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Burrowing inhibition by fine textured beach fill: Implications for recovery of beach ecosystems

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ABSTRACT

Beach nourishment is often considered the most environmentally sound method of maintaining eroding shorelines. However, the ecological consequences are poorly understood. Fill activities cause intense disturbance and high mortality and have the potential to alter the diversity, abundance, and distribution of intertidal macroinvertebrates for months to years. Ecological recovery following fill activities depends on successful recolonization and recruitment of the entire sandy intertidal community. The use of incompatible sediments as fill material can strongly affect ecosystem recovery. We hypothesized that burrowing inhibition of intertidal animals by incompatible fine fill sediments contributes to ecological impacts and limits recovery in beach ecosystems. We experimentally investigated the influence of intertidal zone and burrowing mode on responses of beach invertebrates to altered sediment texture (28–38% fines), and ultimately the potential for colonization and recovery of beaches disturbed by beach filling. Using experimental trials in fill material and natural beach sand, we found that the mismatched fine fill sediments significantly inhibited burrowing of characteristic species from all intertidal zones, including sand crabs, clams, polychaetes, isopods, and talitrid amphipods. Burrowing performance of all five species we tested was consistently reduced in the fill material and burrowing was completely inhibited for several species. The threshold for burrowing inhibition by fine sediment content in middle and lower beach macroinvertebrates varied by species, with highest sensitivity for the polychaete (4% fines, below the USA regulatory limit of 10% fines), followed by sand crabs and clams (20% fines). These results suggest broader investigation of thresholds for burrowing inhibition in fine fill material is needed for beach animals. Burrowing inhibition caused by mismatched fill sediments exposes beach macroinvertebrates to stresses, which could depress recruitment and survival at all intertidal zones. Our results suggest use of incompatible fine fill sediments from dredging projects creates unsuitable intertidal habitat that excludes burrowing macroinvertebrates and could delay beach ecosystem recovery. Through effects on beach invertebrates that are prey for shorebirds and fish, the ecological impacts of filling with mismatched fine sediments could influence higher trophic levels and extend beyond the beach itself.

1. Introduction

In spite of the general acceptance of beach nourishment as the most ecologically sound method of maintaining eroding shorelines, the impacts of nourishment projects on the biota of beaches and adjacent habitats are variable and poorly understood (e.g. Peterson and Bishop, 2005; Speybroeck et al., 2006; Leewis et al., 2012). Many biological components of surf zone-beach-dune systems and adjacent ecosystems may be altered during nourishment projects including coastal strand and dune plants, birds, intertidal invertebrates, and marine animals (Peterson et al., 2000, 2006; Speybroeck et al., 2006; Jordan et al., 2010). Factors that may influence the ecological response to nourishment projects include pre-project site conditions, timing, frequency of disturbance, method of application, quantity of added material, matching of sediment texture, and cumulative effects (Peterson and Bishop, 2005; Speybroeck et al., 2006; Van Tomme et al., 2012). The great variety of fill project sites and approaches has complicated understanding of the ecological impacts and the recovery of beach ecosystems.

Many beach macroinvertebrates are suitable ecological indicators (in part because of their low dispersal rates), which allows spatial patterns to imply causation (Peterson and Bishop, 2005). Some studies have assumed, or shown (Schlacher et al., 2012), that beach nourishment projects leave project sites devoid of living macroinvertebrate communities, and that ecosystem recovery depends on dispersal abilities and habitat requirements of potential

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colonizing species (e.g. Van Tomme et al., 2012). If macroinvertebrate communities are to successfully recolonize and recover on the filled beach following disturbance associated with nourishment, then sediment characteristics must match the needs of those species, (Van Tomme et al., 2012). For many species, the time course of recovery depends on the availability of propagules from unaffected beaches as well as habitat suitability. Reported estimates of recovery times for intertidal invertebrates range from recovery in abundance in less than one year for four dominant species (Leewis et al., 2012), no recovery in five months on the upper shore (Schlacher et al., 2012), to greater than two years for subtidal communities (Rakocinski et al., 1996).

Sediment texture is considered to be an important factor in matching both the morphodynamic and biological suitability of fill material, but even recent studies have generally focused on impacts of beach fills on distribution and abundance of macrofauna (e.g. Leewis et al., 2012; Schlacher et al., 2012), rather than the mechanisms driving the observed biotic responses (Speybroeck et al., 2006). Ecological impacts to the abundance and distribution of intertidal animals have been shown for fill sediments that are coarser (Peterson et al., 2000, 2006) and finer (Rakocinski et al., 1996) than native sediments with some effects lasting for years. The addition of fill containing much coarser material than natural beach sand was associated with a range of morphodynamic and ecological effects: including steeper beach slopes and altered beach habitat, depressed abundance of macroinvertebrates and birds, and reduced trophic transfer (Peterson et al., 2006). Fluctuations in total densities, species richness and the densities of key indicator species associated with increased clay/silt loading of fill material persisted for more than two years after nourishment (Rakocinski et al., 1996).

