Flotilla of mating green turtles at Raine Island, Great Barrier Reef, Australia. © 2006 DAVID DOUBILET

In August 2006, a handful of international sea turtle experts gathered in Washington, D.C., to address critical issues in sea turtle conservation at the third Burning Issues retreat of the IUCN–World Conservation Union's Marine Turtle Specialist Group, a meeting now referred to as BI:3. Much like the film *MI:3,* the BI:3 team tackled the "Mission Impossible" of defining the great unanswered questions, armed with only a few centuries of cumulative firsthand experience and the results of a simple survey administered among some 300 of the world's leading sea turtle experts from 80 countries.

Framing the questions is a first step in creating plans and strategies that will eventually fill critical knowledge gaps and lead to sound conservation strategies. The results of BI:3—the seven unsolved mysteries described in these next articles—highlight the great unknowns about sea turtles. They provide a framework for focusing scientific progress, intellectual powers, and investment in global research, and they serve as a public relations tool to generate greater interest and financing for conserving marine turtles and their habitats.

Roderic B. Mast, Co-Chair, IUCN Marine Turtle Specialist Group

The Unsolved Mysteries of Sea Turtles

Where do sea turtles spend their first years of life?

What are the ecological roles of sea turtles, and how many turtles are needed to fulfill those roles?

What proportion of males to females is necessary to maintain a healthy sea turtle population?

How do sea turtles sense their environment?

How do sea turtles navigate?

What causes fibropapillomas?

How will climate change affect sea turtles?

Source: These questions are the result of BI:3, the third Burning Issues retreat of the IUCN Species Survival Commission's Marine Turtle Specialist Group, Washington, D.C., August 2006.

The Mystery of Lost Little Turtles

Where do sea turtles spend their first years of life?

On entering the world, sea turtles almost immediately get lost. These tiny, finger-length hatchlings scramble from their sandy nests, rush into the surf, and beat their flippers out to sea beyond where scientists can comfortably catalog their lives.

It is not that the turtles themselves are lost. To the contrary, even little turtles in a big ocean seem to know a lot about where they are and where they would like to be. *"Elusive"* is a better word to describe these youngsters. They are certainly lost to us, as terrestrial observers, until they reappear as juveniles swimming in coastal waters where we can more easily locate them. Most important for the turtles, life upon the open ocean means that they are lost to the wide variety of coastal predators that would make them a meal during this initial, bite-sized life stage. Indeed, disappearing into a big ocean is reasoned to be an important survival strategy for young sea turtles.

Hatchlings of all sea turtle species disperse as they swim away from the nesting beach. This scattering begins with the hatchling frenzy—a burst of swimming that propels them away from the shore, where predatory fish concentrate and where currents could sweep them back onto land. For all species but the flatback, this initial burn of swim energy often boosts hatchlings into currents that orbit entire ocean basins. For these hatchlings, a few days of directed swimming launches a drifting journey that may span many years and thousands of miles.

Life is distributed in patches in the open ocean—a great benefit to a tiny drifter wishing to avoid predatory encounters. To live and to grow, however, a turtle must find food in this vast liquid desert. There are occasional concentrations of food at the surface, but these oceanic oases are fleeting. Such phenomena occur at the whim of shear zones between ocean currents, eddy centers, downwellings where currents collide, and upwellings where deep water meets the surface. These are oceanographic events that assemble floating life, such as plankton, seaweed, creatures that cling to flotsam, and young turtles. The menu at these sea turtle smorgasbords includes tiny crustaceans, jelly plankton, sailing snails, blue-button chondrophores, and a wide variety of small, slow-moving creatures such as barnacles, hydroids, bryozoans, and tubeworms.

To avoid being part of the menu themselves, little turtles have ways of avoiding attention. Young loggerheads, hawksbills, and Ridleys try to blend in with the flotsam. When small, these turtles are lumpy

Hawksbill hatchlings emerge from the nest and make their way toward the sea.
© NICOLAS J. PILCHER

and grayish or brownish, much like the other floating matter at the surface. Most young turtles seen on the open ocean remain close to other floating items and are almost as inactive as their surroundings, frequently floating in a "tuck" position, with their flippers held tightly against their body. Small green turtles and leatherbacks are a bit more active, relying on countershading to hide them from predators both above and below. This is most evident in young oceanic green turtles, which are bright white underneath (like the bright sky seen from below) and deep charcoal blue on top (like the dark ocean depths as seen from above).

