produce a substantial increase in the thermal conductivity[24,62] of renourished relative to natural beaches. This difference is likely to be important in two different contexts. First, sea turtle nests increase in temperature above beach temperature as incubation progresses,[31] with the center of the nest increasing in temperature to a greater extent than the periphery. The increase in temperature is a function of the degree to which heat is conducted away from the nest. Thus, if beach thermal conductivity increases, we would expect to find that the temperature in nests in renourished beaches would increase substantially less than in natural nests. The difference should be sufficient to influence both the duration of incubation and the water exchange of the egg[7,33] in clutches in renourished beaches. The second context involves the temperature of the beach rather than the temperature of the clutch. Beach temperature will be strongly dependent on the movement of heat inside the beach and on heat exchange at the beach surface. These processes are well understood for soils in general,[24] but, to my knowledge, have not been applied to nesting beaches. Renourished beaches should have greater thermal conductivity than natural beaches as a consequence of their increased in water content. In addition, because water stores large quantities of heat (relatively) an increase in beach water content will result in an increase in the heat capacity[63] of the beach. The differences in these thermal properties are likely to cause differences in the beach temperature of renourished and natural beaches on a daily and seasonal basis. The magnitude of such differences cannot be easily or reliably predicted. However, it is well known that incubation temperature influences important biological variables such as hatchling sex ratio, where even small differences in temperature at the right time and temperature can have important effects on sex determination. Sand water content also influences the gas permeability of sand.[24,45] It appears likely that observed water content differences[40] could result in a substantial decrease in gas permeability of renourished beaches. It can be estimated[49] that the gas exchange of nests in renourished beaches would be impeded to some extent. This is likely to result in lower concentrations of oxygen and higher concentrations of carbon dioxide

in the center of the clutch. The biological relevance of this potential effect remains to be investigated, but it has been shown experimentally that sea turtle eggs are sensitive to altered respiratory gas exchange.[2,64]

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5 Orientation, Navigation, and Natal Beach Homing in Sea Turtles

Kenneth J. Lohmann, Blair E. Witherington, Catherine M. F. Lohmann, and Michael Salmon

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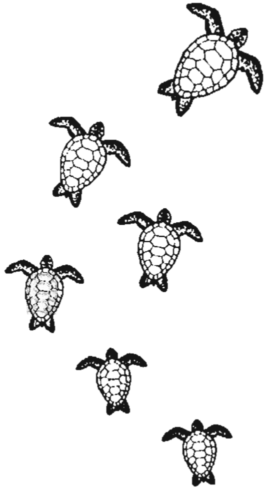

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Incidental Capture and Mortality of Olive Ridley Turtles (*Lepidochelys olivacea*) in Commercial Trawl Fisheries in Coastal Waters of Orissa, India

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Incidental Capture and Mortality of Olive Ridley Turtles (*Lepidochelys olivacea*) in Commercial Trawl Fisheries in Coastal Waters of Orissa, India

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ABSTRACT. – **A shrimp trawl fishery study was conducted in the coastal waters of Orissa, India, from November 2001 to March 2002; 76 trawls in water of 6–35 fathoms resulted in the capture of 26 olive ridley turtles (*Lepidochelys olivacea*). Most turtle captures occurred within 5 km of the shoreline and at a depth of less than 10 fathoms, emphasizing the need for greater protection of these nearshore habitats. Data revealed a strong relationship between tow time and mortality of turtles.**

Sea turtles face threats at every stage of their life cycles from natural and human-induced factors—both on land where females nest and hatchlings emerge and in offshore waters where they spend their life as hatchlings, juveniles, and adults. Of all known causes, fishery-related mortality is, by far, the most important cause of mortality of adult sea turtles and is considered the single largest threat to sea turtle populations globally. Five species of endangered sea turtles inhabit India's coastal waters, of which four are known to occur in Orissa: olive ridley (*Lepidochelys olivacea*), green (*Chelonia mydas*), hawksbill (*Eretmochelys imbricatta*), and leatherback (*Dermochelys coriacea*). All species occurring in India are legally protected in Schedule I of the Indian Wildlife (Protection) Act, 1972.

Orissa has three major mass nesting grounds for *L. olivacea*: Gahirmatha, Devi River mouth, and Rushikulya River mouth. There is global concern regarding the future of olive ridleys in Orissa, particularly due to large-scale mortality of sea turtles from incidental capture-related mortality (Rajagopalan et al. 1996; Pandav et al. 1998; Shanker and Mohanty 1999).

Sea turtle strandings related to shrimp fisheries on beaches of the southeastern United States was first documented in the early 1970s (Ulrich 1978; Murphy and Hopkins 1989). Hillestead et al. (1982) documented that sea turtles are caught in fisheries around the world, especially in trawl nets, and also reported that incidental or accidental capture in fishing nets was emerging as a global problem for sea turtle survival. Magnusson et al. (1990) emphasized that drowning in trawl nets in the Gulf of Mexico and along the US Atlantic coast is the major cause of sea turtle mortality due to human activities; this was also previously noted by Henwood and Stuntz (1987) who demonstrated a strong positive relationship between tow time and incidence of sea turtle mortality in the shrimp fishery.

Gove et al. (2001) highlighted the impact of shallow-water shrimp trawlers operating in Safola Bank, which caught between 1932 and 5436 sea turtles every year; these figures placed the shrimp fishery as one of the main sources of marine turtle mortality in central Mozambique. Guinea and Whiting (1997) inferred that flatback, loggerhead, and olive ridley turtles were being caught in Queensland waters. Dash and Kar (1990) and Pandav et al. (1997) have suggested that uncontrolled, mechanized fishing in areas of high sea turtle concentration has resulted in large-scale mortality of olive ridleys during the last two decades in Orissa. However, no quantified information about sea turtle and shrimp fishery interactions is available from the coastal waters off Orissa, and information on actual capture levels is relatively scarce.

The intent of this study was to estimate the incidental captures of sea turtles in the shrimp fishery off Orissa coastal waters. The rationale of the study was to determine which species were affected, what size classes, where captures occurred, and catch per unit effort (CPUE) of sea turtles in stratified study zones. We also wanted to determine the relationship between tow time and turtle mortality and to assess the relationship between sea turtle strandings and shrimp trawling patterns. The study also recommends conservation measures to safeguard sea turtle populations of Orissa while they are in offshore waters.

Study Area. — Orissa, an important maritime state on the east coast of India, has a coastline of 480 km and a continental shelf area of 24,000 km forming 8% and 4.5%, respectively, of the nation's total area. Orissa accounts for an annual production of 6858 tons of shrimp and 125,000 tons of other marine fisheries. A total of 545,109,387 USD are earned per annum by export of marine products from Orissa (Anonymous 1997). High sea turtle concentrations occur in Brahmini-Bhaitarini, Devi, and Rushikulya river mouths. Thus, the coastline between Brahmini-Baitarini and the Devi river mouths was chosen for sampling (Fig. 1). For easy accessibility to these areas, Paradip was selected as the base station to carry out the experimental trawling. The selected coastline was classified into three zones of 35, 55, and 60 km (Fig. 1):(Zone I) the coastal waters of Gahirmatha that extend from Dhamra River to Barunei, the mouth of River Hansua and forms the eastern boundary of the Bhitarkanika Wildlife Sanctuary, (Zone II) the coastal waters of Paradip that stretch from Barunei to the mouth of Jatadhara, near Paradip, the only natural harbor along the Orissa coast where the Mahanadhi enters Bay of Bengal, and (Zone III) the coastal waters of Devi that stretches from the Jatadhra River mouth to the Kadua River mouth. Operation of mechanized and nonmechanized boats in Orissa (Anonymous 1997) is given in Table 1.

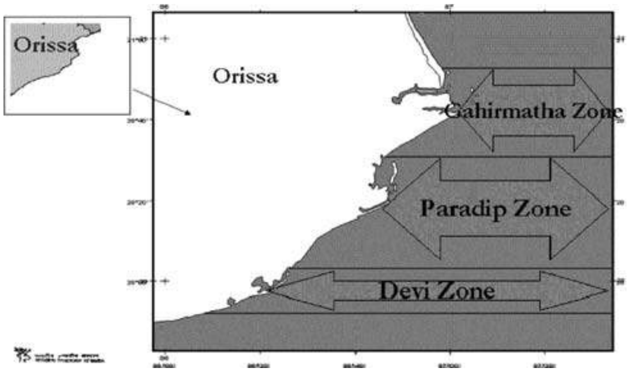

Figure 1. Study area on the coast of Orissa, India.

Table 1. Base-wise operation of mechanized and nonmechanized boats in Orissa.

