Convention on the Conservation of Migratory Species of Wild Animals

Memorandum of Understanding on the Conservation and Management of Marine Turtles and their Habitats of the Indian Ocean and South-East Asia

BEACH MANAGEMENT AND HATCHERY PRACTICES

(Prepared by the Advisory Committee with support from Dr Andrea Phillott)

1. MOS8 in 2019 requested the Advisory Committee to "*develop guidelines on the management of beaches for successful hatchling production, including management of hatcheries if and when required*."

2. Section 1 on Beach Management Practices provides the rationale for habitat protection. It highlights the conditions required for an intact functioning beach ecosystem, which creates ideal nesting and incubation conditions for sea turtles. It then highlights several anthropogenic disruptions that damage beach ecosystems, requiring active interventions and management to restore them. When these measures fail, incubation in hatcheries should be considered.

3. Section 2 on Hatchery Management Practices proposes a structured decision-making framework to help practitioners (conservationists, managers, beach monitoring personnel) decide which action(s) to take to protect sea turtle eggs and hatchlings and maximise hatchling production.

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Section 1: Beach Management Practices

Rationale for Holistic Coastal Beach Management Practices

Nearly a billion people live within 10 km of a coast, supporting an abundance of economic and social services such as marine ports and tourism industries. However, these endeavours cause significant anthropogenic pressure on coastal ecosystems by accommodating these coastal (human) populations and activities, or to derive valuable goods and services from the coast. In the process, the natural environment and ecosystems are modified or transformed with devastating consequences to both people and nature.

Ecosystem goods are resources and materials derived from coastal ecosystems, such as minerals and precious stones, building sand from rivers, beaches and dunes, or freshwater wells abstracting water from coastal aquifers. The most apparent services are beach-related tourism or cultural, religious, and sports activities, with beach tourism one of the most extensive contributors to employment (Houston 2018), and coastal (beach) properties of the most expensive real estate per unit area of all ecosystems (Costanza et al., 2006). The unique beach services are more cryptic and thus often overlooked; these under-appreciated services are frequently derived from biodiversity-related attributes like food collection, recreation in clean coastal waters (filtered and purified through coastal ecosystems), nutrient recycling, storm buffering from dunes, or observing vulnerable life history stages such as sea turtle nesting. For the environment to keep supporting these services, it requires intact, functioning ecosystems with all its abiotic (water and sand) and biotic components (from micro-organisms like bacteria and fungi that process nutrients) to megafauna bringing in nutrients to the beach and macrofauna that breaks down these marine-derived subsidies, to be intact (Harris and Defeo 2022).

Beaches as ecosystems

Sandy beaches are one of the most undervalued coastal ecosystems (Dugan et al., 2010). It has been described as the Cinderella ecosystem (Schlacher et al., 2008) because it is under-recognized and under-valued as nothing more than sand and waves for most people. This image is derived from the apparent absence of large plants other than those on stabilizing dunes. However, ecosystem status does not depend on the presence of macrophytes[1]; intact functioning (sandy) beach ecosystems harbour unique and endemic species and process nutrients from plankton, wrack, or carrion[2] washed in from the ocean through the sand. These organisms then release the processed nutrients back to the beach and adjacent surf to be used on reefs, mangroves, seagrass beds, or the hinterland, like dunes. Thus, it is a semi-closed ecosystem with unique biota on the beach that derives nutrients through imports and exports them again to adjacent systems.

One valuable import of nutrients on tropical, nutrient-starved shores is turtle-derived energy as eggs, brought in and deposited by nesting females onto the high shore. These shores are off oligotrophic oceans (i.e., low in nutrients), and nesting females import large quantities of nutrients through their clutches of eggs. Most of these clutches will incubate successfully and leave the beach as hatchlings to maintain healthy, self-sustaining turtle populations. However, the eggs that do not incubate to term, ideally less than 25-30% of eggs/clutches, will remain on the beach. The energy and nutrients from failed eggs will be processed by plants and animals and exported to the hinterland or surf zone. The direct benefits of these nutrients

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[1] Large aquatic plants

[2] Wrack and carrion are washed-up plant (wrack) and animal (carrion) material like stranded algae or washed-up fish or marine mammals.

include vigorous vegetation growth that traps sand on dunes. Dune sand, in turn, protects the coastline from storm surges, or the unique invertebrate and vertebrate fauna, including ants, ghost crabs, and meiofauna, release nutrients that end up in the surf zone where it is used in food webs. Zooplankton, juvenile fish, and crabs, in the surf attract large fish with an incoming high tide to forage on these organisms, which are also useful for people fishing for food or recreationally. The ecosystem benefits derived from sea turtle nesting are thus direct and indirect to people.

These ecosystem dynamics, however, described thus far, represent pristine functioning conditions requiring the physical (and biological) habitat to be intact. We will, therefore, explain the physical morphodynamic states of typical, undisturbed open ocean beaches and the selection of sea turtles for the pristine nesting beach conditions. We will then describe the human activities that disturb these ideal conditions and the detrimental consequences to the habitat and the biological communities, including sea turtles, that depend on them. Finally, we will provide broad-scale management options to highlight that *post hoc* "band-aid" solutions are not feasible as effective coastal management tools. When these short-sighted options fail, sea turtle populations become threatened. Last resort considerations such as hatcheries for sea turtles may become desirable to safeguard nesting while beach restoration is underway or rescue natural populations in peril.

Physical characteristics of sandy beach ecosystems

The three (main) physical drivers of ocean-facing beach ecosystems are sand, waves, and tides (Defeo et al., 2009). Beach sand arrives on the coast via rivers bringing in weathered terrestrial rock from inland, marine-derived sources like broken-down coral grit or shells, or marine snow[3] pushed onto the shore by waves. The size of waves that move sand onto and off the coast depends on shoreline orientation, i.e., facing into or away from dominant wind/wave directions, and the coastal contour depth slowing down waves when shallow. Sandy beaches off narrow continental shelves or islands facing into the dominant winds typically have large waves (>2m). In contrast, sheltered shores, or those in the lee of an island, are dominated by small waves (less than 0.5m). The third parameter is the tide range. The vertical difference between the highest spring tide and the spring low tide mark is the tide range, which depends on the geographic location. Coasts adjacent to smaller ocean basins, such as the Mediterranean and the Red Sea, have smaller tide ranges (generally less than 2 m and are called micro tidal), whereas coasts off deep, large ocean basins have meso- (2 – 4m) or macro-tidal (larger than 4 m) ranges. The effect is that the larger the vertical displacement, the wider the beach. The interaction among these three parameters, grain size, wave action, and tide range, are the critical determinants of the subtidal and intertidal slope, the morphodynamic state, and the sensitivity and resultant response to physical disturbance. Sea turtles have a broad tolerance for beach state, and we find rookeries on all beach types depending on what is available to them at any specific location. However, beach slope is an important driver of nest site selection (Wood and Bjorndal 2000).

