# Appendix K

**Beach Processes and the Life Histories of Benthic Invertebrates on Beach and Tidal Flat Habitats Affected by the *Cosco Busan* Oil Spill, California**

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**Introduction**

The spill of an estimated 53,000 gallons of a heavy fuel oil (HFO 380) from the M/V *Cosco Busan* into San Francisco Bay on 7 November 2007 affected extensive areas of intertidal habitat both in San Francisco Bay and also on the outer coast. The natural resource Trustees used the Shoreline Cleanup Assessment Team (SCAT) data on visual oiling characteristics to develop categories of shoreline injury, from heavy to very light. The habitat injury subgroup for beaches, marshes, and tidal flats quantified injury using the Habitat Equivalency Analysis (HEA) approach, by which the injury is scaled in terms of the percent of ecological services present after the spill (compared to pre-spill baseline levels) and the rate at which the lost services recover over time. The Trustees relied upon a variety of literature sources, which document the effects of oil on flora and fauna, and on data collected to develop the inputs into the HEA for these shoreline habitats. Deriving HEA inputs from such sources requires a good understanding of the pathways of exposure to the oil, how the sand beach cycle affects the distribution of intertidal fauna, the life histories of affected intertidal organisms, and their seasonal distributions and behavior. This technical memorandum was prepared to summarize the current understanding of these factors, applied to the conditions during and after the *Cosco Busan* oil spill. The goal is to provide the Trustees with the scientific basis for developing appropriate HEA inputs for injury scaling.

**Pathways of Exposure**

Spilled oil can affect intertidal resources via multiple pathways. For a heavy fuel oil, such as the type of oil spilled from the *Cosco Busan*, one of the primary pathways of exposure and effects on intertidal habitats is by fouling and smothering from direct contact with the oil. Very few studies have even attempted to correlate fouling or smothering with effects on intertidal fauna, although often the response is obvious (e.g., avoidance, lethargy, death). A few such studies have been conducted on birds. Fry and Lowenstine (1985) reported 2 of 3 Cassin's auklets died from application of 3-5 milliliters of oil to the feathers. Tuck (1961) reported that only a small spot of oil on the belly was sufficient to kill murres. There is an obvious need for controlled experiments to determine dose-response curves from physical fouling and smothering of more birds and other intertidal taxa. Nevertheless, it is highly likely that even in the lightest oiling environments, certain proportions of inhabitants were exposed and fouled.

**Seasonal Changes in Beach Processes**

The distribution of intertidal invertebrates on outer coast beaches is highly variable over changing seasons and tidal stages, and can be affected by cycles of erosion and deposition. There is a common misconception that, during the winter months, all sand beaches have reduced profiles and decreased invertebrate biota because winter storm waves have eroded the beaches and transported the sand and biota to offshore bars. The concept of a flat, erosional beach profile in winter is based on the fact that erosional storm waves are more common in the winter, and depositional swell waves are more common in the summer. However, regardless of the season, the sand that is eroded from the beach during a large storm is deposited back on the beach by normal wave action during the post-storm recovery period. When storms occur at short intervals, there is insufficient time for the beach to build back fully before the next storm. However, the

beach sediments do start to return to the intertidal beach shortly after the storm passes. So, there will be "summer" beaches (i.e., depositional) in winter before winter storms occur and when there is sufficient time between storms for the beaches to accrete. Many beach invertebrates are also sufficiently mobile to return quickly to their preferred feeding elevation and thus to preferred habitat on the beach (see later discussion).

There are seasonal changes in the wave climate off Central California; however, the "winter" season actually begins with the onset of large storms, which usually start late in the year. Results from detailed U.S. Geological Survey studies along Ocean Beach, San Francisco for the period 2004-2006 show typical seasonal patterns of beach erosion during the months of higher frequencies of larger storms and accretion during the non-storm periods, with beach sediment volume at a maximum in September/October and at a minimum in January (Bernard et al., 2007). Furthermore, this analysis along Ocean Beach indicates that large waves (significant wave height > 5 m) from azimuths of less than 300° caused the greatest erosion because waves from this direction escape the otherwise significant sheltering effects of the massive ebb tidal delta at the mouth of San Francisco Bay. Waves become increasingly less impeded as they approach Ocean Beach from more southerly directions. For waves from the northwest, wave height is reduced by about 50% as a result of refraction over the northern lobe of the ebb tidal delta. Therefore, the beaches north and south of the Golden Gate are less likely to erode during storms that generate waves from the northwest.