Base	Wooden trawlers	Gill netters	Motorized country crafts
Balosore	293	322	592
Bhadrak	59	220	335
Balasore	1207	1500	475
Jagtsingpur	267	0	282
Kendrapara	28	48	0
Puri	39	18	854
Ganjam	686	1702	938
Total	2579	3810	3476

Methods. — Data collection was carried out between November 2001 and March 2002, and was conducted both at sea and along the coast. Stranded turtles on shore were counted and marked with white paint every 2 weeks from November 2001 to March 2002, and the size class and sex were recorded. Offshore data collection took place between January 2002 and March 2002. A fishing trawler (*M.V. Telaban*) was hired from the Orissa Fisheries Department. The authors also accompanied other private vessels to document the incidental capture of sea turtles in the private vessels. For this study, otter board single net trawling was used uniformly, because such trawlers are common along the Orissa coast. Trawling speed was maintained between 2 to 4.5 knots/h. Trawl time was limited to 1–2 hours in the research vessel to avoid sea turtle mortality due to drowning and 3–4 hours in the observer vessels, where the fishing protocols duplicated those of private vessels. The geographic locations of all the sampling areas (start and end position of the trawler) were taken with Garmin 12 Global Positioning System (GPS). Other parameters, such as start and end times of trawls and depth of the trawl, state of the sea, weather condition, and turtle captures and sightings, were recorded. Turtles caught in the net were kept aboard the vessel, and their physical condition was examined (i.e., alive, comatose, or dead). All turtles were identified by species and sex; and their curved carapace length (CCL), curved carapace width (CCW), straight carapace length (SCL), and straight carapace width (SCW) were measured, after which they were released at sea. The activity of comatose turtles was studied until they recovered. CPUE also was calculated according to the methods suggested by Jamir (1999). For each trawl sampled, effort (E) was standardized to reflect hours towed with a 50-m net using the formula:

$$E = (\text{nets} \times \text{length}/50\text{ m}) \times (\text{min}/60)$$

Where nets = number of nets towed in a trawler, length = head rope length of the net, min = min fished.

$$R = \sum T / \sum E$$

Where R = CPUE, T = number of turtles captured, E = Effort (standardized to 50-m net hours).

To determine the relationship between tow time and mortality, turtles captured were classified as alive, comatose, or dead (Magnusson et al. 1990). Because comatose turtles are already in a stressed condition, cannot swim actively, and will eventually drown, comatose turtles were counted as dead turtles. Tow duration of the trawls that resulted in turtle captures was plotted against the physical condition of the turtles to check the relationship between tow time and mortality. To document the size class of the turtles both caught in the net and stranded on shore, morphometric measurements of the turtles were analyzed using statistical software (SPSS-PC). The relationship between sea turtle stranding and shrimp fisheries was determined by correlating the number of stranded turtles with the number of shrimp vessels operating in each zone.

Results and Discussion. — Seventy-six trawls were carried out from January to March 2002, of which 52 were conducted in the research vessel and 24 in observer vessels. Of the 26 turtles caught, 21 were caught by the research vessel and 5 by the observer vessels. All turtles caught during the study were olive ridleys, of which 13 were males and 13 were females. Morphometric measurements of the turtles captured in trawl nets by the study vessels are given in Table 2. Trawls per zone, depth of trawls, duration of trawls, trawl distance, and distance of trawl from the nearest shoreline are given in Table 3.

During the study, 20 turtles (71.9%) were captured less than 5 km from the shore, and the remaining 6 sea turtles (28.1%) were recorded at varied distances beyond the 5-km line (Fig. 2). As observed during the study, day trawlers operating from fishing bases in Orissa trawl mostly within a distance of 5 km from the shoreline. Although the Orissa Marine Fishing Regulation Act prohibits mechanized trawling within 5 km from shoreline, the trawl operators in Orissa continue to operate in the prohibited zones. This may result in large-scale captures of turtles in nearshore areas.

Of the 26 turtles captured, 18 were captured at depths of less than 10 fathoms. All the captures in zone I were between 6 to 8 fathoms; in zone II, captures occurred between 8 to 18 fathoms; and in zone III, most captures were recorded in less than 10 fathom depth (Fig. 3), which

Table 2. Morphometric measurements of *Lepidochelys olivacea* captured during the study.

Sex	Curved carapace length	Curved carapace width	Straight carapace length	Straight carapace width
Male	69.1 ± 2.62	66.87 ± 2.57	64.5 ± 2.51	57.3 ± 3.34
Female	68.69 ± 2.61	67.32 ± 1.71	64.75 ± 1.98	55.83 ± 2.50

Table. 3. Trawl details by zones.

Zones	No. of trawls	Depth of trawls (fathoms)	Duration of trawls (h)	Trawl distance (km)	Distance from shore (km)
I	12	7.72 ± 0.28	1.24 ± 0.10	6.68 ± 0.93	5.85 ± 1.98
II	29	10.13 ± 0.47	1.21 ± 0.06	4.4 ± 0.29	4.9 ± 0.08
III	11	9.54 ± 0.46	1.24 ± 0.09	4.5 ± 0.53	3.19 ± 0.53
Observer vessel	24	17.41 ± 0.82	4.29 ± 0.22	13.42 ± 1.17	26.40 ± 2.28

was well supported when CPUE was calculated and analyzed. CPUE was calculated for every trawl in each study zone and was comparatively much higher in areas of less than 10 fathom depth and lower in areas of 14 to 35 fathoms depth, where normally turtles do not spend much time.

Most turtles caught on trawls of 1–2 hours were alive (mortality rate 11.1%). Trawls of more than 2 hours duration had a higher mortality rate of 66.6% (Fig. 4), which supports the study of Henwood and Stunz (1987), and Magnusson et al. (1990), who depicted the death rate of sea turtles in trawl nets at near zero until the tow time exceeds 60 minutes; mortality rose with increasing tow time to around 50% for tow times in excess of 200 minutes. Most trawls for the research vessel were restricted to 60-minute duration, and none exceeded 200 minutes. However, in the observer vessel, the minimum trawl duration was 180 minutes and maximum was 6 hours 45 minutes.

A total number of 11,593 (2714 male, 7147 female, 1732 unknown) stranded olive ridley turtles were counted between Paradip to Sonapur (Fig. 5). Mortality rate was higher during December and January, which may be because of the peak fishing season along the Orissa coast. Most dead females encountered during February and March were egg-bearing. The Paradip and Konark coasts accounted for the highest mortality, which can be attributed to high abundance of turtles and high intensity of trawling operations. Although sea turtles also are abundant on the Rushikulya coast due to the presence of the mass nesting site, strandings were much lower compared to other coastal areas due to less intensity of fishing in that area. Sea turtle strandings are mostly the result of a complex interaction between sea turtles and trawl or other fishing gear mortalities. Stranding occurs when a carcass starts to decompose, becomes inflated, and floats. Wind and currents bring a few of them to shore, but most dead turtles never reach the shore because they are

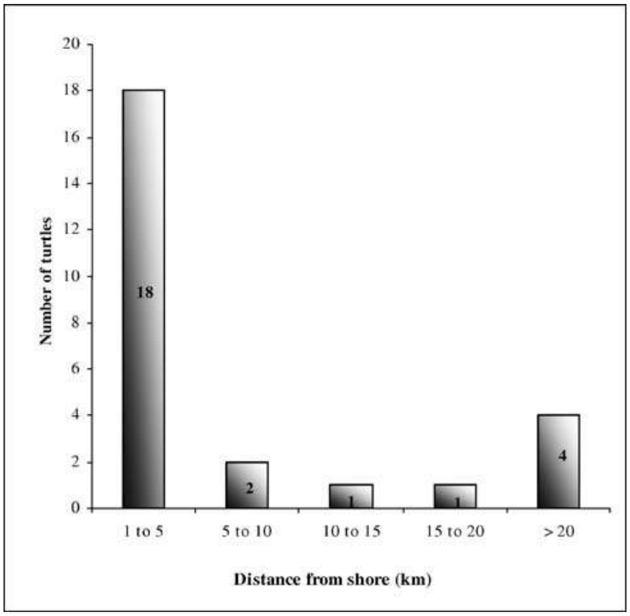

Figure 2. Distance from shore at which turtle captures occurred.

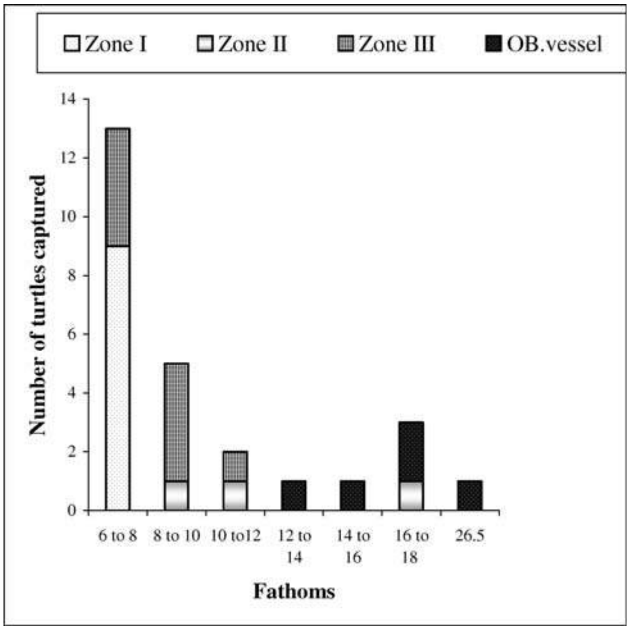

Figure 3. Depth at which captures occurred.