Sandy beach ecosystems, however, comprise more than just the intertidal and backshore but three interacting components: the surf zone, the intertidal zone, and the backshore and dune system. This trio functions as one unit called the littoral active zone (LAZ). Wind and wave forces shape the interactions across the shore. During calm periods, waves move sand onto the shore, and beaches build up. The wind then blows dry sand from the tide line onto dunes, where it gets trapped in vegetation or "rubble" and builds up the dunes. During seasonal or extreme storms like hurricanes, wave height (and storm surge) increases, and wave run-up increases, eroding sand back from the backshore and dunes stores. Sand gets dumped in the

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[3] Marine snow is both organic and inorganic matter but the inorganic components like shells from microscopic organisms like foraminifera made of calcium carbonate, become part of the sediments where they die.

surf zone, causing waves to break further out and so performs an essential ecosystem service protecting the coast from damaging storm waves. When high wave conditions ameliorate, sand buildup starts again, and the shore steepens.

In addition to moving sand onshore and offshore, it also moves alongshore with coastal currents and wind functioning as a massive sand conveyor belt. Sand is distributed following the dominant wind/wave direction in the surf zone and nearshore, from bay to bay, or where there are high wind regimes, by overland dune bypass systems. The LAZ functions as a connected longshore unit moving with great speed and volume in high energy regimes, along with it materials, nutrients, and biological elements, like plant seeds, larvae, or small fishes or plankton and other invertebrates in the surf, providing structural, functional, trophic, and genetic connectivity at this land-sea interface.

Shorescape approach to nesting beach selection

Sea turtles, across their life cycle, are part of this nutrient and trophic connectivity cycle. Females migrate long distances from distant foraging grounds to deposit several clutches of eggs above the high tide line on sandy shores. The eggs that successfully incubated produce hatchlings that run across the shore, and those few individuals that survive to adulthood will return to the vicinity of their nesting beach (called natal philopatry) after decades at sea to nest themselves. The question is how do they choose a nesting location on the high shore before emerging from the water?

The answer is that they likely don't! Being out at sea for several decades and "knowing" where the natal beach is requires several intact ecological cues. Many of these cues are poorly studied, but there is strong evidence for large-scale drivers such as magnetic and stellar cues and odour plumes that bring turtles "home" to an approximate location. It is then most likely the entire sea- and landscape with all its visual, sound and odour cues in the water (including reefs and surf energy) or on land that indicates the general beach location and condition that gets assessed by a female as potentially suitable or not before she emerges onto the shore. First-time nesters may follow more experienced nesters where to emerge, although this has not yet been demonstrated; this is called social facilitation. If a female is successful in nesting, this specific beach location is "remembered" as a nesting location and used repeatedly with more targeted nest site selection over time as females become more experienced.

Intertidal selection and ideal nesting habitat

While ashore in the swash, non-threatening conditions on the backshore, such as a quiet, disturbance-free high shore devoid of bright lights (if she nests at night), noise, or sudden excessive movement, will encourage the female to continue up-shore. Given that there is no or only a small berm that can be scaled, once she is above the high tide mark, a collection of internal (physiological) states and location cues will encourage the female to initiate digging a body pit. These location cues are species-specific and rookery-specific, so it is challenging to define universal nesting cues. A green turtle female (for example) may dig several body pits in a single night, sometimes lasting 3 – 6 hours, whereas a leatherback, once emerged, will dig one body pit and egg chamber, and lay a clutch 90% of the time and be done in less than two hours. The types of factors females select for are, however, the same (as summarised from Mortimer, 1990; Reine, 2022): i) the location needs to be accessible to and from the ocean, ii) high enough to avoid tidal inundation, iii) adequate moisture, and sand compatibility to facilitate successful body pitting, egg chamber construction and hatching, and iv) sufficient sand to cover and disguise the nest. Successful incubation and hatchling emergence are desired but unpredictable to the female because incubation conditions change throughout the incubation period with changing weather and environmental conditions (e.g. sand deposition/erosion from strong winds or moisture content changing with precipitation). Egg chamber construction conditions are thus the best predictor of incubation success for the female.

The microhabitat facilitating egg chamber construction includes damp sand, medium grain size (~ 250 – 500 μm median range), well- to moderately-sorted sand (which limits beach shear resistance or hardness and compaction) and limited organics and salts. No large pieces of debris or obstructions (buried plastics, roots, rocks, trunks) that interfere with female and hatchling digging, and sand of sufficient depth (>1.5m depth for larger species) to construct a body pit and egg chamber without reaching bedrock, saturated sand or the water table, and sufficient volume of loose sand to bury the egg clutch and disguise/camouflage the nest. Incubation temperature is important but difficult to select for. It is affected by a multitude of shore conditions, including sand colour, nest depth, distance from the sea or vegetation, shore orientation, and surface sediment fluctuating with ambient temperature changes.

Few of these ideal nesting and incubation factors are altered by beach management unless through major interventions like beach nourishment, mining and mineral extraction, dunes altered though construction, (exotic) vegetation planted or removed, excessive trampling and beach driving compacting or digging up sand, or clutches relocated to foreign locations such as to a different beach or a hatchery. However, before we investigate how these factors can be manipulated to benefit turtle populations, we must understand what disrupts beach functioning and requires management intervention to protect the habitat.

Threats to beach ecosystems

Anthropogenic alteration and use of the sandy beach environment can threaten sea turtle populations in three different ways; i) it can either alter the beach morphodynamic state or functioning, putting the entire habitat at risk, or ii) affect the nesting or incubation environment or iii) prevent hatchling emergences out of the nest, the beach crawl, or offshore dispersal. We should also recognise a fourth factor i.e., (iv) natural processes affecting sea turtle populations on nesting beaches.

i. Threats to the habitat

Most coastlines are now threatened by serial coastal development (Brown and McLachlan 2002) and accelerated sea level rise from climate change (Nerem et al., 2018). Most historic coastal construction projects only accounted for the impact on the development footprint locally without considering "upstream" (e.g., sand accumulation), "downstream" (e.g., sand erosion), or long-term or across-shore effects like coastal squeeze. Odum (1982) referred to this kind of isolated decision making in coastal management as the "*Tyranny of small decisions,*" where local decisions dominate without realising the larger or longer-term consequences. On beaches, upstream and downstream effects are caused by activities or infrastructure that alter the longshore sediment transport (and connectivity) on a significant scale. This could start in the hinterland by damming or sand mining of rivers, shore-normal constructions like harbours, groin or pier constructions that block sediment movement, or in the nearshore, constructions that alter the wave regime like artificial reefs, breakwaters or tidal pools that alter the coastal configuration (Brown and McLachlan 2002). All these threats affect the habitat available to sea turtles (Table 1).