Figure 1 shows the significant wave height for the NOAA buoy Station 46026 (18 nautical miles west of San Francisco) for the period of 1 September 2007 to 30 March 2008. It shows that the wave climate prior to and for a month after the 7 November 2007 spill consisted of the normal incident swell waves, with significant wave heights generally 4 m or less. About a month after the spill, more typical "winter storms" occurred with the offshore significant wave heights greater than 5 m: on 4-7 December, 4-5 January, 26 January, and 24 February. Therefore, the outer coast beaches, particularly those south of San Francisco, would not have been highly
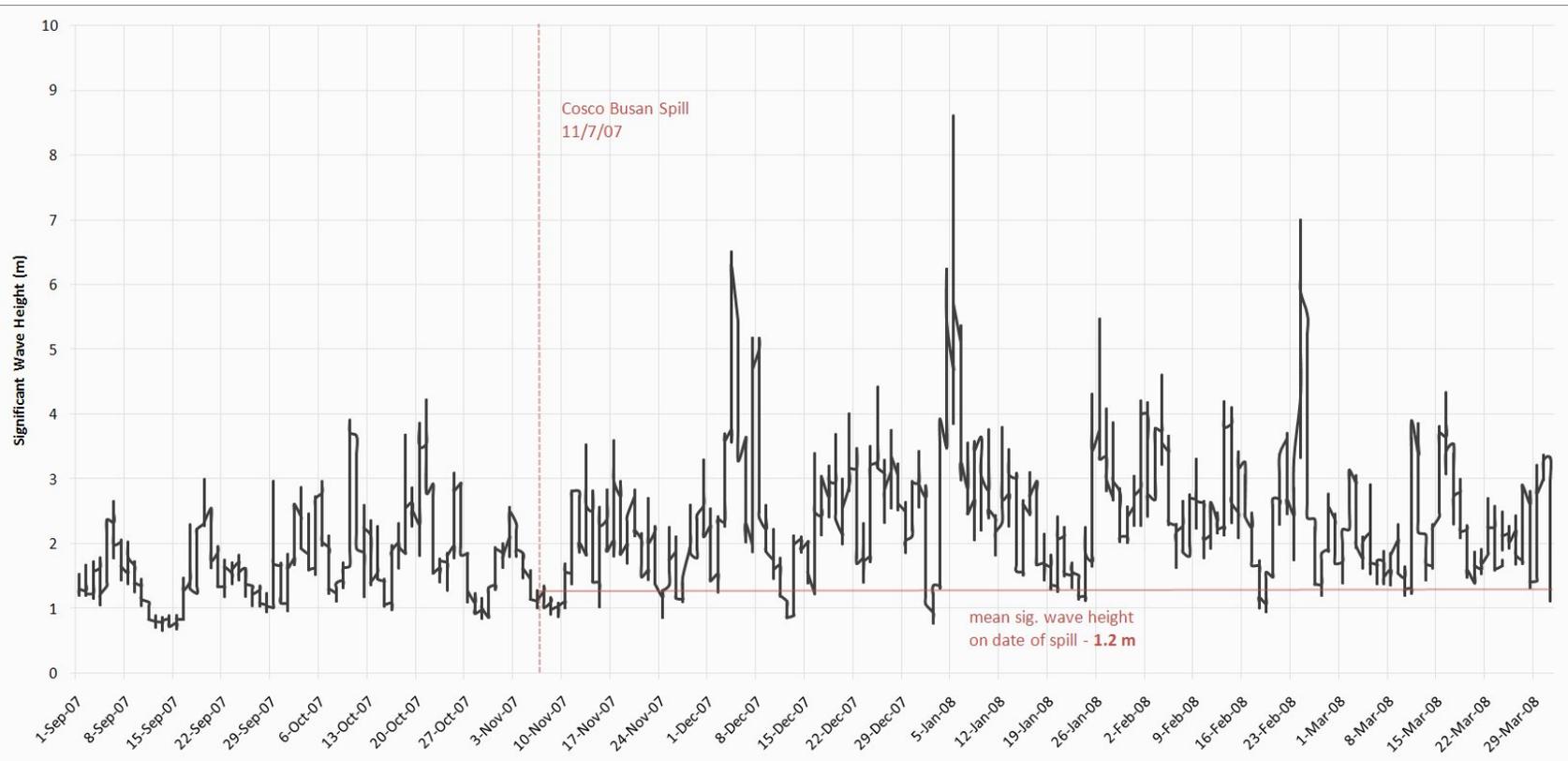
**Figure 1.** Significant wave height for the period 1 September 2007-30 March 2009 for Station 46026 -18NM West of San Francisco, CA, from the NBDC.

erosional prior to or shortly after the spill. In addition, there were 3-4 weeks between the late winter storms, which would allow time for sand transport back to the beach, and for re-colonization by infaunal (those buried in the sediments) invertebrates, to occur.

**Biota on Sand Beaches**

In this section, we offer our analysis of the ecological importance, distribution, habitat, and life history of the sand crab *Emerita analoga*. Populations of *E. analoga* are major components of invertebrate macrofaunal communities of exposed sandy beaches in temperate zones of the Pacific Ocean of North and South America, often making up the majority of the total intertidal abundance and biomass (Jaramillo and McLachlan, 1993; Dugan et al., 1995, 1996, 2000a, 2003). Densities of *E. analoga* can exceed 100,000 individuals per square meter on beaches on the central coast of California and elsewhere (Dugan et al., 2003). This species is important as prey for vertebrate predators, such as shorebirds, seabirds, surf fishes, and marine mammals.