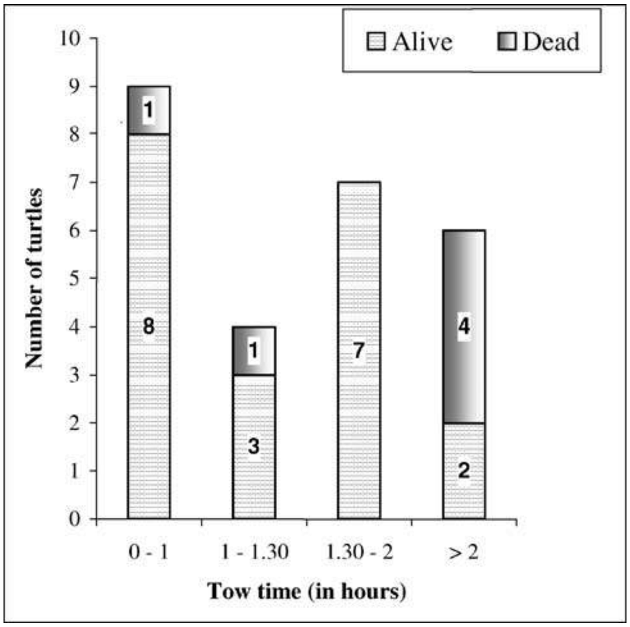

Figure 4. Relationship between tow time and mortality.

either eaten by scavengers, break apart, or burst and sink. Stranding has been used as an index of sea turtle mortality from shrimping activities (Caillouet et al. 1991) but is subject to error due to many factors including wind, currents, etc. Murphy and Hopkins-Murphy (1989) reported only 6 of 22 tagged loggerhead carcasses at sea turned up as strandings. Thus, sea turtle strandings represent only a small fraction of actual mortality.

Conclusions. — This study concludes that more than 70% of turtle captures in shrimp trawl fisheries in Orissa occurred within 5 km from shore. These were in generally shallow waters, less than 10 fathoms. A steep increase occurred in the mortality rate when the duration of the trawl was extended beyond 2 hours. Strandings were higher in zones where there is heavy marine fishing and high sea turtle abundance. These findings will help in the management of the sea turtle crisis that exists today. Because the peak turtle mating and breeding period coincides with the main fishing season (October–May), the turtles are most vulnerable at this time. Strict enforcement of the Orissa Marine Fishing Regulation Act in nearshore areas and in areas of high sea turtle concentration, and mandatory use of Turtle Excluder Devices (TEDs) in all fishing zones would reduce turtle mortality.

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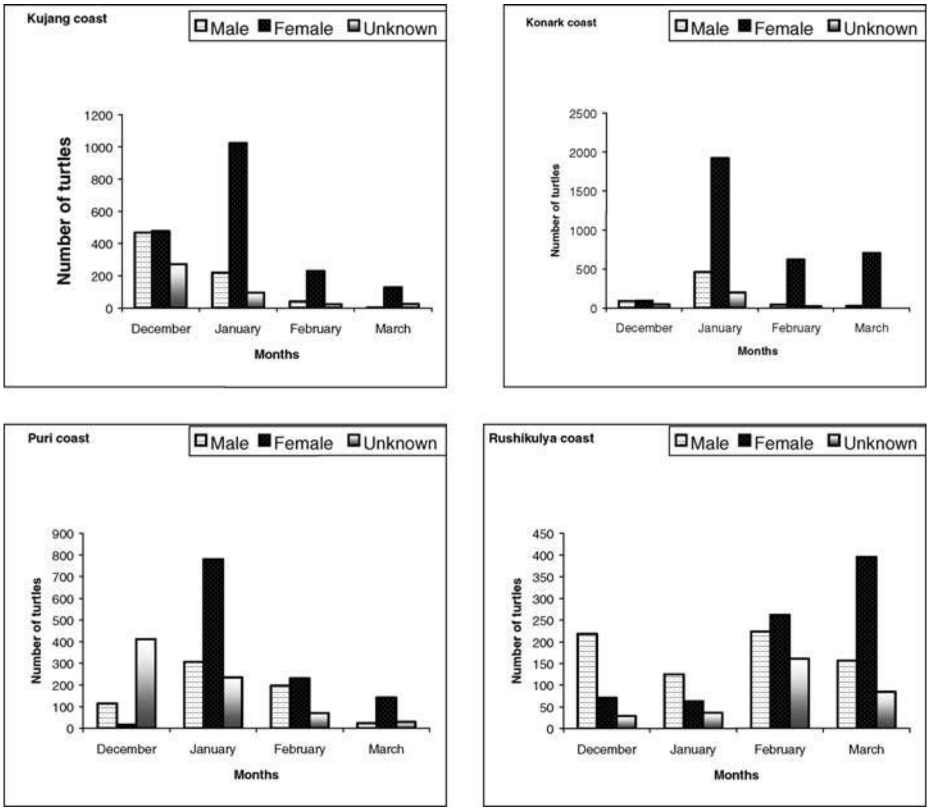

Figure 5. Sea turtle strandings and spatiotemporal pattern of the shrimp fishery.

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Reproductive Biology of the Six-Tubercled Amazon River Turtle *Podocnemis sextuberculata* (Testudines: Podocnemididae), in the Biological Reserve of Rio Trombetas, Pará, Brazil

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Abstract. – **We investigated the reproductive biology of *Podocnemis sextuberculata* in the Reserva Biológica do Rio Trombetas, state of Pará, Brazil. Female carapace length was positively correlated with number, average weight, and volume of eggs. Clutch size varied from 8 to 24 eggs, incubation period varied from 48 to 64 days, and hatching occurred about 1 month before the beginning of the rainy season. Local inhabitants regularly use females, nests, and neonates as food sources.**

Amazonian chelonians, mainly species of the genus *Podocnemis*, are one of the richest biological resources of Brazil. For centuries, the high quality of their meat and eggs has been essential to support the people who live in the region (Veríssimo 1895; Smith 1979; Cantarelli 1997). The rational use of these resources may offer alternatives for the social and economical development of the region. Nevertheless, to manage turtle populations and produce appropriate conservation plans, it is necessary to document aspects of their breeding biology. Although the distribution of species of *Podocnemis* covers a large area of the Amazon Basin, very little is known about their reproductive strategies.

Six species of *Podocnemis* are currently recognized, all restricted to South America: *P. expansa* and *P. unifilis* are widely distributed in the Amazon and Orinoco basins; *P. sextuberculata* is restricted to the Amazon basin; *P. erythrocephala* occurs mainly in the Rio Negro basin; *P. vogli* in the Orinoco; and *P. lewyana* in the Rio Magdalena (Pritchard and Trebbau 1984; Iverson 1992). Studies of reproductive biology have been published on *P. expansa* (Vanzolini, 1977; Alho et al., 1979; Alho and Pádua, 1982a,b; Pádua and Alho 1982; Valenzuela 2001), *P. unifilis* (Foote 1978; Pritchard and Trebbau 1984; Thorbjarnarson et al. 1993; Souza and Vogt 1994; Thorbjarnarson and Silveira 1996; Escalona and Fa 1998), *P. sextuberculata* (Vanzolini and Gomes 1979; Pezzuti and Vogt 1999), and *P. erythrocephala* (Castano-Mora et al. 2003).

Threats to sea turtles on the Rameswaram – Dhanushkhodi Coast

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Exploitation for trade

Turtle fishing has been practiced for a long time in the Gulf of Mannar and Palk Bay in Tamil Nadu. Five species of sea turtles - olive ridleys, green turtles, hawksbill turtles, loggerhead and leatherback turtles are recorded from this area (Bhupathy and Saravanan, 2002). Prior to 1972, there was legal live turtle trade between India and Sri Lanka. Live turtles were transported by sailing boats from Pamban, Tamil Nadu to Jaffna, Sri Lanka (Agastheesapillai, 1996) and turtle shells were exported to France, U.K. and several other European countries. In 1960, it was estimated that an average of about 3000 to 4000 turtles were landed every year in the Gulf of Mannar area and 1000 turtles in the Palk Bay; green turtles formed 75% of the landings, and olive ridley and loggerhead formed 20% (Jones and Fernando, 1973). The turtle trade was stopped in the early 1980s.