Table 1. Physical disturbances to beach morphodynamic functioning cause alternative beach states and require major management or engineering interventions (Brown and McLachlan 2002).

Physical process affected	Examples of causes of the disruption
Sediment movement onto the coast	Damming of rivers, sand mining of riverbeds (wadis) or the beach
Onshore and offshore movement of sand	Artificial reefs, bulkheads, seawalls, tidal pools, dune stabilization with exotic plant species,

Sediment movement along-shore	Harbour walls, jetties, groins, piers, marinas
Sediment movement over land	Dune stabilization, building construction/development

These activities (Table 1) lead to coastal erosion and sometimes sand buildup in different locations. If feasible, management solutions could “counter” these historic decisions with engineering solutions such as sand nourishment, dredging, or mechanical bypass systems. These "solutions" are generally short-term and large enough to warrant independent environmental assessments both on the footprint of donor and recipient sites. Few development projects, however, investigate effects outside of the footprint – so upstream and downstream effects - that threaten the beach habitat itself. These responsibilities reside with governments that have a broader perspective and management mandate.

ii. Threats to the sea turtle nesting/egg incubation environment

Even if the beach morphodynamic processes are in place, it does not mean that the shorescape (here used as the coastal sea-and-land interface) provides suitable and sufficient nesting environments for adult females that guarantee successful incubation after nesting. Coastal development projects may be managed well during construction but less during operational phases as land use changes over time.

Beaches generally become sacrificial areas for supporting biodiversity services because the social (e.g., tourism) and economic benefits take precedence (Houston 2018). People flock to the coast to conduct "business" on the shore or undertake cultural and recreational activities. These activities affect biota generally negatively (trampling, noise, and continuous disturbance), and the cryptic biota (either because it is buried or nest at night or seasonally) are sacrificed due to extreme economic and recreational value, which may not be dependent on biota (Harris and Defeo 2022). However, suppose sea turtles nest on these shores; in that case, the beaches must be managed differently as it can affect sea turtles' shore/sea-finding abilities (Table 2), or they will be displaced along with the rest of the biota and ecosystem services they perform.

Table 2. Summary of the factors that would affect the value of the shore for sea turtle nesting. (Note: The references provided are not an exhaustive list but just an example of each disruption.)

Process affected	Examples of causes of the disruption	Reference
Obstructions to crawling and digging while ashore	Beach furniture, logs, plastics and discarded nets which impede movement	Fujisaki and Lamont, 2016
Disruption to light/dark horizon	Direct lights blinding turtles on the beach, or removal of dune and/or coastal vegetation causing a light glow disorienting turtles	Salmon 2003
Disruption to quiet/safe nearshore and nesting habitat	Noisy high-density tourism, events or tourism groups, motorised craft (boats or vehicles), or loud music and explosions/fireworks making noise (or vibrations)	Lindborg et al., 2016; Schofield et al., 2021
Disruption to chemical (hormonal and environmental) signals*	Oil and other chemical spills (have been poorly studied), but females respond to airborne odours, and both females and hatchlings are vulnerable to chemical toxins.	Endres et al., 2009; Endres and Lohman 2012; Milton et al., 2003
Disruption to static/safe environment	Crowds milling on the beach and playing in the surf	Oliver de la Esperanza et al., 2017

Disruption of thermal regime	Beach shading, mining of dark/light minerals	Hays et al., 2001; Shamblott et al., 2021;
Disruption of moisture content	Water abstraction from aquafers, irrigation of dunes or backshore for rehabilitation or golf courses	Hill et al., 2015; Ariano-Sánchez et al., 2023
Disruption of sediment quality	Beach nourishment, cement factory dust, beach mining	Cineros et al., 2017
Presence of excessive organics, and pathogens.	Wastewater discharge onto beaches or estuaries	Defeo et al., 2009;

* Inferred – not yet demonstrated experimentally.

These activities may all deter a female sea turtle from coming ashore, encouraging her to use alternative beaches instead or from completing a body pit or egg chamber and so abandon a nest mid-laying if she did come ashore, increasing nesting effort and success. It is thus critical to view nesting beaches in the broader *shorescape* (for example, using a spatial plan) to ensure that alternative quiet beaches of sufficient quality and quantity are available in proximity and perpetuity should a beach be deemed sacrificial.

iii. Preventing hatchlings from emerging safely

Hatchling emergence cues have been understudied relative to nest site selection of adult females (e.g., Wood et al., 2014). However, several emerging studies indicate that the process is much more complex and sophisticated than predicted (Field et al., 2021). For example, *in situ* communication (even using ultrasonic sounds) and coordination among hatchlings while digging seems probable (de Melo et al., 2023). If a female did nest successfully, and that incubation is completed to term, hatchlings may emerge from their eggs, but without making it ever to the sand surface or down the beach; digging out of the nest chamber is metabolically taxing, requiring sufficient energy and oxygen, which takes a coordinated effort among hatchlings over days to surface. During the dash down the beach, they hide in numbers to escape predators. Some anthropogenic activities disrupt these natural processes (Table 3).

Table 3 Disturbance events affect the emergence and survivorship of sea turtle hatchlings in the nest or crawling down the shore.

Emergence process affected	**Examples of causes of the disruption**	**Reference**
Direct threats to individuals		
Predation by wild predators (including native and invasive species) in artificially high numbers	Human settlements with poor rubbish and waste disposal attract opportunistic foragers like monkeys, honey badgers, raccoons, pigs onto the beach that dig up incubating or emerging nests.	O'Connor et al., 2017
Predation by domesticated predators	Holidaymakers and recreationists walk, particularly dogs, off leashes on the beach, which chase birds or dig up incubating or emerging nests. (This is incidental rather than a large-scale impact.)	Incidental; no studies available
Indirect threats affecting the incubation conditions		
Disruption to quiet emergence habitat	Vibrations in the sand (from loud music/dredging/driving) disrupt the hatchling digging process	Maeda et al., 2024
Disruption of thermal regime	Beach shading and mining dark/light minerals may raise or lower beach temperature and slow development, producing larger/smaller hatchlings or dehydrating animals if sand gets too hot.	Hays et al., 2001; Wood et al., 2014; Ariano-Sánchez et al., 2023

