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

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Abstract

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

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

Effects of Beach Nourishment on Nesting Females

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

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

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

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

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

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

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

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

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

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

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

Effects of Beach Nourishment on Eggs and Hatchlings

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

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

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

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

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

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

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

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

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

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

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

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

Research Priorities

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

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

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

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

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

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

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

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

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

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

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

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

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