Accidental catch

Introduction of mechanisation in fisheries resulted in the accidental catch of turtles in gillnets, which became a major threat to their populations. The Indo-Norwegian project established a boat-building yard in Mandapam to construct 32-foot trawlers in 1970. Several trawlers were constructed under this programme and the fishermen of Mandapam, Pamban, Rameswaram and Kilakarai availed of loans to buy trawlers. The operation of trawlers in this area not only increased fish catch but also resulted in a substantial increase in the accidental catch and mortality of sea turtles. A recent study of sea turtles off the Tamil Nadu coast revealed that fishing is one of the major causes of turtle mortality there (Bhupathy and Saravanan, 2002).

Although rates of accidental catches of sea turtles are relatively high in this area, most of them go unreported or unnoticed. Accidental catch of olive ridleys, *Lepidochelys olivacea*, was reported at Pamban (Kasinathan, 1988) and off Dhanushkodi (Krishna Pillai *et. al.* 1989). The accidental catch of leatherback turtles, *Dermochelys coriacea*, was reported from Dhanushkodi (Krishna Pillai *et. al.* 1989), Rameswaram (Krishna Pillai *et. al.* 1995) and Mandapam (Rao *et. al.* 1989). Due to more attention in recent times to the conservation and management of sea turtles, (Jayaprakash *et. al* 1993), the stranding of turtles has been reported more frequently (Kasinathan and Palanichamy, 2002).

Recently, another threat has emerged in the form of dynamite fishing along the 19 km Rameswaram-Dhanushkodi coast. Dynamite fishing is practiced to catch fish, particularly soles, along the coast of Tamil Nadu and Kerala. Dynamite fishing in the Chaliyar river, north Kerala was reported by Lal Mohan (1991). Dynamite fishing is regularly practiced in the Rameswaram area, which often causes the death of endangered species, such as dolphins and sea turtles. Regular and continuous dynamite fishing operations caused the death of more than 10 turtles which were washed ashore during the end of January 2004 along the Rameswaram-Dhanushkodi coast.

Conclusion

Sea turtle populations in this area have already been depleted due to their over-exploitation for trade and from accidental drowning in fishing gear of gill nets and trawlers (Bhupathy and Saravanan, 2002). Boat propellers can also cause damage to the flippers and shells of sea turtles. Recently, dynamite fishing has become yet another threat to their populations. Such dynamite fishing should be stopped during the turtle nesting season (from December to March) to save the turtles from this additional threat. The state fisheries department, forest department and its wildlife wing, the Coast Guard and the local police should work together and take action to stop dynamite fishing and prevent further turtle mortality.

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November 24, 2022

TO WHOMSOEVER IT MAY CONCERN

November 23, 2022

To,
Asian Waterbirds Census Coordinator
Tamil Nadu

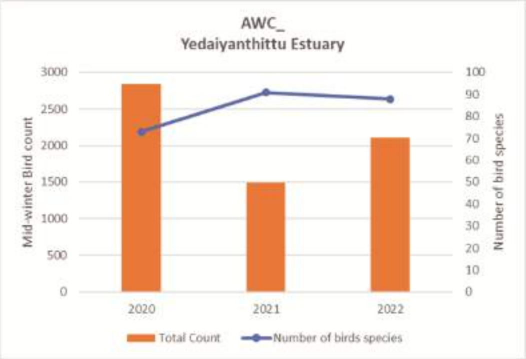
Subject: Reg. Avifaunal diversity at Yedaiyanthittu Estuary

Yedaiyanthittu Estuary and Kaliveli Tank in the Villupuram district of Tamil Nadu are extremely important staging and wintering areas for a wide variety of migratory waterfowl using the Central Asian Flyway (Pieter 1987, Scott 1989). Pieter (1987) noted about 40,000 birds in the Tank, and another 20,000 in the Estuary. More recently, citizen scientists and experts have reported 165 species of birds (at eBird portal) from the Estuary. However, due to increasing anthropogenic disturbances, the bird population is fluctuating and the last three-year Asian Waterbirds Census mid-winter counts available on eBird (see graph below) indicates that 91 bird species and over 2000 birds visit the wetland area regularly. The Estuary also supports a rich diversity of ichthyofauna as nearly 75 species of fishes have been reported this coastal wetland (Eric Ramanujam, M. and R. Anbarasan, 2009).

Given its rich biodiversity and ecological connectivity with the Kaliveli Tank, I request you to kindly strengthen the monitoring of this particular coastal wetland to support conservation actions with relevant stakeholders.

I look forward to coverage of this site in AWC 2023, with due participation of the AWC network and members of the State Biodiversity Board officials local committees.

Image: Bird count and number of species reported from the Yedaiyanthittu Estuary during 2020-2022



Yours sincerely

Dhruv Verma
AWC India Coordinator
Senior Technical Officer
Wetlands International South Asia

January 2022 bird census data -

Common name	scientific_name	Lat	Long	Count	Date
Ashy Prinia	Prinia socialis	12.23635	79.97214	6	01-29-2022
Asian Koel	Eudynamys scolopaceus	12.23635	79.97214	2	01-29-2022
Asian Openbill	Anastomus oscitans	12.23635	79.97214	151	01-29-2022
Asian Palm-Swift	Cypsiurus balasiensis	12.23635	79.97214	56	01-29-2022
Barn Swallow	Hirundo rustica	12.23635	79.97214	1	01-29-2022
Black Drongo	Dicrurus macrocercus	12.23635	79.97214	8	01-29-2022
Black-bellied Plover	Pluvialis squatarola	12.23635	79.97214	3	01-29-2022
Black-crowned Night-Heron	Nycticorax nycticorax	12.23635	79.97214	22	01-29-2022
Black-headed Ibis	Threskiornis melanocephalus	12.23635	79.97214	73	01-29-2022
Black-rumped Flameback	Dinopium benghalense	12.23635	79.97214	6	01-29-2022
Black-winged Stilt	Himantopus himantopus	12.23635	79.97214	7	01-29-2022
Blue-tailed Bee-eater	Merops philippinus	12.23635	79.97214	8	01-29-2022
Blyth's Reed Warbler	Acrocephalus dumetorum	12.23635	79.97214	7	01-29-2022
Brahminy Starling	Sturnia pagodarum	12.23635	79.97214	2	01-29-2022
Brown-headed Gull	Chroicocephalus brunnicephalus	12.23635	79.97214	391	01-29-2022
Caspian Tern	Hydroprogne caspia	12.23635	79.97214	19	01-29-2022
Cattle Egret	Bubulcus ibis	12.23635	79.97214	23	01-29-2022
Common Greenshank	Tringa nebularia	12.23635	79.97214	5	01-29-2022
Common Hawk-Cuckoo	Hierococcyx varius	12.23635	79.97214	5	01-29-2022
Common Iora	Aegithina tiphia	12.23635	79.97214	3	01-29-2022
Common Kingfisher	Alcedo atthis	12.23635	79.97214	2	01-29-2022

Common Myna	Acridotheres tristis	12.23635	79.97214	50	01-29-2022
Common Redshank	Tringa totanus	12.23635	79.97214	5	01-29-2022
Common Sandpiper	Actitis hypoleucos	12.23635	79.97214	5	01-29-2022
Common Tailorbird	Orthotomus sutorius	12.23635	79.97214	15	01-29-2022
Coppersmith Barbet	Psilopogon haemacephalus	12.23635	79.97214	1	01-29-2022
Eurasian Collared-Dove	Streptopelia decaocto	12.23635	79.97214	4	01-29-2022
Eurasian Curlew	Numenius arquata	12.23635	79.97214	1	01-29-2022
Eurasian Hoopoe	Upupa epops	12.23635	79.97214	1	01-29-2022
Glossy Ibis	Plegadis falcinellus	12.23635	79.97214	114	01-29-2022
Gray Francolin	Ortygornis pondicerianus	12.23635	79.97214	6	01-29-2022
Gray Heron	Ardea cinerea	12.23635	79.97214	11	01-29-2022
Great Crested Tern	Thalasseus bergii	12.23635	79.97214	9	01-29-2022
Great Egret	Ardea alba	12.23635	79.97214	9	01-29-2022
Greater Coucal	Centropus sinensis	12.23635	79.97214	3	01-29-2022
Green Bee-eater	Merops orientalis	12.23635	79.97214	4	01-29-2022
Green Sandpiper	Tringa ochropus	12.23635	79.97214	1	01-29-2022
Gull-billed Tern	Gelochelidon nilotica	12.23635	79.97214	4	01-29-2022
House Crow	Corvus splendens	12.23635	79.97214	28	01-29-2022
Indian Golden Oriole	Oriolus kundoo	12.23635	79.97214	1	01-29-2022
Indian Paradise-Flycatcher	Terpsiphone paradisi	12.23635	79.97214	1	01-29-2022
Indian Peafowl	Pavo cristatus	12.23635	79.97214	4	01-29-2022
Indian Pond-Heron	Ardeola grayii	12.23635	79.97214	28	01-29-2022
Indian Robin	Copsychus fulicatus	12.23635	79.97214	1	01-29-2022
Indian Roller	Coracias benghalensis	12.23635	79.97214	1	01-29-