Disruption of moisture content	Water abstraction from aquifers may dry out the beach dehydrating the sand and animals, affecting hatchling performance; irrigation of dunes or backshore for rehabilitation or for golf courses will cool beaches.	Matthews et al., 2021
Disruption of sediment quality incl. compaction	Beach nourishment, cement factory dust, mining, and driving cause ruts, sediment disturbance, or compaction.	Pilcher 1999; Cisneros et al., 2017
Physical movement (crawling and digging) onshore	Beach furniture, logs, plastics, and discarded nets can catch hatchlings crawling down the shore or mechanical grooming.	Triessnig et al., 2012
Disruption to light/dark horizon	Lights on the beach, removal of dune and/or coastal vegetation can disorient and misorient hatchlings while finding the sea's light horizon.	Witherington 1997; Kamrowski et al., 2015; Truscott et al., 2017

iv. Natural processes affecting nesting, incubation and emergence

In addition to these anthropogenic disturbances, we must recognise that several natural processes (exacerbated by anthropogenic climate change) also disrupt successful nesting, incubation, or emergence events. These include increased storminess driving erosion and berm formation (and slumping), storm inundation (Lindborg et al., 2016), and wind erosion. Biotic processes such as natural predation (by ants, birds, or ghost crabs), or disease/fungal infections (Sarmiento-Ramírez et al., 2010) that affect nest success. Sea turtle nests are part of the beach ecosystem experiencing natural forces, and it is natural to lose a fraction of the clutches. However, intervention may be required when these natural events become too severe over multiple seasons.

To maintain a healthy functioning sea turtle population, the rule of thumb is that about 70% of nests or eggs must produce hatchlings (Mortimer 1999). A major caveat in stating this number is that the population's success is determined by not only nesting and incubation success but also subsequent levels of mortality across year classes (Chaloupka 2002, Mazaris et al., 2006). Female survivorship, fecundity, and surviving the first year at sea, significantly affect population dynamics. Thus, populations with high at-sea mortality will require higher hatchling production values (and vice versa) to be maintained.

In addition to abundance and hatching success, it is also essential to monitor sex ratios of populations to ensure a near-balanced sex ratio is produced across the turtle nesting season (early to late part of the season), and across the entire rookery for multiple seasons. Because of temperature-dependent sex determination (TSD) in sea turtles, where temperatures above ~30^{o}C temperatures produce more females (Yntema and Mrosovsky 1982), effective population size as a result of extreme sex ratio biases (Maurer et al., 2021) may jeopardize population outlook or recovery. Conservation strategies aimed at manipulating sex ratios require careful consideration of local beach characteristics and continuous monitoring of beach and incubation temperatures (and a detailed discussion is beyond the scope of this assessment). However, monitoring sand temperatures along the beach for multiple seasons allows for tracking of beach thermoprofiles and monitoring the rate at which warming occurs *in situ*. It does provide a basic indication of the likely feminization of hatchling beach productions (see Wyneken and Lolavar 2015 for a critical review).

Other climate-related effects may affect both incubation temperature and hatching success. Sea level rise and increased storm events may increase beach erosion, resulting in loss of nesting habitat and nests. Inundation events may alter the incubation environment or cause direct mortality of developing embryos. As such, hatching success and recruitment drastically decrease. To keep track of all these impacts, it is important to monitor nesting, hatching, and emergence success.

Monitoring Incubation success (to assess alternative incubation options)

An excellent case study of nest monitoring, hatching, and emergence success estimates can be found in Brost et al., (2015). This study provides a clear account of monitoring procedures (including a statistical power analysis to estimate appropriate sample sizes based on expected conditions) to be used over an extended area for a decade to estimate hatchling production for three species on 16 beaches in Florida. They used the definitions described by and procedures outlined by Miller (1999) to estimate nest success (number of nests with a “full" egg clutch), hatching success, and emergence success. (We suggest both are reviewed in detail to estimate hatchling production for a population.)

It should be noted that Brost et al., (2015) indicated hatching production for three species to be *ca.* 52% for loggerheads, 50% for green turtles, and 39% for leatherbacks, which is clearly below the expected 70%. Despite these "low" hatchling production numbers, these populations are currently increasing, suggesting that hatchling production values and a blanket 70% are not sufficient to induce alternative management strategies. Hatchling production was higher in the later seasons for all three species, but it also enforces that these populations need careful ongoing monitoring and knowing the treats faced at sea.

Recommendations for Nest and Beach Management

Given the conditions that can affect individual turtles on the beach and their offspring, or the habitat itself, recommendations for beach management should include both. Managing individuals on beaches or the conditions required for nesting is more straightforward than maintaining the habitat if serial mismanagement, exacerbated by coastal squeeze, disrupted sediment budgets, or altered wave regimes, has already started coastal erosion. Mclachlan et al., (2013) provide a matrix for evaluating beaches' recreational and conservation value and ten guiding principles to assess and manage accordingly. Nesting beaches should be protected *a priori*, with careful management of mixed-use zones and activities. Where and when management fails, engineering interventions may be required to restore the habitat and activities. Six options are discussed; they are not presented as alternatives to each other, and it may be that a combination of the management options should be employed simultaneously.

> **Option 1 –** *Managing threats to individual females, nests, and hatchlings.*
>
> Threats to sea turtles and their offspring have been discussed extensively in the academic and management literature, including the publications in Tables 2 and 3, and Boulon (1999) and Witherington (1999). Most of these publications advocate for a minimal interference approach, including avoiding egg relocation. When "a hands-off" approach is no longer an option, then manage threats by preventing them from occurring in the first place. Activities include regular beach patrols to deter predators and poachers or reduce threats through beach cleanups, *in situ* protection against predators using screens or cages, or chemical deterrents like wolf urine to deter coyotes (Wauson and Rogers 2021). When these options are inappropriate, egg relocation to sites where the threats can be managed or avoided should be considered.

These previous interventions, however, protect turtles or handle nests or individual hatchlings. They are generally easy to implement, requiring only local decisions or authority. Threats to the habitat are much more challenging to manage as they are essentially a failure of policy. Coastal habitats, including sandy beaches, are now under pressure from poor coastal management practices exacerbated by sea level rise (SLR). Therefore, the rest of the recommendations here will be based on habitat protection and management but realising that it will require policy changes to be implemented. These policy changes and management actions are not unique to, but also include sea turtle nesting beaches.

Option 2 – *Prevent beach erosion with sound coastal management practices.*

Avoid serial coastal development, especially along high-energy coasts. Any developments require a thorough study of sediment and hydrodynamic processes and sand budgets upstream and downstream of the intervention, including a sober inclusion of SLR projections. Prosecute or strongly deter illegal sand mining practices along the coast and address policy issues where necessary to eliminate the need for these devastating customs (Masalu 2002). Management actions should target the entire LAZ, including sediment sources upstream and not just the backshore or nesting beaches. Sandy beaches should be able to respond naturally to perturbations like storms. Setting appropriate setback lines (~100m minimum) would benefit the coast by providing a modest buffer to perturbations (Fish et al., 2008).