There are many other mysteries about the lives of these smallest sea turtles. How quickly do they grow? How long is their oceanic stage? Which food items are most important? How do they conserve energy between meals? Do they depend on currents to bring meals, or do they actively seek their food? Are we able to pinpoint the areas of ocean where young sea turtles concentrate? What proportion of turtles survives the oceanic stage? How many succumb to effects from ingesting ubiquitous plastics and tar? Are oil spills and other floating hazards that concentrate with turtles critical threats to their populations?

The clues will not come easily. Sea turtles, it seems, are animals for which mystery is an adaptation. Getting lost and remaining elusive is to be expected, especially for the segment of their lives lived in the wildest and most remote portions of our planet.

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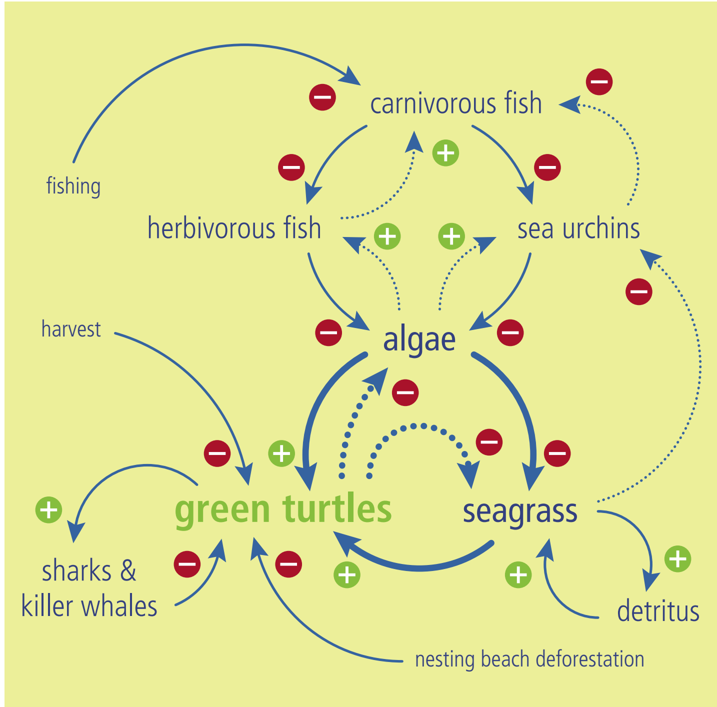
The Mystery of Their Purpose

What are the ecological roles of sea turtles, and how many turtles are needed to fulfill those roles?

A leatherback sea turtle feeds on a Cyanea species of jellyfish in the Trinity Bay area of Newfoundland, Canada. © CANADIAN SEA TURTLE NETWORK



This conceptual diagram shows a virtual green turtle population in the context of its ecosystem, using causal loop techniques for *qualitative* modeling of complex biological systems. It is remarkably difficult to develop *quantitative* models of this sort without a substantial amount of time-series data. Such data do not currently exist for any marine species. DIAGRAM COURTESY OF MILANI CHALOUPKA

Nature is a wise organizer. After 100 million years of survival and co-evolution, marine turtles surely play critical roles in coastal and oceanic ecology. But what are those roles, and how important are turtles in ecosystem services and functions? Are marine turtle populations regulated more by food availability or by predation? And given that sea turtles have been seriously depleted over the past four centuries, have their ecological roles changed? Most important, what would happen to Earth (ecologically speaking) if sea turtles were to disappear? Challenging questions such as these make ecological roles one of the great unsolved mysteries of marine turtle natural history.

Marine turtles are found in habitats from the shores to the abyss, and they range in their oceanic movements from the tropics to polar waters. They are a food source for marine, terrestrial, and airborne predators and even for some people. They are major consumers of sea life, and their lifestyles and waste products make them *ecosystem engineers* through their effects on coral reefs, seagrass pastures, seabottom habitats, and possibly oceanographic forces. Their reproductive routines make sea turtles a dynamic link between land and sea, resulting in the transfer of vast amounts of energy and matter from the oceans to the nesting beaches that affect the ecology of terrestrial consumers from raccoons to soil microbes.