**Distribution of *Emerita analoga* (extracted from Dugan et al., 2005)**
California beaches are among those inhabited by high abundances and biomass of the suspension-feeder, *E. analoga.* The North American range of *E. analoga* spans Point Conception, an important transition zone between coastal oceanographic regimes and the Oregonian and California marine faunal provinces (Seapy and Littler, 1980). Studies to date have found very little genetic variability in populations of this species across its North American range and recent results suggest that the populations may be essentially panmictic (Beckwitt, 1985; Barber et al. unpublished).

***Emerita analoga* habitat (extracted from Dugan et al., 2005)**
*E. analoga* is a highly mobile and rapidly burrowing sediment generalist (sensu Alexander et al., 1993) with excellent orientation, swimming, and digging abilities, allowing it to successfully inhabit the full range of exposed sandy beaches from fully reflective to dissipative morphodynamic states (Dugan et al., 2000b; Jaramillo et al., 2000). This sand crab is an active tidal migrant, moving with the tide level up and then down the intertidal beach so as to maintain aggregations in the active swash zone. Intertidal zonation patterns in this species vary across the tidal cycle, seasonally, and among beaches (Cubit, 1969; Fusaro, 1980; Jaramillo et al., 2000). Juveniles of *E. analoga* and other hippid crabs generally occupy a notably higher intertidal level than adult crabs (Fusaro, 1980; Haley, 1982), while adult crabs can extend their distribution into the shallow subtidal zone during higher tides, periods of beach erosion, and on some beach types (Jaramillo et al., 2000). The ability of *E. analoga* to burrow at similar speeds across a range of sediment grain sizes likely contributes to the success of this species even in the coarse sediments and harsher swash conditions typical of beaches with reflective characteristics (see Dugan and Hubbard, 1996; Dugan et al., 2000b). As such, *E. analoga* may also be able to survive temporal changes in sediment grain size, such as those occurring on many intermediate type beaches (Dugan, unpublished).

***Emerita analoga* food habits (extracted from Dugan et al., 2005)**
*E. analoga* is a suspension feeder that uses the plumose second antennae to sieve fine particles from the turbulent moving water in the swash zone (Efford, 1966). This species feeds primarily on phytoplankton, which is reflected in carbon and nitrogen stable isotope values (Dugan

unpublished). In addition, individual growth rates (molt increments) and life history characteristics of *E. analoga* are significantly correlated with food availability, which can be estimated from surf-zone chlorophyll concentrations (Dugan, 1990; Dugan et al., 1994). The delicacy and precision of the plumes on the second antennae of feeding *E. analoga*, which move repeatedly through the water to capture and filter out individual phytoplankters, are incompatible with encounters with heavy fuel oil in the form of rolling tarballs, floating particulate oil, or emulsions. Encounters between the feeding plumes and the heavy fuel oil will cause fouling of the plumes and inhibit the filtration process via physical smothering. In addition, oil adhering to the surfaces of any food and suspended sediment particles will lead to further fouling of feeding antennae of sand crabs such as *E. analoga*. Conova (1999) demonstrated that increasing the hydrophobic nature of particles by changing the compounds on the surface of the particles increases the rate of capture of those particles by disarticulated *Emerita* antennae (demonstrating that the change was a passive process of chemical attraction and did not involve active behavior by the crab). Particles that have surfaces covered with oil will be hydrophobic and passively accumulate on *Emerita* antennae in high proportions, resulting in impairment of feeding capacity.

## Life history of *Emerita analoga* in Central California (Santa Barbara County northwards)

Proper assessment of *E. analoga* injury after an oil spill, such as heavy fuel oil, that grounds on ocean beaches in Central California includes need to properly characterize the annual life history of this species of sand (mole) crab. This species generally represents the most important infaunal invertebrate on these ocean beaches because of its seasonally high biomass and importance as prey to shorebirds, crabs, and surf fish. *E. analoga* in this biogeographic area expresses high variability in abundance from beach to beach, among seasons, and between years (e.g., Fusaro, 1980). This variability has inhibited full understanding of the life history. Particularly problematic are studies based entirely on beach sampling without also including sampling of the water column off the beach to incorporate early life stages.

The most comprehensive study of *E. analoga* life history is probably that of Barnes and Wenner (1968). This study provides a rare view of the full life history that includes the early pelagic life stages and, thereby, provides the functional linkages to the older age classes observable in the intertidal and shallow subtidal swash zones of the ocean beaches. Egg production characterized as "berrying" appears in females in late spring and intensifies and continues through summer (Boolotian et al., 1959; Dudley and Cox, 1967). Barnes and Wenner (1968) demonstrated that the zoeae in the plankton increase dramatically around the beginning of August and remain abundant until April, when the numbers drop dramatically. Wharton (1942) documented a larval development period of at least 2-2.5 months, corresponding to the high abundances of late-stage zoeae from mid August onwards through winter. Barnes and Wenner (1968) showed that the next life stage, the megalopae, arrive on the beach in abundance in fall and continue at high levels through winter into spring. Barnes and Wenner (1968) then documented the presence of larger juvenile and adult *E. analoga* on the beach during the warmer months and lasting until late fall. This study that merges pelagic life history stages with benthic stages on the beach provides the widely accepted model of its seasonal life history in Central California. Rather than presuming that the population on the beach is sustained largely or solely by breeding of adult *E. analoga* that have overwintered offshore in deeper waters, Barnes and Wenner (1968) show that

the early life history stages recruit heavily to the beach in fall and winter, allowing them to complete development and spawn in the warm season to sustain the abundance of larger individuals on the beach. An alternative life history model based on the assumption that large numbers of adult females are present in the subtidal during winter and uncharacteristically mate and release larvae in that cold season, has little substantive support, only a casual winter observation of some adult *E. analoga* in deeper waters, and is inconsistent with the seasonal pattern of abundance of their pelagic zoeae larvae as demonstrated in Barnes and Wenner (1968).