Option 3 – *Managed retreat*

Projected sea level rise (SLR) rates indicate that not only sea turtle nesting beaches but more than a billion people living within 100km of the coast will be impacted by 2100. The potential solutions to avoid severe impact on society, infrastructure, or the environment include accommodating risks by raising buildings (for example) or protecting the coast using engineering solutions, or the more sustainable solution consists of a managed retreat of infrastructure. The retreat can be achieved through a phased approach: either i) moving all infrastructure at once under a planned and coordinated framework, ii) using threshold triggers to be reached before implementation, or iii) reactive responses when parts of the coast are under imminent threat (Setter et al., 2023). There is no perfect solution, but a trade-off exists between financial cost (as retreating is financially expensive) and a risk-gain balance. In the short term, it may be more cost-effective to limit retreat (spatially longshore and inland), but the risk is averted for only a tiny section of the coast and for a short period.

Moving infrastructure timeously well away from the dune base on nesting beaches favours current nesting (by managing shorescape disturbances like ALAN[4] pollution) and resilience in the habitat if the LAZ is intact and can respond seasonally to perturbations (McLachlan et al., 2013).

Option 4 – *Protect or defend coastal infrastructure/turtle nesting beaches through beach nourishment schemes.*

Coastal defences generally include two categories of solutions: i**) hard defences**, such as seawalls or flood defences, or ii) **soft solutions,** including beach nourishment, geofabric sandbags or green shelter belts. Hard defences are generally the preferred option in urban settings where extensive infrastructure is being protected (like waterfronts or ports) and was the "go-to solution" of the previous century. Several documented cases indicate the limitations of these "solutions," including the vulnerability to SLR, which causes coastal squeeze. It is also detrimental to sea turtle nesting, with turtles avoiding beaches backed by sea walls. These sea walls alter nest placement and put nests at risk with increased risk of inundation (Rizkalla and Savage 2011). Beach nourishment is now employed as an alternative to protect infrastructure and tourism, but it must be repeated and is expensive. Nourishment also impacts

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[4] ALAN is the acronym for Artificial Light At Night.

nesting and hatching success, especially in the first year after nourishment (Brock et al., 2009). Still, reproductive success seems to stabilize after some time, providing that habitat quality is not altered through nourishment (e.g., using coarser/finer sand).

Option 5 – *Sacrifice infrastructure and re-establish coastal processes.*

The least preferred option by local governments, often requiring courageous decisions, is sacrificing coastal infrastructure. This is generally necessary where infrastructure was clearly put in the wrong place, or the ecosystem has been altered subsequently, or because of SLR. Repeated "rescue" interventions are usually ineffective or exceed the protected infrastructure's value. This is not a large-scale practice but would require local decisions such as rerouting specific sections of roads because they are overrun by sand dunes or water. There are no known examples where beach infrastructure has been sacrificed to favour sea turtle nesting, but there are many examples where infrastructure is moved or not rebuilt after hurricane damage or sacrificed because dunes overtake infrastructure.

Option 6 – *Apply spatial planning approaches to ensure sufficient habitat is available away from competing activities and connectivity maintained.*

After a century of learning from isolated decision-making in the coastal zone and the recent development of spatial management tools, ranging from GIS platforms, satellite imaginary, fast internet, and highspeed computer processing, with software like MARXAN Connect (that allows for marine spatial or conservation planning including connectivity among habitats and populations), many of the coastal management mistakes can be avoided. Sea turtle nesting beaches should be explicitly included in planning layers and setting conservation targets for these habitats (for example, in Chalastani et al., 2020). Robust spatial planning should ensure we have sufficient habitat to maintain turtle populations in perpetuity. It also allows for seamless integration with at-sea habitats, like courtship or foraging areas (Schofield et al., 2013), protecting the entire land and seascape for social and environmental benefits. Marine Spatial Planning tools also allow for scenario planning, such as habitat becoming unavailable (e.g. sea level rise); one can identify the closest other connected beaches available for sea turtle populations. It should also be modelled if these beaches can deal with density increases; for example, should a proportion of an arribada beach become unavailable to olive ridleys, is there sufficient beach habitat available to accommodate the whole population, or would they need to nest elsewhere?

Many of these management options will take time to consider, resource, and implement. Temporarily boosting nesting numbers through hatcheries may be necessary.

Option 7 - *The appropriate use of in situ protection and ex situ egg relocation or hatchery use where all other options have failed.*

[Described Below]

Section 2: Hatchery Management Practices

Overview of a Structured Decision-Making Framework for Evidence-Based Assessment of Threats and Protection of Sea Turtle Eggs and Hatchlings

Background

A structured decision-making framework is proposed to help practitioners (conservationists, managers, beach monitoring personnel) decide on which action(s) to take in protecting sea turtle eggs and hatchlings to maximise hatchling production.

The framework recognises that eggs and hatchlings have an important ecological role as a nutrient source for beach and in-shore ecosystems, and not every egg/hatchling needs to be protected from threats.

Mortimer (1999) suggests that hatchlings should emerge from ~70% of nests/eggs. The framework proposes that if <30% of clutches/eggs are affected by the threat(s) then conservation actions may not be required unless the population is demonstrating significant decline or is in the early stages of recovery.

There are four common actions that practitioners can choose among to mitigate threats to eggs and/or hatchlings (Table 1). Additional conservation actions can also be applied to the entire beach (e.g., turtle friendly lighting).

Table 1. Common actions for the mitigation of threats to eggs and/or hatchlings

Action	Description of Action
Unprotected *in situ*	Eggs remain where laid; no protective action take
Protected *in situ*	Eggs remain where laid; protective action taken to reduce specific threat
Relocated- Beach	Clutch moved to individual location on beach where specific threat is reduced
Relocated-Hatchery	Clutch moved to hatchery (a defined area to which eggs are moved and incubated for protection) where all threats are reduced

Steps in the decision-making process to choose which of these conservation actions to use are:

1. Assess threats to eggs and/or hatchling using evidence-based methods.
2. Consider the potential conservation actions to achieve the objectives.
3. Evaluate the risk for each action based on available resources and other requirements.
4. Implement the conservation action.
5. Evaluate the outcome based on data and modify the action if needed again in the future.