					2022
Indian Silverbill	Euodice malabarica	12.23635	79.97214	1	01-29-2022
Indian Spot-billed Duck	Anas poecilorhyncha	12.23635	79.97214	5	01-29-2022
Indian Thick-knee	Burhinus indicus	12.23635	79.97214	5	01-29-2022
Intermediate Egret	Ardea intermedia	12.23635	79.97214	3	01-29-2022
Jerdon's Bushlark	Mirafra affinis	12.23635	79.97214	9	01-29-2022
Large-billed Crow	Corvus macrorhynchos	12.23635	79.97214	16	01-29-2022
Lesser Black-backed Gull	Larus fuscus	12.23635	79.97214	2	01-29-2022
Little Cormorant	Microcarbo niger	12.23635	79.97214	53	01-29-2022
Little Egret	Egretta garzetta	12.23635	79.97214	48	01-29-2022
Little Ringed Plover	Charadrius dubius	12.23635	79.97214	6	01-29-2022
Little Stint	Calidris minuta	12.23635	79.97214	2	01-29-2022
Loten's Sunbird	Cinnyris lotenius	12.23635	79.97214	7	01-29-2022
Marsh Sandpiper	Tringa stagnatilis	12.23635	79.97214	2	01-29-2022
Northern Pintail	Anas acuta	12.23635	79.97214	630	01-29-2022
Oriental Magpie-Robin	Copsychus saularis	12.23635	79.97214	1	01-29-2022
Pacific Golden-Plover	Pluvialis fulva	12.23635	79.97214	60	01-29-2022
Paddyfield Pipit	Anthus rufulus	12.23635	79.97214	5	01-29-2022
Painted Stork	Mycteria leucocephala	12.23635	79.97214	1	01-29-2022
Pale-billed Flowerpecker	Dicaeum erythrorhynchos	12.23635	79.97214	1	01-29-2022
Pied Bushchat	Saxicola caprata	12.23635	79.97214	2	01-29-2022
Pied Kingfisher	Ceryle rudis	12.23635	79.97214	2	01-29-2022
Pin-tailed Snipe	Gallinago stenura	12.23635	79.97214	8	01-29-2022
Plain Prinia	Prinia inornata	12.23635	79.97214	1	01-29-2022

Purple Heron	Ardea purpurea	12.23635	79.97214	1	01-29-2022
Purple Sunbird	Cinnyris asiaticus	12.23635	79.97214	1	01-29-2022
Purple-rumped Sunbird	Leptocoma zeylonica	12.23635	79.97214	8	01-29-2022
Red-vented Bulbul	Pycnonotus cafer	12.23635	79.97214	17	01-29-2022
Red-wattled Lapwing	Vanellus indicus	12.23635	79.97214	15	01-29-2022
Rock Pigeon	Columba livia	12.23635	79.97214	1	01-29-2022
Rose-ringed Parakeet	Psittacula krameri	12.23635	79.97214	14	01-29-2022
Rufous Treepie	Dendrocitta vagabunda	12.23635	79.97214	2	01-29-2022
Shikra	Accipiter badius	12.23635	79.97214	1	01-29-2022
Spotted Dove	Streptopelia chinensis	12.23635	79.97214	14	01-29-2022
Spotted Owlet	Athene brama	12.23635	79.97214	2	01-29-2022
Striated Heron	Butorides striata	12.23635	79.97214	4	01-29-2022
Whimbrel	Numenius phaeopus	12.23635	79.97214	9	01-29-2022
Whiskered Tern	Chlidonias hybrida	12.23635	79.97214	5	01-29-2022
White-browed Bulbul	Pycnonotus luteolus	12.23635	79.97214	13	01-29-2022
White-browed Wagtail	Motacilla maderaspatensis	12.23635	79.97214	6	01-29-2022
White-throated Kingfisher	Halcyon smyrnensis	12.23635	79.97214	7	01-29-2022
Wood Sandpiper	Tringa glareola	12.23635	79.97214	6	01-29-2022
Yellow-billed Babbler	Argya affinis	12.23635	79.97214	2	01-29-2022
Yellow-wattled Lapwing	Vanellus malabaricus	12.23635	79.97214	2	01-29-2022

December 2020 bird census data -

Ashy Prinia	**Prinia socialis**	12.23635	79.97214	2	25-12-2020
Asian Koel	**Eudynamys scolopaceus**	12.23635	79.97214	1	25-12-2020

Asian Palm-Swift	**Cypsiurus balasiensis**	12.23635	79.97214	12	25-12-2020
Barn Swallow	**Hirundo rustica**	12.23635	79.97214	4	25-12-2020
Black Drongo	**Dicrurus macrocercus**	12.23635	79.97214	6	25-12-2020
Black-bellied Plover	**Pluvialis squatarola**	12.23635	79.97214	4	25-12-2020
Black-crowned Night-Heron	**Nycticorax nycticorax**	12.23635	79.97214	2	25-12-2020
Black-rumped Flameback	**Dinopium benghalense**	12.23635	79.97214	2	25-12-2020
Black-winged Stilt	**Himantopus himantopus**	12.23635	79.97214	4	25-12-2020
Blue-faced Malkoha	**Phaenicophaeus viridirostris**	12.23635	79.97214	1	25-12-2020
Blue-tailed Bee-eater	**Merops philippinus**	12.23635	79.97214	1	25-12-2020
Blyth's Reed Warbler	**Acrocephalus dumetorum**	12.23635	79.97214	2	25-12-2020
Brown-headed Gull	**Chroicocephalus brunnicephalus**	12.23635	79.97214	34	25-12-2020
Caspian Tern	**Hydroprogne caspia**	12.23635	79.97214	6	25-12-2020
Cattle Egret	**Bubulcus ibis**	12.23635	79.97214	4	25-12-2020
Common Greenshank	**Tringa nebularia**	12.23635	79.97214	7	25-12-2020
Common Iora	**Aegithina tiphia**	12.23635	79.97214	2	25-12-2020
Common Kingfisher	**Alcedo atthis**	12.23635	79.97214	2	25-12-2020
Common Myna	**Acridotheres tristis**	12.23635	79.97214	10	25-12-2020
Common Redshank	**Tringa totanus**	12.23635	79.97214	34	25-12-2020
Common Sandpiper	**Actitis hypoleucos**	12.23635	79.97214	6	25-12-2020
Common Snipe	**Gallinago gallinago**	12.23635	79.97214	2	25-12-2020
Common Tailorbird	**Orthotomus sutorius**	12.23635	79.97214	6	25-12-2020
Common Woodshrike	**Tephrodornis pondicerianus**	12.23635	79.97214	1	25-12-2020
Eurasian Collared-Dove	**Streptopelia decaocto**	12.23635	79.97214	1	25-12-2020
Eurasian Curlew	**Numenius arquata**	12.23635	79.97214	2	25-12-

					2020
Eurasian Marsh-Harrier	**Circus aeruginosus**	12.23635	79.97214	1	25-12-2020
Glossy Ibis	**Plegadis falcinellus**	12.23635	79.97214	40	25-12-2020
Gray Francolin	**Ortygornis pondicerianus**	12.23635	79.97214	10	25-12-2020
Gray Heron	**Ardea cinerea**	12.23635	79.97214	3	25-12-2020
Great Crested Tern	**Thalasseus bergii**	12.23635	79.97214	29	25-12-2020
Great Egret	**Ardea alba**	12.23635	79.97214	7	25-12-2020
Greater Coucal	**Centropus sinensis**	12.23635	79.97214	1	25-12-2020
Green Bee-eater	**Merops orientalis**	12.23635	79.97214	9	25-12-2020
Gull-billed Tern	**Gelochelidon nilotica**	12.23635	79.97214	13	25-12-2020
House Crow	**Corvus splendens**	12.23635	79.97214	16	25-12-2020
Indian Golden Oriole	**Oriolus kundoo**	12.23635	79.97214	1	25-12-2020
Indian Paradise-Flycatcher	**Terpsiphone paradisi**	12.23635	79.97214	1	25-12-2020
Indian Peafowl	**Pavo cristatus**	12.23635	79.97214	5	25-12-2020
Indian Pond-Heron	**Ardeola grayii**	12.23635	79.97214	22	25-12-2020
Indian Robin	**Copsychus fulicatus**	12.23635	79.97214	2	25-12-2020
Indian Silverbill	**Euodice malabarica**	12.23635	79.97214	2	25-12-2020
Indian Spot-billed Duck	**Anas poecilorhyncha**	12.23635	79.97214	2	25-12-2020
Jerdon's Bushlark	**Mirafra affinis**	12.23635	79.97214	2	25-12-2020
Large-billed Crow	**Corvus macrorhynchos**	12.23635	79.97214	6	25-12-2020
Lesser Black-backed Gull	**Larus fuscus**	12.23635	79.97214	3	25-12-2020
Little Cormorant	**Microcarbo niger**	12.23635	79.97214	21	25-12-2020
Little Egret	**Egretta garzetta**	12.23635	79.97214	9	25-12-2020
Little Ringed Plover	**Charadrius dubius**	12.23635	79.97214	25	25-12-2020