**Likely Exposure to and Effects of Spilled *Cosco Busan* Oil**

The significance of using the correct life history of *E. analoga* for the *Cosco Busan* injury assessment is made evident in the following synthesis. The spilled oil first landed on the ocean beaches in early November and then persisted and re-oiled beaches into winter, which is when the beaches receive and hold the small megalopae of *E. analoga.* This life stage that is expected to have been present during the initial oiling and subsequent re-oiling events develops into the larger juveniles and adults that occupy the sandy beach during spring and summer. Consequently, the occurrence of oil contamination of the ocean beaches when the "seeds" of the local *E. analoga* population would have been present likely resulted in suppression of the population well into the following summer and beyond. The failure to observe large numbers of dead *E. analoga* on oiled beaches during the *Cosco Busan* spill is not surprising, as the megalopae are what are expected to be common at that time, and these would be readily overlooked during a SCAT survey and by casual observers because of their extremely small size and likelihood of being readily scavenged by birds, mammals, and beach crustaceans.

Any analysis that presumes that sand crabs like *E. analoga* are largely transported as passive particles like sand grains during storm events that temporarily erode sand off intertidal beaches is mistaken and has misleading implication about risk of injury to spilled oil. Such a presumption ignores the behavior of sand crabs and their great mobility. A recent study (Peterson et al., unpublished) of the east coast sand crab, *Emerita talpoida*, illustrates how sand crabs can and do maintain or rapidly restore their abundances on the intertidal beach after major storms. This study on Onslow Beach, North Carolina provides sampling evidence of how beach sands were eroded by two successive storms, a tropical storm (Hanna) followed by a nine-day northeaster in September 2008 and how *E. talpoida* abundance responded. Figure 2 shows the wind speeds and directions during each storm as well as the significant wave heights and water levels. Wave heights were similar during each storm, but the northeaster generated far higher storm surge for several days longer than the tropical storm. Figure 3 reveals that the consequences of these differences in water levels and storm duration on beach elevation, measured by laser scanner, were large: the tropical storm caused little beach erosion, whereas the northeaster induced substantial erosion of sands in the intertidal foreshore and in the backshore at both ends of the island. Figure 4 demonstrates that sand crab abundances on the low and mid intertidal levels of the beach did not vary from before to after the northeaster in the pattern that would be predicted by the presumption of passive transport matching the sediment loss. By five days after the end of the northeaster, *E. talpoida* had increased in abundance on the south end, where sediment erosion was high enough to reduce elevations by 40-60 cm. *E. talpoida* abundances in the intertidal zone did not change detectably at the north end, where modest sediment erosion of about 20 cm in elevation occurred during the northeaster. In the middle of the island, where sediment elevation