Marine turtles are major consumers, spanning several levels in the food web (see figure above). The green turtle is the most abundant of marine megaherbivores, consuming countless tons of seagrasses and algae. Similarly, the hawksbill is an abundant spongivore on coral reefs, while leatherbacks focus on gelatinous zooplankton. Olive Ridleys, Kemp's Ridleys, flatbacks, and loggerheads consume vast amounts of invertebrates, from crustaceans to conch shells. However, consumption rates are not well known for marine turtles, and we are unsure what effect the historic depletion of turtles has had on marine food webs and ecosystem functions. Moreover, functional predator–prey responses remain a mystery for sea turtles, and we cannot estimate the extent of prey switching when preferred prey is depleted. An understanding

Loggerhead sea turtles mating, Florida Keys, U.S.A. © 2005 DAVID DOUBILET

of these and other variables will be necessary before we can develop meaningful models of the ecological role of marine turtles today and in the past.

In addition to what they consume, marine turtles also transfer nutrients and energy from the ocean to the land at nesting beaches when they deposit their eggs, and they are bioturbators, affecting the structure and functioning of foraging habitats such as coral reefs, seagrass meadows, algal beds, and soft substrate sea bottom. This ecosystem engineering contributes to nutrient recycling, as do the vast amounts of waste excreted from millions of turtles worldwide. Leatherbacks, which spend most of their lives in the oceanic habitat, and loggerheads, which aggregate in pelagic productivity hotspots, likely affect even long-term oceanographic patterns. Furthermore, marine turtles are important hosts for parasites and pathogens and are dispersal platforms for a vast range of epibionts, including barnacles, tunicates, and mollusks.

By themselves, the aforementioned observations of ecological functions and services tell us little about the effect marine turtles have on their habitats. Greater insights will derive from experimentation and ecosystem modeling and will require much more and better data than are currently available. In April 2006, a special session was held at the Annual Sea Turtle Symposium in Crete, Greece, with the purpose of addressing the gaps in our understanding of the ecological roles of marine turtles. The session brought together a range of people working on different facets of sea turtles' ecological roles, and we are expecting exciting new developments in the months and years ahead as we struggle to unlock these mysteries.

Milani Chaloupka *is the director of Ecological Modelling Services P/L in Australia and is a vice chair of the IUCN Marine Turtle Specialist Group.*

The Mystery of "Enough"

What proportion of males to females is necessary to maintain a healthy sea turtle population?

Populations are groups of animals that share genes and other characteristics such as nesting or feeding locations. The "health" of a sea turtle population—its likelihood of persistence over time—may be evaluated with information on how fast the turtles within the population grow, how long they live, how productive they are as adults, and the numbers and proportions of juveniles and adult males and adult females in the population.

A healthy population is a resilient one that can withstand natural variability, such as hurricanes, disease, large-scale nesting beach erosion, and some human impacts. Predicting how populations will decline or recover in response to changes (both positive and negative ones) is fundamentally important as we try to identify the most effective conservation methods. The best conservation mechanisms depend on sound understanding of the turtle populations and the threats that cause declines. There are many black holes in our knowledge of the structure of sea turtle populations, and in examining any individual population, one of these unsolved mysteries is: *Are there enough males present for the population to survive?*

One egg and one sperm: a simple recipe to make a turtle, but it is a recipe with a lot of critical biology behind it. To produce viable hatchlings, there must be enough mature males and females in the right place at the right time and enough good nesting beaches to incubate the eggs. Because higher temperature nests tend to produce more females than males, the sex ratios of these commonly tropical and subtropical turtle nests—and, thus, the sea turtle populations—are often skewed.

For a healthy population to have "enough" male and female breeders under skewed conditions implies at least three things: first, that females are able to find viable males; second, that one male can mate with many females; and finally, that females can store sperm and then allocate these gametes over the season to successfully fertilize several clutches of eggs. Currently, clutches of infertile eggs are rare, and some clutches have more than one father.

Simply having enough males to fertilize the eggs may not be enough. The consequence of small proportions of males in populations is unclear. Does a low number of viable males reduce the number of healthy, fertile eggs that each female lays? Does a low number of males increase the number of years between nesting seasons? Our understanding of these aspects of sea turtle biology is truly limited because we do not know the resilience of populations with low numbers of males. In some animal species, when animal populations are seriously depleted, there may be insufficient numbers of males to mate with the females or too few breeders to ensure adequate genetic mixing, thereby exacerbating the population decline and complicating recovery efforts.

One critical need for assessing sea turtle population health is to understand how fast turtles grow, how long it takes them to grow up to adulthood, and if males and females reach reproductive maturity at the same age or even the same size. New methods for counting "growth rings" in the bones of dead turtles can help us to better define how long sea turtles live, as well as how old they are when they migrate into new habitats or reproduce for the first time.