Loten's Sunbird	**Cinnyris lotenius**	12.23635	79.97214	3	25-12-2020
Marsh Sandpiper	**Tringa stagnatilis**	12.23635	79.97214	2	25-12-2020
Oriental Magpie-Robin	**Copsychus saularis**	12.23635	79.97214	1	25-12-2020
Oriental Skylark	**Alauda gulgula**	12.23635	79.97214	2	25-12-2020
Osprey	**Pandion haliaetus**	12.23635	79.97214	2	25-12-2020
Pacific Golden-Plover	**Pluvialis fulva**	12.23635	79.97214	74	25-12-2020
Paddyfield Pipit	**Anthus rufulus**	12.23635	79.97214	2	25-12-2020
Pied Cuckoo	**Clamator jacobinus**	12.23635	79.97214	1	25-12-2020
Pied Kingfisher	**Ceryle rudis**	12.23635	79.97214	4	25-12-2020
Pin-tailed Snipe	**Gallinago stenura**	12.23635	79.97214	1	25-12-2020
Purple Sunbird	**Cinnyris asiaticus**	12.23635	79.97214	2	25-12-2020
Purple-rumped Sunbird	**Leptocoma zeylonica**	12.23635	79.97214	1	25-12-2020
Red-vented Bulbul	**Pycnonotus cafer**	12.23635	79.97214	6	25-12-2020
Red-wattled Lapwing	**Vanellus indicus**	12.23635	79.97214	5	25-12-2020
Rose-ringed Parakeet	**Psittacula krameri**	12.23635	79.97214	5	25-12-2020
Rufous Treepie	**Dendrocitta vagabunda**	12.23635	79.97214	4	25-12-2020
Spot-billed Pelican	**Pelecanus philippensis**	12.23635	79.97214	1	25-12-2020
Spotted Dove	**Streptopelia chinensis**	12.23635	79.97214	30	25-12-2020
Spotted Redshank	**Tringa erythropus**	12.23635	79.97214	1	25-12-2020
Western Reef-Heron	**Egretta gularis**	12.23635	79.97214	2	25-12-2020
Whimbrel	**Numenius phaeopus**	12.23635	79.97214	9	25-12-2020
Whiskered Tern	**Chlidonias hybrida**	12.23635	79.97214	4	25-12-2020
White-breasted Waterhen	**Amaurornis phoenicurus**	12.23635	79.97214	2	25-12-2020
White-browed Bulbul	**Pycnonotus luteolus**	12.23635	79.97214	8	25-12-

					2020
White-throated Kingfisher	**Halcyon smyrnensis**	12.23635	79.97214	5	25-12-2020
Yellow-billed Babbler	**Argya affinis**	12.23635	79.97214	8	25-12-2020

January 2020 bird census data -

Ashy Prinia	Prinia socialis	12.23635	79.97214	2	2020-01-19
Asian Palm-Swift	Cypsiurus balasiensis	12.23635	79.97214	2	2020-01-19
Black-bellied Plover	Pluvialis squatarola	12.23635	79.97214	10	2020-01-19
Black-tailed Godwit	Limosa limosa	12.23635	79.97214	6	2020-01-19
Black-winged Stilt	Himantopus himantopus	12.23635	79.97214	85	2020-01-19
Black Drongo	Dicrurus macrocercus	12.23635	79.97214	2	2020-01-19
Blyth's Reed Warbler	Acrocephalus dumetorum	12.23635	79.97214	2	2020-01-19
Booted Warbler	Iduna caligata	12.23635	79.97214	1	2020-01-19
Brahminy Starling	Sturnia pagodarum	12.23635	79.97214	2	2020-01-19
Caspian Tern	Hydroprogne caspia	12.23635	79.97214	15	2020-01-19
Cattle Egret	Bubulcus ibis	12.23635	79.97214	18	2020-01-19
Common Greenshank	Tringa nebularia	12.23635	79.97214	4	2020-01-19
Common Iora	Aegithina tiphia	12.23635	79.97214	2	2020-01-19
Common Kingfisher	Alcedo atthis	12.23635	79.97214	1	2020-01-19
Eurasian Moorhen	Gallinula chloropus	12.23635	79.97214	8	2020-01-19
Common Myna	Acridotheres tristis	12.23635	79.97214	10	2020-01-19
Common Redshank	Tringa totanus	12.23635	79.97214	55	2020-01-19
Common Sandpiper	Actitis hypoleucos	12.23635	79.97214	3	2020-01-19
Common Snipe	Gallinago gallinago	12.23635	79.97214	12	2020-01-19
Common Tern	Sterna hirundo	12.23635	79.97214	3	2020-01-

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Common Woodshrike	Tephrodornis pondicerianus	12.23635	79.97214	1	2020-01-19
Coppersmith Barbet	Psilopogon haemacephalus	12.23635	79.97214	6	2020-01-19
Eurasian Curlew	Numenius arquata	12.23635	79.97214	35	2020-01-19
Eurasian Wigeon	Mareca penelope	12.23635	79.97214	450	2020-01-19
Green-winged Teal	Anas crecca	12.23635	79.97214	250	2020-01-19
Gray Heron	Ardea cinerea	12.23635	79.97214	2	2020-01-19
Green Bee-eater	Merops orientalis	12.23635	79.97214	10	2020-01-19
Great Egret	Ardea alba	12.23635	79.97214	15	2020-01-19
Greater Flamingo	Phoenicopterus roseus	12.23635	79.97214	55	2020-01-19
Green Sandpiper	Tringa ochropus	12.23635	79.97214	1	2020-01-19
Gull-billed Tern	Gelochelidon nilotica	12.23635	79.97214	2	2020-01-19
Eurasian Hoopoe	Upupa epops	12.23635	79.97214	1	2020-01-19
House Crow	Corvus splendens	12.23635	79.97214	7	2020-01-19
Indian Cormorant	Phalacrocorax fuscicollis	12.23635	79.97214	35	2020-01-19
Indian Pond-Heron	Ardeola grayii	12.23635	79.97214	20	2020-01-19
Intermediate Egret	Ardea intermedia	12.23635	79.97214	5	2020-01-19
Jerdon's Bushlark	Mirafra affinis	12.23635	79.97214	3	2020-01-19
Kentish Plover	Charadrius alexandrinus	12.23635	79.97214	3	2020-01-19
Large-billed Crow	Corvus macrorhynchos	12.23635	79.97214	2	2020-01-19
Lesser Sand-Plover	Charadrius mongolus	12.23635	79.97214	35	2020-01-19
Little Ringed Plover	Charadrius dubius	12.23635	79.97214	4	2020-01-19
Little Cormorant	Microcarbo niger	12.23635	79.97214	12	2020-01-19
Little Egret	Egretta garzetta	12.23635	79.97214	16	2020-01-19
Little Grebe	Tachybaptus ruficollis	12.23635	79.97214	3	2020-01-

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Little Stint	Calidris minuta	12.23635	79.97214	4	2020-01-19
Oriental Magpie-Robin	Copsychus saularis	12.23635	79.97214	1	2020-01-19
Marsh Sandpiper	Tringa stagnatilis	12.23635	79.97214	5	2020-01-19
Northern Pintail	Anas acuta	12.23635	79.97214	1000	2020-01-19
Northern Shoveler	Spatula clypeata	12.23635	79.97214	300	2020-01-19
Paddyfield Pipit	Anthus rufulus	12.23635	79.97214	4	2020-01-19
Osprey	Pandion haliaetus	12.23635	79.97214	1	2020-01-19
Pale-billed Flowerpecker	Dicaeum erythrorhynchos	12.23635	79.97214	1	2020-01-19
Pacific Golden-Plover	Pluvialis fulva	12.23635	79.97214	35	2020-01-19
Pied Bushchat	Saxicola caprata	12.23635	79.97214	1	2020-01-19
Pied Cuckoo	Clamator jacobinus	12.23635	79.97214	1	2020-01-19
Pied Kingfisher	Ceryle rudis	12.23635	79.97214	3	2020-01-19
Purple-rumped Sunbird	Leptocoma zeylonica	12.23635	79.97214	1	2020-01-19
Purple Sunbird	Cinnyris asiaticus	12.23635	79.97214	1	2020-01-19
Red-wattled Lapwing	Vanellus indicus	12.23635	79.97214	12	2020-01-19
Ruff	Calidris pugnax	12.23635	79.97214	25	2020-01-19
Rufous Treepie	Dendrocitta vagabunda	12.23635	79.97214	1	2020-01-19
Shikra	Accipiter badius	12.23635	79.97214	2	2020-01-19
Spot-billed Pelican	Pelecanus philippensis	12.23635	79.97214	120	2020-01-19
Spotted Owlet	Athene brama	12.23635	79.97214	1	2020-01-19
Tricolored Munia	Lonchura malacca	12.23635	79.97214	2	2020-01-19
Western Reef-Heron	Egretta gularis	12.23635	79.97214	1	2020-01-19
White-browed Wagtail	Motacilla maderaspatensis	12.23635	79.97214	1	2020-01-19
White-breasted Waterhen	Amaurornis phoenicurus	12.23635	79.97214	1	2020-01-