changed the least during the northeaster, *E. talpoida* increased in abundance nearly as much as on the south end. As a consequence of behavioral adaptations, sand crabs, as a group, are able to maintain and/or rapidly restore their intertidal abundance even during dramatic erosion of intertidal beach sands during storms. A direct comparison of changes in *E. talpoida* abundance to amounts of erosion/deposition of sediments on the beach demonstrated no relationship (Fig. 5). Sediment transport in-and offshore does not predict sand crab persistence and abundance on the intertidal beach. Consequently, the assumption that sand crabs like *E. analoga* are passively transported off the intertidal beach during winter storms and then reside in deeper water is not supported by available process-oriented evidence.
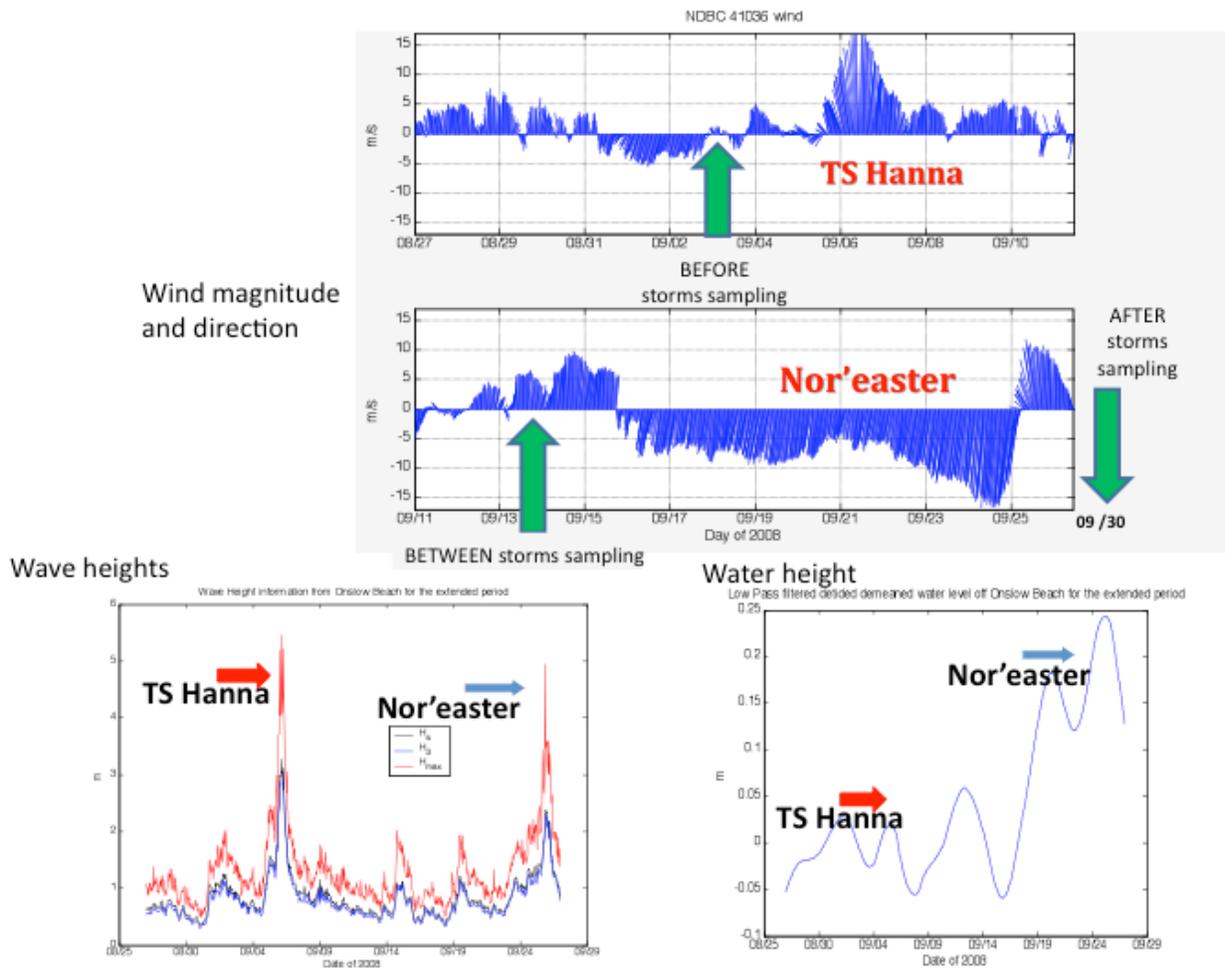