It is essential that populations have a critical mass that can cope with change. In most instances, we do not know what that number should be for sea turtles, but we do know that global sea turtle numbers are a small fraction of what they were a few centuries ago. While we are working to restore their numbers, we must simultaneously understand how individuals and their environments vary and what factors are most important in determining how their populations will respond to change. Ultimately we must understand the family of "hows": *how many, how big, how long,* and *how old is enough* to ensure that populations will be healthy "enough" for sea turtles to thrive.

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The Mystery of Turtle Senses

How do sea turtles sense their environment?


A loggerhead surfaces to breathe. © JAMI GARRISON

Sensory information plays a vital role in helping animals find food, locate mates, evade predators, and navigate from place to place. The way an animal senses its environment can determine its survival strategies. A bat, for instance, uses echolocation to locate prey and thus can hunt at night; a human being uses vision and is thus restricted to daylight. So how do sea turtles sense the world? How do their abilities influence their survival? Such questions are critical in assessing the habitat needs of sea turtles and other endangered species and in identifying risks that might otherwise be overlooked.

Sea turtles, like humans, have a well-developed visual sense. They can perceive color and have visual acuity sufficient for detecting small benthic prey and for recognizing and evading sharks. They may also have visual adaptations that suit them for their marine environment. The distribution of rods in the eye suggests good low-light vision for foraging at depth and for finding the sea as hatchlings. Evidence suggests that turtles might perceive some visual cues that humans cannot, including ultraviolet light and possibly polarized light. If so, these abilities may help turtles to perceive prey such as jellyfish that would otherwise be transparent.

Sea turtles are capable of hearing, but they appear sensitive only to low-frequency sounds commonly found in near-shore waters (such as the sounds of ocean waves breaking on beaches). It has been suggested, though not proven, that adult turtles use these sounds to help them locate nesting beaches once they have drawn into the vicinity. The possibility that turtles can detect infrasound (sound too low for humans to hear) has also not yet been investigated.

Like all other aquatic animals, sea turtles can sense chemicals in sea water. Amino acids and other biochemicals emanate from all organisms and enable turtles to locate underwater food sources. In principle, turtles might also use chemoreception to identify the chemical signatures of particular geographic areas, but again, this is unknown. Similarly, it is possible that sea turtles detect airborne chemicals when surfacing to breathe, although such ability has not yet been demonstrated.

Sea turtles are exceedingly sensitive to water movements associated with ocean waves. Hatchlings entering the sea for the first time use this ability to guide themselves offshore by orienting their swimming relative to wave direction. We do not know if adults retain this sensitivity. The ability might be useful in maintaining consistent courses, in detecting wave patterns associated with islands (from distances at which the islands cannot be seen), or in detecting changes in underwater landscape in relatively shallow water.

Sea turtles have at least one major sensory ability that humans lack: the ability to perceive Earth's magnetic field. The magnetic sense of sea turtles appears to be remarkably sophisticated, allowing them to obtain both directional and positional information. Turtles can perceive the direction of the magnetic field much as a compass does and can thus distinguish between north and south, as one example. In addition, they can detect subtle variations in Earth's magnetic field, and they use this ability in long-distance navigation. The magnetic field is a particularly useful source of navigational information in the ocean, because it is present at all depths, remains constant during day and night, and does not vary with weather or season.

Many questions remain. What sensory abilities are used in locating mates or in communication? Do sea turtles possess any other major sensory abilities that have been overlooked? At this time, there is no evidence that they have the anatomical structures needed for echolocation, electroreception, or infrared detection. But there is, of course, no way to be sure that they do not have other sensory abilities or use common abilities in novel ways. Only time and careful research will tell.

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The Mystery of Getting Where They Need to Go

How do sea turtles navigate?

The long-distance migrations of sea turtles involve some of the most remarkable feats of orientation and navigation in the animal kingdom. As hatchlings, turtles chart unerring courses toward the open sea and maintain course even beyond sight of land. Juvenile turtles often follow complex migratory pathways that lead across entire ocean basins and back. As adults, turtles migrate from their feeding grounds, to specific mating and nesting areas, and back again to the feeding grounds. How turtles migrate so precisely and consistently across vast distances in the seemingly featureless ocean is among the most long-standing mysteries of sea turtle biology—a mystery that scientists are only now beginning to solve.