					19
Whimbrel	Numenius phaeopus	12.23635	79.97214	35	2020-01-19
Whiskered Tern	Chlidonias hybrida	12.23635	79.97214	5	2020-01-19
White-throated Kingfisher	Halcyon smyrnensis	12.23635	79.97214	1	2020-01-19
Wood Sandpiper	Tringa glareola	12.23635	79.97214	65	2020-01-19
Zitting Cisticola	Cisticola juncidis	12.23635	79.97214	1	2020-01-19

KV Sudhakar

(K.V. SUDHAKAR)

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BIRD COUNT INDIA

Dated: 15 November 2022

TO WHOM IT MAY CONCERN

Yedaiyanthittu Estuary (இடையன் திட்டு கழிமுகம்), on the eastern coast of Tamil Nadu, is an important staging ground for inter-continental migrant birds from the northern hemisphere. Regular monitoring in the last five years has recorded 157 species of birds (list attached) in the public global repository eBird (www.ebird.org/india), including ten species that are classified as Threatened or Near Threatened as per the International Union for the Conservation of Nature (IUCN).

The Great Knot, an endangered shorebird, was reported in 2015. The estuary is one of one three sites in India where the Near Threatened Grey-tailed Tattler has ever been recorded. Apart from this, 12 bird species included in the Schedule I of the Wildlife Protection Act of 1972 are found here, as well as 46 species that are categorised as of High or Moderate Conservation Concern in the State of India's Birds 2020 report (www.stateofindiasbirds.in). Waterbirds occur in large congregations in winter - about 2,000 ducks, and 300 each of Pacific Golden Plovers and Brown-headed Gulls have been reported in the month of January during the annual Asian Waterbird Census.

Yedaiyanthittu Estuary is one of the few natural and unmodified estuaries left in India, and is of considerable conservation value, as the information above attests.

Faithfully,

Praveen J
Coordinator, Bird Count India
Email: skimmer@birdcount.in

Bird Count India is an informal partnership of a large number of organisations and groups working together to increase our collective knowledge about bird distributions and populations
www.birdcount.in

Yedayanthittu Estuary

	English Name	**Scientific Name**
1.	Lesser Whistling-Duck	Dendrocygna javanica
2.	Greylag Goose	Anser anser
3.	Garganey	Spatula querquedula
4.	Northern Shoveler	Spatula clypeata
5.	Eurasian Wigeon	Mareca penelope
6.	Indian Spot-billed Duck	Anas poecilorhyncha
7.	Northern Pintail	Anas acuta
8.	Green-winged Teal (Common Teal)	Anas crecca
9.	Indian Peafowl	Pavo cristatus
10.	Grey Francolin	Ortygornis pondicerianus
11.	Greater Flamingo	Phoenicopterus roseus
12.	Little Grebe	Tachybaptus ruficollis
13.	Rock Pigeon (Blue Rock Pigeon)	Columba livia
14.	Eurasian Collared-Dove	Streptopelia decaocto
15.	Spotted Dove	Spilopelia chinensis
16.	Greater Coucal	Centropus sinensis
17.	Blue-faced Malkoha	Phaenicophaeus viridirostris
18.	Pied Cuckoo (Jacobin Cuckoo)	Clamator jacobinus
19.	Asian Koel	Eudynamys scolopaceus
20.	Common Hawk-Cuckoo	Hierococcyx varius
21.	Asian Palm Swift	Cypsiurus balasiensis
22.	Eurasian Moorhen	Gallinula chloropus
23.	White-breasted Waterhen	Amaurornis phoenicurus
24.	Indian Thick-knee (Indian Stone-curlew)	Burhinus indicus
25.	Black-winged Stilt	Himantopus himantopus
26.	Black-bellied Plover (Grey Plover)	Pluvialis squatarola
27.	Pacific Golden-Plover	Pluvialis fulva
28.	Yellow-wattled Lapwing	Vanellus malabaricus
29.	Red-wattled Lapwing	Vanellus indicus
30.	Lesser Sand-Plover	Charadrius mongolus
31.	Greater Sand-Plover	Charadrius leschenaultii
32.	Kentish Plover	Charadrius alexandrinus
33.	Little Ringed Plover	Charadrius dubius
34.	Whimbrel	Numenius phaeopus
35.	Eurasian Curlew	Numenius arquata
36.	Black-tailed Godwit	Limosa limosa
37.	Ruff	Calidris pugnax
38.	Curlew Sandpiper	Calidris ferruginea
39.	Temminck's Stint	Calidris temminckii
40.	Dunlin	Calidris alpina
41.	Little Stint	Calidris minuta

42.	Common Snipe	Gallinago gallinago
43.	Pin-tailed Snipe	Gallinago stenura
44.	Terek Sandpiper	Xenus cinereus
45.	Common Sandpiper	Actitis hypoleucos
46.	Green Sandpiper	Tringa ochropus
47.	Grey-tailed Tattler	Tringa brevipes
48.	Spotted Redshank	Tringa erythropus
49.	Common Greenshank	Tringa nebularia
50.	Marsh Sandpiper	Tringa stagnatilis
51.	Wood Sandpiper	Tringa glareola
52.	Common Redshank	Tringa totanus
53.	Black-headed Gull	Chroicocephalus ridibundus
54.	Brown-headed Gull	Chroicocephalus brunnicephalus
55.	Pallas's Gull	Ichthyaetus ichthyaetus
56.	Lesser Black-backed Gull	Larus fuscus
57.	Little Tern	Sternula albifrons
58.	Gull-billed Tern	Gelochelidon nilotica
59.	Caspian Tern	Hydroprogne caspia
60.	White-winged Tern	Chlidonias leucopterus
61.	Whiskered Tern	Chlidonias hybrida
62.	Common Tern	Sterna hirundo
63.	Great Crested Tern	Thalasseus bergii
64.	Lesser Crested Tern	Thalasseus bengalensis
65.	Asian Openbill	Anastomus oscitans
66.	Painted Stork	Mycteria leucocephala
67.	Oriental Darter	Anhinga melanogaster
68.	Little Cormorant	Microcarbo niger
69.	Indian Cormorant (Indian Shag)	Phalacrocorax fuscicollis
70.	Spot-billed Pelican	Pelecanus philippensis
71.	Yellow Bittern	Ixobrychus sinensis
72.	Grey Heron	Ardea cinerea
73.	Purple Heron	Ardea purpurea
74.	Great Egret	Ardea alba
75.	Intermediate Egret	Ardea intermedia
76.	Little Egret	Egretta garzetta
77.	Western Reef-Heron (Western Reef-Egret)	Egretta gularis
78.	Cattle Egret	Bubulcus ibis
79.	Indian Pond-Heron	Ardeola grayii
80.	Striated Heron (Little Heron)	Butorides striata
81.	Black-crowned Night-Heron	Nycticorax nycticorax
82.	Glossy Ibis	Plegadis falcinellus
83.	Black-headed Ibis	Threskiornis melanocephalus
84.	Osprey	Pandion haliaetus
85.	Black-winged Kite (Black-shouldered Kite)	Elanus caeruleus