Decision-making Step 1. Assess threats to eggs and/or hatchling using evidence-based methods

Practitioners should use evidence-based methods to assess risks to sea turtle eggs and hatchlings, and not apply the precautionary principle (Kriebel et al., 2001) and take preventative action when uncertain about the risks unless it is an index population in demonstrated decline and/or with significant threats to other life-stages or habitats placing the population at risk.

The evidence-based methods for assessment of common threats, potential actions, and key references are outlined in Table 2.

Step 2. Consider possible conservation actions

Threats can often be reduced more than one possible conservation action. Practitioners can choose from among the four possible actions when making decisions about mitigating threats to sea turtle eggs and/or hatchlings (Tables 1-2).

Step 3. Evaluate the risk for each action based on available resources and other requirements

Each conservation action for eggs/hatchlings has requirements to be successful. Actions also have inherent risk and may result in additional risks when implemented. Hence, action requirements and risk reduction should also be considered in the decision-making process (Table 3).

An alternative action should be implemented if requirements for a specific action cannot be met (Table 4). The action should be re-considered during decision-making for other clutches (Table 4) if a trigger-point is reached.

Step 4. Implement the conservation action

The conservation action should be implemented once the risks have been weighed and it is determined that requirements can be met.

Step 5. Evaluate the outcome based on data and modify the action if needed again in the future

Monitoring nests throughout the incubation period as needed and excavating nests to determine hatching and emergence success at the end of the season are primary indicators for outcome of the conservation action. If observations and data indicate that the mitigation action is not successful for >70% of clutches, exposes the nest to additional threats, or requirements for the action to be implemented correctly cannot be met, then a different conservation action should be selected in future. Clutches protected *in situ*, relocated to a safer location on the beach, or relocated to a hatchery should achieve an average higher hatching success over the nesting season than unprotected *in situ* clutches.

Table 2. Evidence-based assessment of threats to eggs and/or hatchlings and potential mitigation actions at the individual clutch- and beach-level

		Potential Mitigation Actions				
		<30% clutches/eggs threatened	**>30% clutches/eggs threatened**			
Common Threats	**Threat Assessment Method(s)**	**Unprotected *in situ***	**Protected *in situ***	**Relocated-Beach**	**Relocated-Hatchery**	**Beach Level**
Nest depredation	Monitoring (e.g., observations, camera traps); predation hazards modelling; LEK	✓	✓	✓	✓	✓
Tidal inundation/washover and groundwater flooding of nests	Water-level loggers; PVC devices; wave runup modelling; GIS-based models; LEK	✓		✓	✓	
Illegal take of eggs/hatchlings	Monitoring nests; market surveys	✓	✓	✓	✓	✓
High nest temperature	Temperature loggers; signs of thermal stress in embryos and hatchlings	✓	✓	✓	✓	
Dry nest substrate	Moisture loggers	✓	✓	✓	✓	
Hatchling disorientation or misorientation due to ALAN	Fan mapping of hatchling dispersal on beach; tracking hatchling dispersal in-water	✓		✓	✓	✓

Table 3. Potential risks when implementing common actions for the mitigation of threats to eggs and/or hatchlings.

Action	Potential Risks	Risk Reduction
Unprotected *in situ*	Clutch might be exposed to different threat(s)	Assess for common threats when clutch is laid
Protected *in situ*	Protective action may not be successful	Check protective action throughout incubation and reinforce if needed
	Clutch may be exposed to additional threat(s)	Assess for common threats when clutch is laid
Relocated- Beach	Movement-induced mortality of embryos	Move eggs in <3 hr (optimal) or <6hr (acceptable) of being laid
	Clutch may be exposed to additional threat(s)	Assess for common threats when clutch is relocated
	Nest microclimate is different to the *in situ* nest	Select a nest location similar in substrate characteristics to the *in situ* nest and replicate the nest shape and depth known for that species
Relocated- Hatchery	Movement-induced mortality of embryos	Move eggs in <3 hr (preferable) or <6hr (tolerable) of being laid Train personnel in egg-movement practices Minimise distance between nesting beach from which eggs are collected and hatchery
	Homogenous microclimate for all hatchery nests; different to *in situ* nests	Replicate the nest shape and depth for the species; create heterogenous nest microenvironments in hatchery
	Lower average hatching success than *in situ* nests	Follow best practices for hatcheries
	Altered hatchling sex ratio, fitness indicators	Measure sex ratio and fitness indicators in hatchlings from hatchery and *in situ* nests; adjust hatchery practices if needed
	Increased depredation of hatchlings when released	Release hatchlings at different locations and times to avoid creation of "feeding stations" for local predators

Table 4. Requirements to meet before implementing common actions for the mitigation of threats to eggs and/or hatchlings and trigger-points for reconsidering the decision-making process

Action	Condition	Requirement(s)	Trigger-point
Unprotected *in situ*	<30% of clutches/eggs will be lost to threats throughout the nesting season	Regular monitoring of nests throughout the incubation period	Increase in threat(s) so >30% of clutches/eggs will be lost throughout the nesting season
Protected *in situ*	>30% of clutches/eggs will be lost to threats throughout the nesting season if not protected	Resources are available to protect clutches *in situ* and monitor regularly to ensure effectiveness	Increase in threat(s) so >30% of clutches/eggs will be lost throughout the nesting season
Relocated- Beach	>30% of clutches/eggs will be lost to threats throughout the nesting season if eggs are not moved to elsewhere on the beach or a hatchery	Experienced personnel are available to monitor beaches for nesting turtles throughout the night for the nesting season and move eggs within the time limit using best practices then monitor regularly to ensure effectiveness	If sufficient trained personnel are not available to meet the requirement(s) then consider *in situ* protection or moving eggs to a hatchery (see requirements for each)
Relocated- Hatchery	>30% of clutches/eggs will be lost to threats throughout the nesting season if eggs are not moved to a hatchery	Experienced personnel are available to monitor beaches for nesting turtles throughout the night for the nesting season and move eggs within the time limit using best practices AND the hatchery has the resources to apply best practices in the collection, handling, transport and incubation of eggs and release of hatchlings AND can assess hatching/emergence success and/or hatchling sex ratios and fitness indicators	Sufficient resources are not available to meet the requirement(s) OR average hatching success of hatchery nests is lower than *in situ* nests then consider *in situ* protection or relocation (see requirements for each) Incubation conditions should be adjusted if hatchling sex ratios and/or fitness indicators do not reflect those from *in situ* nests.

References

Ariano-Sánchez, D., Nesthus, A., Rosell, F., & Reinhardt, S. (2023). Developed black beaches-too hot to emerge? Factors affecting sand temperatures at nesting grounds of olive ridley sea turtles (*Lepidochelys olivacea*). *Climate Change Ecology*, *5*, 100074.