Considerable progress has been made in understanding the cues that guide hatchling turtles from their nests to the open ocean. Florida loggerhead hatchlings appear to use three sets of cues in sequence. After emerging from their nests, they find the ocean using visual cues. In the sea, they establish offshore headings by swimming directly into oncoming waves, which in shallow water move directly toward shore and reliably lead the turtles seaward. Farther out to sea, where waves may move in any direction relative to the shoreline, the turtles switch to using Earth's magnetic field to guide themselves in much the same way that we use a magnetic compass to steer ourselves north or south.

In the open ocean, turtles add still another navigational trick: they use Earth's magnetic field not only as a compass, but also as a source of information about where they are. Earth's field varies in such a way that each oceanic region has a unique magnetic field associated with it. Turtles detect these subtle differences and follow inborn instructions

A juvenile green turtle in a cloth harness is tethered to an electronic tracking system inside a magnetic coil. This methodology is used for magnetic navigation studies.
© KENNETH J. LOHMANN

that tell them how to respond to each field and, thus, in which direction to swim at different locations along the migratory route.

Juvenile turtles living in coastal feeding grounds also use Earth's magnetic field in navigation. They apparently learn the magnetic landscape of the areas in which they live and use this information as a kind of magnetic map to guide them to particular destinations. Unraveling the organization, capabilities, and limitations of this remarkable magnetic navigational system will be an exciting area of research in coming years.

Many questions about sea turtle navigation remain. For example, do turtles use environmental cues other than ocean wave direction and Earth's magnetic field in navigation? Although many navigational cues have been discussed—including chemical cues, visual landmarks (such as mountains along a coast), features of the underwater landscape, oceanic temperature gradients, and low-frequency sounds (caused, for example, by waves breaking on distant islands)—there is no clear evidence that turtles use any of these.

And how do adult turtles navigate back to their natal beaches? It is possible that they imprint on the magnetic signature of the home region, but whether they imprint on any aspect of the natal beach, magnetic or otherwise, remains an important mystery to be investigated.

Finally, to what extent is the migratory route of a young turtle inflexibly hardwired into its genes? Loggerhead hatchlings from Florida appear programmed to steer along a set course by recognizing and responding to magnetic fields characteristic of specific geographic locations. If these responses have a genetic basis, then populations that follow different migratory routes presumably inherit different responses to different regional fields. If so, attempts to reestablish an extinct nesting population by transplanting hatchlings from one location to another would fail, if the normal migratory route of the introduced turtles differs significantly from that of the extinct group. An improved understanding of sea turtle navigation will clearly assist efforts to protect and restore sea turtle populations throughout the world.

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The Mystery of the Tumors

What causes fibropapillomas?

Pathogens—new pathogens and the reemergence of common pathogens made virulent by anthropogenic changes to the biosphere—are some of the key hazards to biodiversity today, and sea turtles are no exception to that threat. Fibropapillomatosis is a disease that manifests in sea turtles as benign, cutaneous tumors on the turtles' soft and hard tissues, including flippers, neck, plastron and carapace, eyelids, and cornea. The tumors, which often have a "cauliflower" look to them, can weigh up to three pounds. They cause turtles to become weak and anemic and to lose maneuverability; at times, they even result in blindness and starvation. The growths are also found on turtles' internal organs such as lungs, kidneys, and liver. External tumors can be removed but grow back. While fibropapillomas can kill many turtles, observations suggest that some turtles may spontaneously recover (called tumor regression).

The disease was first described in a green turtle captured in Key West, Florida, in 1938 and was later sent to the New York Aquarium for display. Since that time, fibropapillomas in greens have increased dramatically. In some populations in Florida, it is estimated that as many as 70 percent of juvenile and sub-adult turtles are afflicted. Fibropapillomas have also been recorded in adult green turtles in Hawaii and are occasionally seen in loggerheads, Kemp's Ridleys, and olive Ridleys. Worldwide, fibropapillomatosis has been reported throughout the Caribbean, Hawaii, Australia, and Japan, and it seems to be more common in warm, equatorial waters. Thus far, cases have not been reported in colder waters. Fibropapillomatosis has been most intensively studied in Florida and Hawaii where differences are apparent. In Florida, few turtles have oral tumors, whereas these are much more common in Hawaii. Also, while the epizootic continues in Florida, fibropapillomatosis is declining in wild turtles from Hawaii. The reasons for this decline are unclear.