**Figure 2.** Wind speeds and directions during Tropical Storm Hanna and a nor'easter as well as the significant wave heights and water levels for the Onslow Beach, North Carolina study.
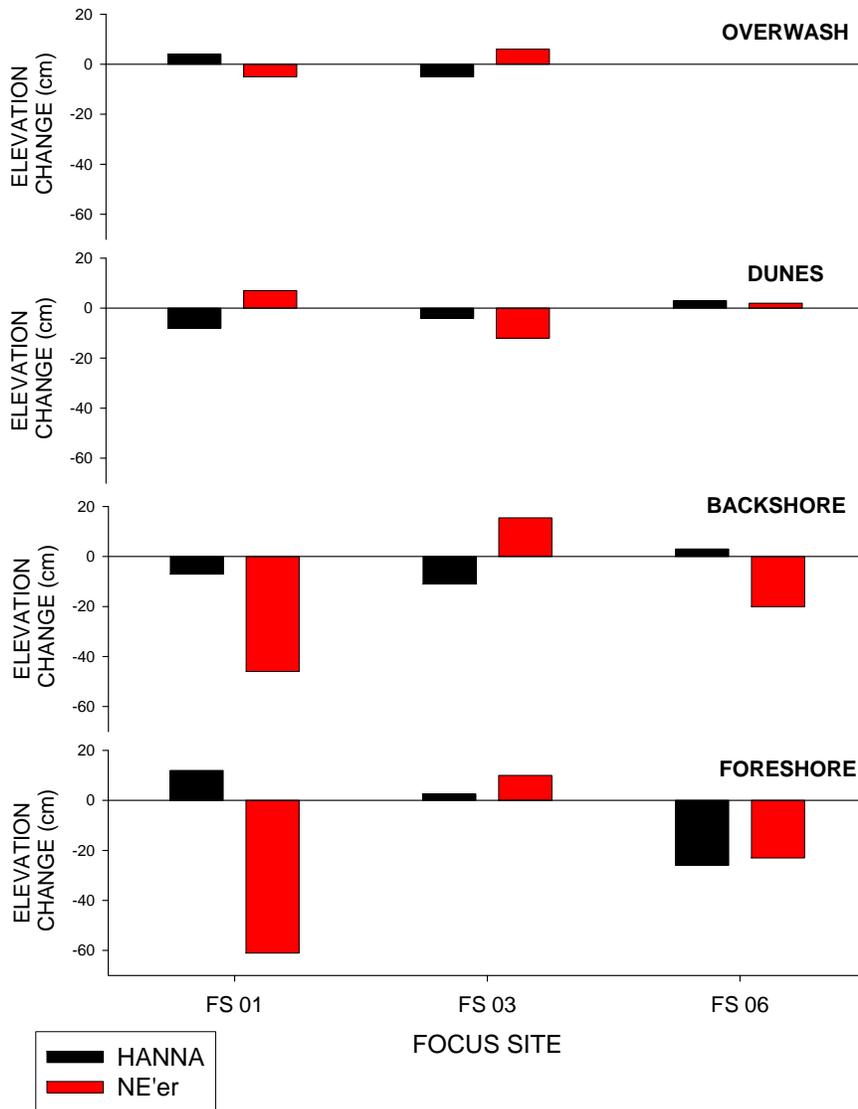
**Figure 3.** Mean changes in elevation by focus site and location within focus sites (locations along the beach) caused by TS Hanna and, later, by a northeaster at Onslow Beach, North Carolina.
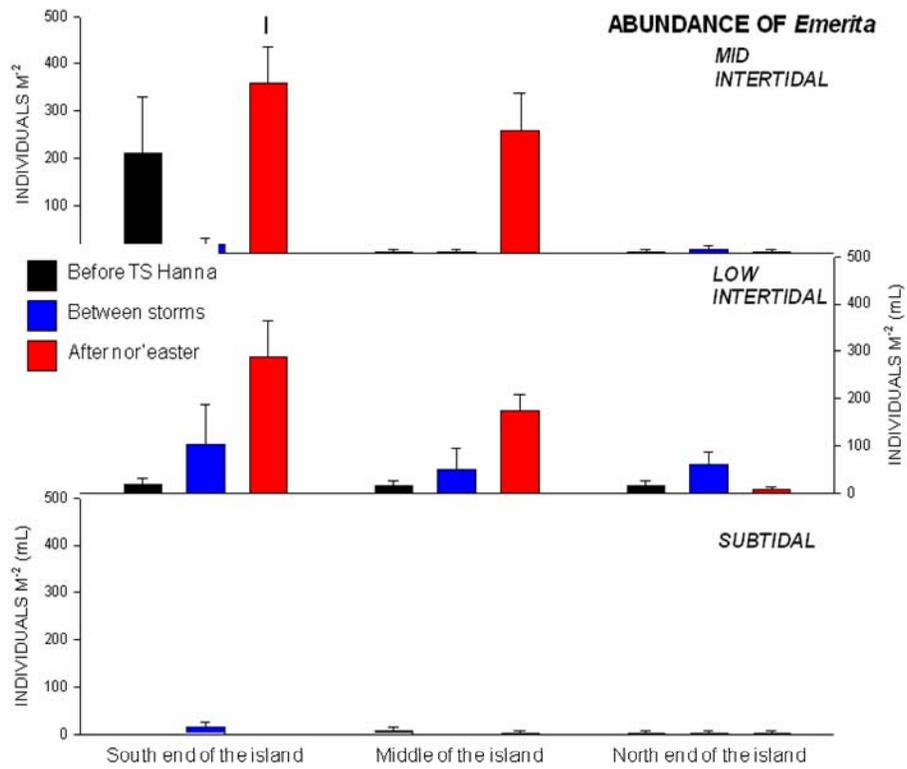
**Figure 4.** Abundance of *Emerita talpoida* by tidal elevation prior to tropical storm Hanna, between storms, and after a large nor'easter storm at Onslow Beach, North Carolina.
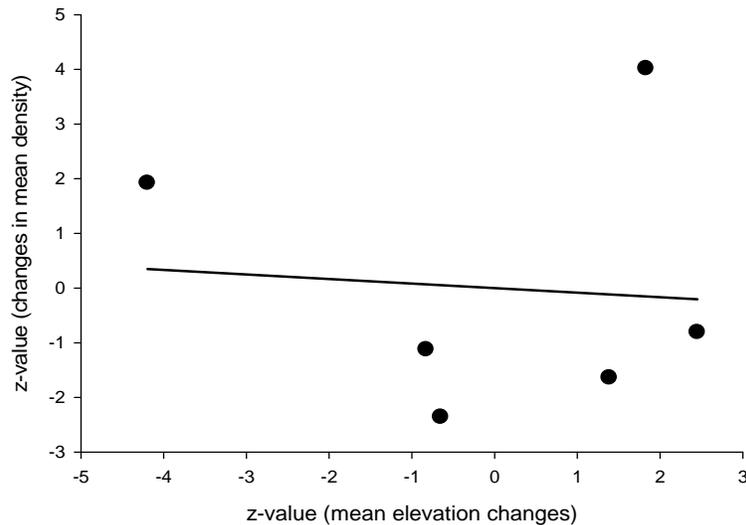


**Figure 5.** Mean changes in *Emerita talpoida* population density compared to mean changes in beach elevation. All values have been standardized to z-values to ease comparison. The linear regression is not significantly different from 0 indicating that changes in *E. talpoida* population density varied independently of the amount of beach erosion or sediment deposition.