Brost, B., Witherington, B., Meylan, A., Leone, E., Ehrhart, L., & Bagley, D. (2015). Sea turtle hatchling production from Florida (USA) beaches, 2002-2012, with recommendations for analyzing hatching success. *Endangered Species Research*, *27*(1), 53-68.

Brock, K. A., Reece, J. S., & Ehrhart, L. M. (2009). The effects of artificial beach nourishment on marine turtles: differences between loggerhead and green turtles. *Restoration Ecology*, *17*(2), 297-307.

Brown, A. C., & McLachlan, A. (2002). Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental conservation*, *29*(1), 62-77.

Boulon, R. H. (1999). Reducing threats to eggs and hatchlings: in situ protection. *Research and management techniques for the conservation of sea turtles*, *4*, 169-174.

Chalastani, V. I., Manetos, P., Al-Suwailem, A. M., Hale, J. A., Vijayan, A. P., Pagano, J., ... & Duarte, C. M. (2020). Reconciling tourism development and conservation outcomes through marine spatial planning for a Saudi Giga-Project in the Red Sea (The Red Sea Project, Vision 2030). *Frontiers in Marine Science*, *7*, 168.

Chaloupka, M. (2002). Stochastic simulation modelling of southern Great Barrier Reef green turtle population dynamics. *Ecological modelling*, *148*(1), 79-109.

Cisneros, J. A., Briggs, T. R., & Martin, K. (2017). Placed sediment characteristics compared to sea turtle nesting and hatching patterns: a case study from Palm Beach County, FL. *Shore & Beach*, *85*(2), 35.

Costanza, R., Wilson, M. A., Troy, A., Voinov, A., Liu, S., & D'Agostino, J. (2006). The value of New Jersey's ecosystem services and natural capital.

de Melo, S. N. D., de Souza Dias da Silva, M. F., dos Santos, P. J. P., da Silva Neves, V. C., & Bezerra, B. M. (2023). Sound production in sea turtle nests and hatchlings (*Eretmochelys imbricata* and *Caretta caretta*) in Northeast Brazil. *Bioacoustics*, *32*(6), 693-707.

Defeo, O., McLachlan, A., Schoeman, D. S., Schlacher, T. A., Dugan, J., Jones, A., ... & Scapini, F. (2009). Threats to sandy beach ecosystems: a review. *Estuarine, coastal and shelf science*, *81*(1), 1-12.

Dugan, J. E., Defeo, O., Jaramillo, E., Jones, A. R., Lastra, M., Nel, R., ... & Schoeman, D. S. (2010). Give beach ecosystems their day in the sun. *Science*, *329*(5996), 1146-1146.

Endres, C. S., Putman, N. F., & Lohmann, K. J. (2009). Perception of airborne odors by loggerhead sea turtles. *Journal of Experimental Biology*, *212*(23), 3823-3827.

Endres, C. S., & Lohmann, K. J. (2012). Perception of dimethyl sulfide (DMS) by loggerhead sea turtles: a possible mechanism for locating high-productivity oceanic regions for foraging. *Journal of Experimental Biology*, *215*(20), 3535-3538.

Field, A., McGlashan, J. K., & Salmon, M. (2021). Evidence for synchronous hatching in marine turtle (Caretta caretta) embryos and its influence on the timing of nest emergence. *Chelonian Conservation and Biology: Celebrating 25 Years as the World's Turtle and Tortoise Journal*, *20*(2), 173-183.

Fish, M. R., Cote, I. M., Horrocks, J. A., Mulligan, B., Watkinson, A. R., & Jones, A. P. (2008). Construction setback regulations and sea-level rise: mitigating sea turtle nesting beach loss. *Ocean & Coastal Management*, *51*(4), 330-341.

Fujisaki, I., & Lamont, M. M. (2016). The effects of large beach debris on nesting sea turtles. *Journal of Experimental Marine Biology and Ecology*, *482*, 33-37.

Harris, L. R., & Defeo, O. (2022). Sandy shore ecosystem services, ecological infrastructure, and bundles: New insights and perspectives. *Ecosystem Services*, *57*, 101477.

Houston, J. R. (2018). The economic value of America's beaches—a 2018 update. *Shore & Beach*, *86*(2), 3-13.

Hays, G. C., Ashworth, J. S., Barnsley, M. J., Broderick, A. C., Emery, D. R., Godley, B. J., ... & Jones, E. L. (2001). The importance of sand albedo for the thermal conditions on sea turtle nesting beaches. *Oikos*, *93*(1), 87-94.

Hill, J. E., Paladino, F. V., Spotila, J. R., & Tomillo, P. S. (2015). Shading and watering as a tool to mitigate the impacts of climate change in sea turtle nests. *PloS one*, *10*(6), e0129528.

Kamrowski, R. L., Limpus, C., Pendoley, K., & Hamann, M. (2015). Influence of industrial light pollution on the sea-finding behaviour of flatback turtle hatchlings. *Wildlife Research*, *41*(5), 421-434.

Kriebel, D., Tickner J., Epstein P., Lemons J., Levins R., Loechler E.L., et al.,,. 2001. Environmental Health Perspectives 109: 871-876.

Lindborg, R., Neidhardt, E., Witherington, B., Smith, J. R., & Savage, A. (2016). Factors influencing loggerhead (*Caretta caretta*) and green turtle (*Chelonia mydas*) reproductive success on a mixed use beach in Florida. *Chelonian Conservation and Biology*, *15*(2), 238-248.

Maeda, Y., Nishizawa, H., Kondo, S., Ijichi, T., & Ichikawa, K. (2024). Effect of noise on sand digging and emergence activities in green turtle (*Chelonia mydas*) hatchlings. *Journal of Experimental Marine Biology and Ecology*, *570*, 151974.

Matthews, B. L., Gatto, C. R., & Reina, R. D. (2021). Effects of moisture during incubation on green sea turtle (*Chelonia mydas*) development, morphology and performance. *Endangered Species Research*, *46*, 253-268.

Masalu, D. C. (2002). Coastal erosion and its social and environmental aspects in Tanzania: a case study in illegal sand mining. *Coastal Management*, *30*(4), 347-359.

Maurer, A. S., Seminoff, J. A., Layman, C. A., Stapleton, S. P., Godfrey, M. H., & Reiskind, M. O. B. (2021). Population viability of sea turtles in the context of global warming. *BioScience*, *71*(8), 790-804.

Mazaris, A. D., Broder, B., & Matsinos, Y. G. (2006). An individual based model of a sea turtle population to analyze effects of age dependent mortality. *Ecological Modelling*, *198*(1-2), 174-182.