Research in Florida showed that fibropapillomas can be experimentally transmitted among turtles. Subsequent studies in Hawaii and Florida revealed the presence of herpes virus DNA in tumored but not non-tumored tissue of fibropapilloma-afflicted green and loggerhead turtles. This, along with occasional microscopic evidence of herpes viral-like particles in tumors, provides the most compelling evidence that a herpes virus is associated with the disease. The unexplained lack of fibropapillomas in certain areas of Florida and Hawaii also suggests environmental factors play a role in the disease.

In the end, much mystery remains. Why did fibropapillomas appear? Is it a virus that actually causes the disease? Could other pathogens be involved, alone or in conjunction with a virus? Are there environmental factors that contribute to fibropapillomas? Theories abound, but only time and study will tell.

The author of this article, __Sue Schaf__, has been the manager of The Turtle Hospital in Marathon, Florida, for the past 10 years. __Thierry Work__, wildlife disease specialist at the USGS–National Wildlife Health Center's Honolulu Field Station, provided valuable insight to this piece.

Fibropapilloma on a green turtle. © CHRIS JOHNSON

A female leatherback lays eggs under moonlight on a beach in Costa Rica. © 2004 GENE BEDNAREK / WWW.SOUTHLIGHT.COM

The Mystery of How They Will Adapt

How will climate change affect sea turtles?

Global warming is the environmental problem of the century. The Earth's climate is warming quickly, by geological standards. Climate change will affect weather patterns, cause polar ice caps to melt, and ultimately result in sea levels rising. There are other lesser-known and perhaps related phenomena—the consequences of which could be enormous—such as changes in ocean water quality. Given what we know of sea turtles' ecological roles, at best we can only speculate about the long-term impacts of the changing climate on sea turtle survival, but we can identify some venerable parts of their lifecycle where climate change will likely impact. Not surprisingly, in 2005, the IUCN Marine Turtle Specialist Group identified climate change as one of five key hazards to sea turtles worldwide, making the issue a high priority for further study.

During the next 100 years, the predicted rise in sea level of up to 120 centimeters, combined with the increased frequency and intensity of storms and higher air and water temperatures (estimated at an average 4°C rise), will impact sea turtles in both their foraging areas and at their nesting beaches.

In the foraging areas—seagrass beds, coral reefs, and the open ocean—increasing storm frequency and intensity will add to the turbidity or murkiness of the water. Combined with greater water depth, this turbidity will disrupt the growth of seagrasses, sponges, corals, mollusks, and crustaceans on which sea turtles feed, in turn affecting the frequency of sea turtle reproduction, which is linked closely to food availability.

Sea turtles are perhaps most vulnerable to climate change at their nesting beaches. The females require nesting sites that are accessible from the sea and stable for digging; the sites must also be suitable for incubation of the eggs and adjacent to ocean currents to facilitate hatchling dispersal. These beach characteristics must coincide and be stable through time, because nesting sites are used by successive generations. An increase in storm intensity and frequency will likely alter the topography of beaches through erosion. As primary nesting beaches erode, turtles will be forced to use sub-optimal nesting sites where incubation may not be as successful. Further, as the sea level rises, some nesting areas will be lost altogether. The combined impacts will cause a reduction in hatchling production, affecting the viability of turtle populations decades later.

Before this occurs, however, several less obvious impacts of climate change will add to the pressure. When deposited on the beach, sea turtle eggs are subject to changes in beach conditions—temperature, moisture, and oxygen availability—during development. As the atmospheric temperature increases, so will that of the sand surrounding the eggs, and too much exposure to temperatures over 34°C can be lethal to embryos. At sublethal levels, incubation temperature determines the sex of sea turtle hatchlings; hence, as beach temperatures rise, more females will be produced.

Beach sand moisture content of 2 to 12 percent provides adequate hydric conditions for egg development. As beaches are eroded by storms, waves inundate beaches, and as sea spray splashes ashore, salinity will build up in the nesting beaches. Higher salt content sand reduces available moisture and can cause eggs to dehydrate and die.

The increase in tidal height may also flood eggs from underneath. If the sand is saturated by storm-driven waves or subsurface flooding and does not drain adequately, the embryos will drown.

It is not clear precisely how great the effects of climate change on sea turtle reproduction will be. Comprehensive long-term data sets are needed to fully research the matter. Until then, how the turtles will respond to climatic change remains a matter of speculation. Will sea turtles respond in concert with changing environmental conditions, or will environmental change outpace their ability to adapt to change? The answers to these questions will determine the long-term survival of these remarkable species.

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