**Biota of Tidal Flats**

**The ecology of intertidal flat organisms**

Intertidal sand and mud flats of marine lagoons and estuaries are characterized by highly productive benthic (bottom-dwelling) microalgae (Onuf, 1987; Pinckney and Zingmark, 1993; Sullivan and Currin, 2000), which provide food resources for deposit-feeding invertebrates. The benthic invertebrates of intertidal flats are almost exclusively infaunal (buried) in position with only a few species capable of living on the surface of the mobile sediments (Peterson and Peterson, 1979). Hence, a casual look at the tidal flat fails to reveal the abundance and high productivity of benthic invertebrates. A second important and productive feeding guild of benthic invertebrates is the detritivores. These invertebrates consume plant detritus produced by the nearby salt marsh plants (dominantly succulents like *Sarcocornia* and *Salicornia* and grasses like *Spartina* in San Francisco Bay), by submersed aquatic vegetation (like *Zostera* in San Francisco Bay), by seaweeds (dominantly *Ulva* and *Enteromorpha* in San Francisco Bay), and by death of phytoplankton and benthic microalgae. The third of the most important feeding guilds of benthic invertebrates on sand and mud flats is the suspension feeders (Peterson, 1991). These animals enjoy benefits of food supplementation by tidal current flows, which transport in their phytoplankton foods from the deeper waters of the lagoon or estuary. Benthic microalgae can also contribute to the diets of tide-flat suspension feeders because wind waves can temporarily suspend these benthic microalgae in the water column overlying the flat and thus allow them to be filtered out of the water by suspension feeders. Decomposers like bacteria and fungi play an important role in the food web of tidal flats and in the biogeochemical processing that characterize tidal flats (Kneib, 2003). Detritivorous benthic invertebrates assimilate most of their food energy in the form of bacteria and fungi that are decomposing the detritus formed by marsh plants and submersed aquatic vegetation. The detritus itself is not usually assimilated because of relatively low nutritive value.

In addition to the plants and marine invertebrates at the base of the food chain of intertidal flats, there is a variety of predators and scavengers that feed on the benthic invertebrates of tidal flats. Peterson and Peterson (1979) characterized the intertidal flats as the dining table of the estuary, where much of the entire estuary's secondary production of benthic invertebrates and tertiary production (consumption of those benthic invertebrates) occurs. These predators include most importantly shorebirds, demersal fishes, and crabs of many sorts. In Central California lagoons and estuaries, abundant shorebirds include dunlin, willets, plovers, sandpiper species, marbled godwits and others (White, 1999). Demersal fishes that consume invertebrates on tidal flats include: sculpin, halibut, and several species of ray and shark. Predatory crabs of tidal flats include *Cancer* crabs, such as the Dungeness crab, the smaller *Grapsid* crabs, and hermit crabs. Some predatory benthic invertebrates also exist and are characteristic members of the tidal flat community, such as moon snails (Naticids), blood worms (Glycerid and Nereid polychaetes), and Nemertean worms.

**Taxonomic composition of tidal flat invertebrates**

The benthic invertebrates of tidal flats are divided by size into two major groups, the macrofauna and the meiofauna. Macrofauna are typically defined as all those invertebrates that are retained

on a 0.5-mm mesh. Meiofauna pass through 0.5 mm but are retained on a 67 *u*m mesh. This subdivision corresponds to a taxonomic distinction as well. Macrofaunal phyla that are common on tidal flats are familiar to many people: mollusks like clams and snails; polychaete worms; arthropod crustaceans like burrowing shrimp, amphipods, and crabs; and echinoderms like starfish and sand dollars. Many more phyla of meiofauna occupy tidal flats, although these microscopic animals are mostly unknown to the public: nematodes, harpacticoid copepods, turbellarians, ostracods, tardigrades, kynorhynchs, and more. The meiofauna can be found associated with vegetation (phytal), on the sediment surface (surficial), or within the interstitial spaces among sand grains (interstitial). The meiofauna occupy many different trophic positions from herbivore and detritivore to primary and even secondary predator. To varying degrees, meiofauna are consumed by larger animals such that some fraction of meiofaunal production moves up the food chain to recognizable consumer endpoints.

## Physiology of feeding and respiration in benthic invertebrates – risks of suffocation

Both suspension feeders and deposit feeders, the two dominant feeding types of benthic invertebrates on intertidal flats, have high susceptibility to smothering from contact with particulate oil because of their feeding and respiratory physiology. Infaunal suspension feeders must have unobstructed access to the sediment-water interface to feed and respire. Larger oiled particulates, including tarballs, on the sediment surface would represent a physical barrier reducing or preventing access to the overlying water for feeding and respiring. Because the efficiency of particle capture by suspension feeders is affected by a number of factors including particle surface chemistry (Gerritsen and Porter, 1982) and particle concentration (Bacon et al., 1998), small oiled particulates, even at relatively low concentrations, and tidally resuspended oil droplets would interfere with feeding. Oil (and oiled) particles will adhere more readily than unoiled particles to the surfaces of filters and gills, resulting in clogging (Conova, 1999; Gerritsen and Porter, 1982). The addition of oil-derived particles to the normal seston increases the overall particle concentration of the water, which reduces particle selection efficiency and negatively affects suspension-feeder growth rates (MacDonald et al., 1998). In addition, the ability of bivalves to concentrate and move food from their gills to their mouth depends upon strings of mucus or thick slurries to relay the particles (Ward et al., 1994). It is unclear what effect incorporation of hydrocarbon-rich particles would have on these relay pathways, but alterations to the density of the mucus or slurry would disrupt the ability of cilia to move particles. For deposit feeders that select particles from the sediment surface prior to ingestion, particulate oil on the sediments will be encountered by the feeding palps and tentacles, resulting in decreased capacity to feed and internal fouling if ingested.