McLachlan, A., Defeo, O., Jaramillo, E., & Short, A. D. (2013). Sandy beach conservation and recreation: Guidelines for optimising management strategies for multi-purpose use. *Ocean & coastal management*, *71*, 256-268.

Miller J (1999) Determining clutch size and hatching success. In: Eckert KL, Bjorndal KA, Abreu-Grobois FA,Donnelly M (eds) Research and management techniques for the conservation of sea turtles. Publication No. 4, IUCN/SSC Marine Turtle Specialist Group, Blanchard, PA, p 124-129

Milton, S., Lutz, P., & Shigenaka, G. (2003). Oil toxicity and impacts on sea turtles. *Oil and Sea Turtles: Biology, Planning, and Response. NOAA National Ocean Service*, 35-47.

Mortimer, JA. 1990. The influence of beach sand characteristics on the nesting behavior and clutch survival of green turtles (*Chelonia mydas*). Copeia 3: 802-817.

Mortimer, J. A. (1999). Reducing threats to eggs and hatchlings: hatcheries. *Research and management techniques for the conservation of sea turtles*, *4*, 175-178.

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the national academy of sciences*, *115*(9), 2022-2025.

O'Connor, J. M., Limpus, C. J., Hofmeister, K. M., Allen, B. L., & Burnett, S. E. (2017). Anti-predator meshing may provide greater protection for sea turtle nests than predator removal. *PloS one*, *12*(2), e0171831.

Odum, W. E. (1982). Environmental degradation and the tyranny of small decisions. *BioScience*, *32*(9), 728-729.

Oliver de la Esperanza, A., Arenas Martínez, A., Tzeek Tuz, M., & Pérez-Collazos, E. (2017). Are anthropogenic factors affecting nesting habitat of sea turtles? The case of Kanzul beach, Riviera Maya-Tulum (Mexico). *Journal of coastal conservation*, *21*, 85-93.

Pilcher, N. J. (1999). Cement dust pollution as a cause of sea turtle hatchling mortality at Ras Baridi, Saudi Arabia. *Marine Pollution Bulletin*, *38*(11), 966-969.

Rangel-Buitrago, N., Neal, W., Pilkey, O., & Longo, N. (2023). The global impact of sand mining on beaches and dunes. *Ocean & Coastal Management*, *235*, 106492.

Reimann L, Vafeidis AT, Honsel LE. (2023) development as a driver of coastal risk: Current trends and future pathways. Cambridge Prisms: Coastal Futures. 2023;1:e14.

Reine, K. J. (2022). A literature review of beach nourishment impacts on marine turtles. ERDC/EL TR-22-4. Pages 82.

Rizkalla, C. E., & Savage, A. (2011). Impact of seawalls on loggerhead sea turtle (Caretta caretta) nesting and hatching success. *Journal of Coastal Research*, *27*(1), 166-173.

Salmon, M. (2003). Artificial night lighting and sea turtles. *Biologist*, *50*(4), 163-168.

Sarmiento-Ramírez, J. M., Abella, E., Martín, M. P., Tellería, M. T., Lopez-Jurado, L. F., Marco, A., & Dieguez-Uribeondo, J. (2010). Fusarium solani is responsible for mass mortalities in nests of loggerhead sea turtle, *Caretta caretta*, in Boavista, Cape Verde. *FEMS microbiology letters*, *312*(2), 192-200.

Schlacher, T. A., Schoeman, D. S., Dugan, J., Lastra, M., Jones, A., Scapini, F., & McLachlan, A. (2008). Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts. *Marine ecology*, *29*, 70-90.

Schofield, G., Scott, R., Dimadi, A., Fossette, S., Katselidis, K. A., Koutsoubas, D., ... & Hays, G. C. (2013). Evidence-based marine protected area planning for a highly mobile endangered marine vertebrate. *Biological Conservation*, *161*, 101-109.

Schofield, G., Dickson, L. C., Westover, L., Dujon, A. M., & Katselidis, K. A. (2021). COVID-19 disruption reveals mass-tourism pressure on nearshore sea turtle distributions and access to optimal breeding habitat. *Evolutionary Applications*, *14*(10), 2516-2526.

Shamblott, K. M., Reneker, J. L., & Kamel, S. J. (2021). The thermal impacts of beach nourishment across a regionally important loggerhead sea turtle (Caretta caretta) rookery. *Ecosphere*, *12*(3), e03396.

Setter, R. O., Han, R. X., Tavares, K. D., Newfield, C., Terry, A., Roberson, I. M., ... & Coffman, M. (2023). Managing retreat for sandy beach areas under sea level rise. *Scientific Reports*, *13*(1), 11920.

Triessnig, P., Roetzer, A., & Stachowitsch, M. (2012). Beach condition and marine debris: new hurdles for sea turtle hatchling survival. *Chelonian Conservation and Biology*, *11*(1), 68-77.

Truscott, Z., Booth, D. T., & Limpus, C. J. (2017). The effect of onshore light pollution on sea-turtle hatchlings commencing their off-shore swim. *Wildlife Research*, *44*(2), 127-134.

Wauson, M., & Rogers, W. (2021). A test of the use of gray wolf (*Canis lupus*) urine to reduce coyote (Canis latrans) depredation rates on loggerhead sea turtles (*Caretta caretta*) nests. *Journal for Nature Conservation*, *63*, 126050.

Witherington, B. E. (1997). The problem of photopollution for sea turtles and other nocturnal animals. *Behavioral approaches to conservation in the wild*, 303-328.

Witherington, B. E. (1999). Reducing threats to nesting habitat. *Research and management techniques for the conservation of sea turtles. IUCN/SSC Marine Turtle Specialist Group Publication*, *4*, 179-183.

Wood, A., Booth, D. T., & Limpus, C. J. (2014). Sun exposure, nest temperature and loggerhead turtle hatchlings: Implications for beach shading management strategies at sea turtle rookeries. *Journal of Experimental Marine Biology and Ecology*, *451*, 105-114.

Wood, Daniel W., and Karen A. Bjorndal (2000). "Relation of temperature, moisture, salinity, and slope to nest site selection in loggerhead sea turtles." *Copeia* 2000.1: 119-119.

Wyneken, J., & Lolavar, A. (2015). Loggerhead sea turtle environmental sex determination: implications of moisture and temperature for climate change based predictions for species survival. *Journal of Experimental Zoology Part B: Molecular and Developmental Evolution*, *324*(3), 295-314.

Yntema, C. L., & Mrosovsky, N. (1982). Critical periods and pivotal temperatures for sexual differentiation in loggerhead sea turtles. *Canadian Journal of Zoology*, *60*(5), 1012-1016.