On sandy beaches, intertidal animals are highly mobile, regularly moving to burrow in new locations to adjust to constantly changing beach profiles and conditions (McLachlan and Jaramillo, 1995; Dugan et al., 2013). Beach macroinvertebrates have preferred ranges of sand grain sizes across which they can successfully burrow (Alexander et al., 1993; Dugan et al., 2000; Nel et al., 2001; Van Tomme et al., 2012). Re-colonization of nourished beaches may be impeded if the texture of fill material is not well matched to local beach sand. Reduced burrowing performance of invertebrates can increase exposure times to predators, trampling, heat stress, swash processes, longshore transport and stranding (Dugan et al., 2000). These stressors resulting from short-term exclusion of invertebrates in poorly matched fill material could contribute to reduced abundance and diversity of invertebrates and protracted ecological recovery on nourished beaches. While many studies have suggested burrowing exclusion of macroinvertebrates as a potential mechanism driving ecological responses to nourishment projects (e.g. Speybroeck et al., 2006; Peterson et al., 2006; Van Tomme et al., 2012), few have investigated this directly. Our study evaluates the importance of burrowing as a mechanism contributing to ecological impacts of beach filling by experimentally evaluating the effects of fill material with high fine sediment content on the burrowing performance of characteristic intertidal macroinvertebrates of a California beach.

2. Methods

2.1. Study site and beach fill history

Ongoing beach fill activities at Goleta Beach County Park in Santa Barbara (California, USA) (N: 34.4°, S: -119.8°) motivated this study. This 1280 m south-facing beach experiences episodic erosion. Revetments were constructed and nourishment projects have been frequently employed to protect the parkland and infrastructure from the receding shoreline. The most recent beach fill project at Goleta Beach occurred in Spring 2011, when the Santa Barbara Flood Control District distributed about 24,450 cubic meters of material dredged from creeks and tidal channels of nearby Goleta Slough on the ocean beach. This dredged material contained a high proportion of fine sediments (28–38% fines, which passed through a 0.039 mm sieve, the threshold for silts and clays) (Fugro, 2011). This material formed a consolidated terrace at the west end of the beach. Strong winds and wave action exposed this material at the high tide line and in the intertidal zone. The relatively small footprint (~1 ha) of the 2011 dredge disposal activity at Goleta Beach County Park resulted in intense local alteration of beach habitat but likely did not cause major impacts to beach habitat outside the project area.

Table 1
Intertidal species, taxon, numbers, and ranges of body sizes of animals used in experimental comparisons of burrowing in beach sand and fine fill sediments.

Species	Intertidal zone	Taxon	# Collected	Body size
Alloniscus perconvexus	Upper	Isopod	100	6–12 mm
Megalorchestia corniculata	Upper	Amphipod	100	12–20 mm
Thoracophelia mucronata	Mid	Polychaete	100	15–20 mm
Donax gouldii	Lower	Clam	20	9–15 mm
Emerita analoga (Adult)	Lower	Decapod	100	11–20 mm
Emerita analoga (Juvenile)	Lower	Decapod	100	4 mm

2.2. Study animals

Macroinvertebrate species characteristic of the upper, mid, and low intertidal zones of California beaches were collected from Goleta Beach County Park and nearby beaches for use in the experimental trials. The species we tested represented 3 invertebrate phyla (Mollusca, Annelida, and Arthropoda), including an oniscid isopod, (*Alloniscus perconvexus*) and a talitrid amphipod (*Megalorchestia corniculata*) both wrack consumers from the upper beach, a mid intertidal deposit-feeding polychaete (*Thoracophelia mucronata*), and two suspension feeding species, a donacid clam (*Donax gouldii*), and a hippid crab (*Emerita analoga*) from the low intertidal. Experimental burrowing trials were conducted within 30 min of collection. Numbers and sizes of each species used in trials are listed in Table 1. All animals were released following the conclusion of the burrowing trials.

2.3. Burrowing performance

To investigate the effects of fill containing a high percentage of fines on burrowing performance of the study animals, we conducted experimental burrowing trials in replicate containers containing natural beach sand or fill material in the field during daylight hours. Burrowing trials for the two upper beach species were conducted in covered 14 cm diameter by 12 cm depth plastic cylinders set into the substrate with either natural beach sand from Goleta Beach (controls) or fill material (treatments). Burrowing trials for the middle and lower intertidal species were conducted in 14.5 cm by 14.5 cm by 9 cm depth plastic containers with natural beach sand or fill material covered by a thin layer of seawater. Due to the small particle size and cohesive molecular properties, the fill fine sediments settled and aggregated into a consolidated layer in the experimental containers. This layer was similar to intertidal conditions on the filled section of beach. All containers were shaded to minimize temperature changes.

Time allotted for the burrowing trials differed among species to match burrowing speeds and activity. For juvenile and adult hippid crabs (*Emerita analoga*), which burrow rapidly, trials were 120 s