Meiofauna feeding and respiration are sensitive to particulate oil in both sandy and muddy habitats. With the exceptions of freezing temperatures and eroding surface sediments, meiofaunal abundances are always skewed towards the sediment surface, with generally greater than 70% of all individuals within 10 cm of the surface in sandy sediments and 90% of all individuals within 1 cm of the surface in muddy sediments (Giere, 2009). Greater availability of oxygen and higher concentrations of food (either particulate organic matter or microphytobenthos) appear to determine this surface orientation (Giere, 2009). Oil particles lying on the surface or, if finer, filling the interstices among sand grains would decrease or eliminate the exchange of oxygen-depleted pore water with oxygenated waters overlying the

sediments. Oils have been found to infiltrate intertidal sand sediments to 10 cm (Chung et al., 2004). Meiofauna occurring intertidally show much larger decreases in abundances after an oil spill than the subtidal meiofauna populations (Boucher, 1980), perhaps because the direct contact between particulate oil settling on the sediment surface and meiofaunal feeding organs and respiratory surfaces has such high potential to foul those organs and induce feeding and oxygenation crises. In addition, recovery of oil-affected meiofauna populations is retarded in more protected, low-energy habitats, such as muddy shores (Giere, 2009). The shores of central San Francisco Bay are muddy.

## **Value of and services provided by benthic invertebrates on tidal flats of San Francisco Bay**

Although San Francisco Bay has been colonized by many nonnative benthic invertebrates (Carlton, 1979), these species nonetheless contribute in important ways to ecosystem services. For example, filtration by the Asian clam *Potamocorbula amurensis* controls phytoplankton blooms in San Francisco Bay and greatly reduces turbidity, thereby allowing greater growth of seagrasses, a valuable nursery habitat for marine organisms (Alpine and Cloern, 1992). Any attempt to trivialize the role of the intertidal benthic invertebrates on the mud flats of San Francisco Bay by characterizing the benthos as invasive and by making comparisons to densities at other locations ignores the high production of invertebrates on these intertidal flats and their value as prey to shorebirds, demersal fishes, and crabs. The secondary production of benthic invertebrates is typically higher in salt marsh vegetation than on unvegetated intertidal flats (Lenihan and Micheli, 2001), yet Brusati and Grosholz (2006) show by sampling three locations (two within the central Bay and one in San Pablo Bay) that both density and biomass of macroinvertebrates are as high or higher on mudflats than in salt marshes, both for marshes formed by the native *Spartina foliosa* grass and those formed by a hybrid marsh grass. Higher density and biomass imply higher secondary production on the intertidal flats, especially when the salt marsh possesses some structural protection of infaunal invertebrates from predation, whereas the infauna of the sand flats are exposed to intense predation by shorebirds, crabs, and demersal fishes (Summerson and Peterson, 1984). San Francisco Bay is valued as a shorebird feeding location, sustaining many species during their long-distance seasonal migrations, for which energetic demands are high, and providing other shorebirds and many ducks with food during winter and other seasons of residence. Because so much of the natural wetland habitat of California has been destroyed by development, San Francisco Bay remains a region of critical conservation importance for shorebirds and waterbirds alike. The benthic infauna thus provides critical ecosystem services in the form of food provision for valued shorebirds, as well as crabs like juvenile Dungeness crabs and juvenile demersal fishes like halibut.

## Summary

Because of various aspects of their life histories, their mobility through surface sediments especially in the case of *E. analoga*, their virtually exclusive occupation of surface sediments especially by the meiofauna, physiological susceptibility of their delicate feeding organs to particulate oil, and their need for continuous and unobstructed contact with overlying water for oxygenation, the benthic invertebrates of both sandy ocean beaches and tidal flats in San Francisco Bay and along the adjacent outer shores are very susceptible to exposure and injury through fouling and contact with particulate oil as experienced after the *Cosco Busan* oil spill.

The likely resulting reductions in productivity of the benthic invertebrates via increased mortality and reduced feeding and growth is ecologically significant in both habitats because these invertebrates represent critical prey for ecologically important consumers at higher trophic levels. These include, most importantly, shorebirds, demersal fishes, and crabs. As a consequence, the injuries induced by physical contact with tarballs, surficial oil, emulsions, and particulates of varying dimensions were likely substantial in these two habitats and imply need for restoration to compensate for lost ecosystem services of public societal importance.

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