86.	Oriental Honey-buzzard (Crested Honey Buzzard)	Pernis ptilorhynchus
87.	Eurasian Marsh-Harrier	Circus aeruginosus
88.	Pallid Harrier	Circus macrourus
89.	Montagu's Harrier	Circus pygargus
90.	Shikra	Accipiter badius
91.	Brahminy Kite	Haliastur indus
92.	Spotted Owlet	Athene brama
93.	Eurasian Hoopoe	Upupa epops
94.	Common Kingfisher (Small Blue Kingfisher)	Alcedo atthis
95.	White-throated Kingfisher	Halcyon smyrnensis
96.	Pied Kingfisher	Ceryle rudis
97.	Asian Green Bee-eater	Merops orientalis
98.	Blue-tailed Bee-eater	Merops philippinus
99.	Indian Roller	Coracias benghalensis
100.	Coppersmith Barbet	Psilopogon haemacephalus
101.	Black-rumped Flameback (Lesser Goldenbacked Woodpecker)	Dinopium benghalense
102.	Eurasian Kestrel (Common Kestrel)	Falco tinnunculus
103.	Peregrine Falcon	Falco peregrinus
104.	Rose-ringed Parakeet	Psittacula krameri
105.	Indian Golden Oriole	Oriolus kundoo
106.	Ashy Woodswallow	Artamus fuscus
107.	Common Woodshrike	Tephrodornis pondicerianus
108.	Common Iora	Aegithina tiphia
109.	Black Drongo	Dicrurus macrocercus
110.	Indian Paradise-Flycatcher	Terpsiphone paradisi
111.	Brown Shrike	Lanius cristatus
112.	Bay-backed Shrike	Lanius vittatus
113.	Rufous Treepie	Dendrocitta vagabunda
114.	House Crow	Corvus splendens
115.	Large-billed Crow	Corvus macrorhynchos
116.	Ashy-crowned Sparrow-Lark (Ashy-crowned Finch-Lark)	Eremopterix griseus
117.	Jerdon's Bushlark	Mirafra affinis
118.	Oriental Skylark	Alauda gulgula
119.	Common Tailorbird	Orthotomus sutorius
120.	Ashy Prinia	Prinia socialis
121.	Plain Prinia	Prinia inornata
122.	Zitting Cisticola	Cisticola juncidis
123.	Booted Warbler	Iduna caligata
124.	Blyth's Reed Warbler	Acrocephalus dumetorum
125.	Dusky Crag-Martin	Ptyonoprogne concolor
126.	Barn Swallow	Hirundo rustica
127.	Streak-throated Swallow	Petrochelidon fluvicola

128.	Red-vented Bulbul	Pycnonotus cafer
129.	White-browed Bulbul	Pycnonotus luteolus
130.	Yellow-billed Babbler	Argya affinis
131.	Rosy Starling	Pastor roseus
132.	Brahminy Starling	Sturnia pagodarum
133.	Common Myna	Acridotheres tristis
134.	Asian Brown Flycatcher	Muscicapa dauurica
135.	Indian Robin	Copsychus fulicatus
136.	Oriental Magpie-Robin	Copsychus saularis
137.	Pied Bushchat	Saxicola caprata
138.	Pale-billed Flowerpecker	Dicaeum erythrorhynchos
139.	Purple-rumped Sunbird	Leptocoma zeylonica
140.	Purple Sunbird	Cinnyris asiaticus
141.	Loten's Sunbird (Long-billed Sunbird)	Cinnyris lotenius
142.	Indian Silverbill (White-throated Munia)	Euodice malabarica
143.	Scaly-breasted Munia (Spotted Munia)	Lonchura punctulata
144.	Tricolored Munia (Black-headed Munia)	Lonchura malacca
145.	Eastern Yellow Wagtail	Motacilla tschutschensis
146.	White-browed Wagtail (Large Pied Wagtail)	Motacilla maderaspatensis
147.	Paddyfield Pipit	Anthus rufulus
148.	Blyth's Pipit	Anthus godlewskii

ALAMPARAI FORT - ESTUARY

Sl No.	**English Name**	**Scientific Name**
1.	Indian Spot-billed Duck	Anas poecilorhyncha
2.	Indian Peafowl	Pavo cristatus
3.	Grey Francolin	Ortygornis pondicerianus
4.	Little Grebe	Tachybaptus ruficollis
5.	Rock Pigeon (Blue Rock Pigeon)	Columba livia
6.	Spotted Dove	Spilopelia chinensis
7.	Greater Coucal	Centropus sinensis
8.	Asian Koel	Eudynamys scolopaceus
9.	Common Hawk-Cuckoo	Hierococcyx varius
10.	Asian Palm Swift	Cypsiurus balasiensis
11.	White-breasted Waterhen	Amaurornis phoenicurus
12.	Black-winged Stilt	Himantopus himantopus
13.	Black-bellied Plover (Grey Plover)	Pluvialis squatarola
14.	Pacific Golden-Plover	Pluvialis fulva
15.	Red-wattled Lapwing	Vanellus indicus
16.	Lesser Sand-Plover	Charadrius mongolus
17.	Greater Sand-Plover	Charadrius leschenaultii
18.	Kentish Plover	Charadrius alexandrinus
19.	Little Ringed Plover	Charadrius dubius
20.	Whimbrel	Numenius phaeopus
21.	Eurasian Curlew	Numenius arquata
22.	Sanderling	Calidris alba
23.	Little Stint	Calidris minuta
24.	Terek Sandpiper	Xenus cinereus
25.	Common Sandpiper	Actitis hypoleucos
26.	Common Greenshank	Tringa nebularia
27.	Common Redshank	Tringa totanus
28.	Slender-billed Gull	Chroicocephalus genei
29.	Black-headed Gull	Chroicocephalus ridibundus
30.	Brown-headed Gull	Chroicocephalus brunnicephalus
31.	Pallas's Gull	Ichthyaetus ichthyaetus
32.	Lesser Black-backed Gull	Larus fuscus
33.	Little Tern	Sternula albifrons
34.	Gull-billed Tern	Gelochelidon nilotica
35.	Caspian Tern	Hydroprogne caspia
36.	Whiskered Tern	Chlidonias hybrida
37.	Common Tern	Sterna hirundo
38.	Great Crested Tern	Thalasseus bergii
39.	Lesser Crested Tern	Thalasseus bengalensis
40.	Asian Openbill	Anastomus oscitans
41.	Painted Stork	Mycteria leucocephala
42.	Little Cormorant	Microcarbo niger
43.	Spot-billed Pelican	Pelecanus philippensis
44.	Grey Heron	Ardea cinerea

45.	Great Egret	Ardea alba
46.	Intermediate Egret	Ardea intermedia
47.	Little Egret	Egretta garzetta
48.	Western Reef-Heron (Western Reef-Egret)	Egretta gularis
49.	Cattle Egret	Bubulcus ibis
50.	Indian Pond-Heron	Ardeola grayii
51.	Striated Heron (Little Heron)	Butorides striata
52.	Black-crowned Night-Heron	Nycticorax nycticorax
53.	Glossy Ibis	Plegadis falcinellus
54.	Black-headed Ibis	Threskiornis melanocephalus
55.	Oriental Honey-buzzard (Crested Honey Buzzard)	Pernis ptilorhynchus
56.	Shikra	Accipiter badius
57.	Black Kite	Milvus migrans
58.	Brahminy Kite	Haliastur indus
59.	Spotted Owlet	Athene brama
60.	Eurasian Hoopoe	Upupa epops
61.	Common Kingfisher (Small Blue Kingfisher)	Alcedo atthis
62.	White-throated Kingfisher	Halcyon smyrnensis
63.	Pied Kingfisher	Ceryle rudis
64.	Asian Green Bee-eater	Merops orientalis
65.	Blue-tailed Bee-eater	Merops philippinus
66.	Indian Roller	Coracias benghalensis
67.	Black-rumped Flameback (Lesser Goldenbacked Woodpecker)	Dinopium benghalense
68.	Rose-ringed Parakeet	Psittacula krameri
69.	Indian Golden Oriole	Oriolus kundoo
70.	Ashy Woodswallow	Artamus fuscus
71.	Common Iora	Aegithina tiphia
72.	Black Drongo	Dicrurus macrocercus
73.	Brown Shrike	Lanius cristatus
74.	Rufous Treepie	Dendrocitta vagabunda
75.	House Crow	Corvus splendens
76.	Large-billed Crow	Corvus macrorhynchos
77.	Ashy-crowned Sparrow-Lark (Ashy-crowned Finch-Lark)	Eremopterix griseus
78.	Jerdon's Bushlark	Mirafra affinis
79.	Oriental Skylark	Alauda gulgula
80.	Common Tailorbird	Orthotomus sutorius
81.	Ashy Prinia	Prinia socialis
82.	Barn Swallow	Hirundo rustica
83.	Red-vented Bulbul	Pycnonotus cafer
84.	White-browed Bulbul	Pycnonotus luteolus
85.	Large Grey Babbler	Argya malcolmi
86.	Yellow-billed Babbler	Argya affinis

87.	Brahminy Starling	Sturnia pagodarum
88.	Common Myna	Acridotheres tristis
89.	Indian Robin	Copsychus fulicatus
90.	Pale-billed Flowerpecker	Dicaeum erythrorhynchos
91.	Purple-rumped Sunbird	Leptocoma zeylonica
92.	Purple Sunbird	Cinnyris asiaticus
93.	Loten's Sunbird (Long-billed Sunbird)	Cinnyris lotenius
94.	Richard's Pipit	Anthus richardi
95.	Paddyfield Pipit	Anthus rufulus