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Multi-year persistence of beach habitat degradation from nourishment using coarse shelly sediments

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HIGHLIGHTS

- We monitored recovery of sandy beach fauna for 3–4 years following nourishment.
- The application of unnaturally coarse sediments served as a press disturbance.
- Abundances of haustoriid amphipods and *Donax* were suppressed for the entire study.
- Impacts to invertebrates were matched by reduced abundances of their predators.
- Hence, mismatch of fill and native beach sediments can produce lasting impacts.

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ABSTRACT

Beach nourishment is increasingly used to protect public beach amenity and coastal property from erosion and storm damage. Where beach nourishment uses fill sediments that differ in sedimentology from native beach sands, press disturbances to sandy beach invertebrates and their ecosystem services can occur. How long impacts persist is, however, unclear because monitoring after nourishment typically only extends for several months. Here, monitoring was extended for 3–4 years following each of two spatially separated, replicate nourishment projects using unnaturally coarse sediments. Following both fill events, the contribution to beach sediments of gravel-sized particles and shell fragments was enhanced, and although diminishing through time, remained elevated as compared to control sites at the end of 3–4 years of monitoring, including in the low intertidal and swash zones, where benthic macroinvertebrates concentrate. Consequently, two infaunal invertebrates, haustoriid amphipods and *Donax* spp., exhibited suppressed densities over the entire post-nourishment period of 3–4 years. *Emerita talpoida*, by contrast, exhibited lower densities on nourished than control beaches only in the early summer of the first and second years and polychaetes exhibited little response to nourishment. The overall impact to invertebrates of nourishment was matched by multi-year reductions in abundances of their predators. Ghost crab abundances were suppressed on nourished beaches with impacts disappearing only by the fourth summer. Counts of foraging shorebirds were depressed for 4 years after the first project and 2 years after the second project. Our results challenge the view that beach nourishment is environmentally benign by demonstrating that application of unnaturally coarse and shelly sediments can serve as a press disturbance to degrade the beach habitat and its trophic services to shorebirds for 2–4 years. Recognizing that recovery following nourishment can be slow, studies that monitor impacts for only several months are inadequate.

1. Introduction

Sandy beaches are among the most threatened of all ecosystems, under severe pressure from the combined effects of global climate change and resulting management actions to protect coastal properties from its effects (Schlacher et al., 2007a; Defeo et al., 2009; Dugan et al., 2010). Rising sea levels (Vermeer and Rahmstorf, 2009; Kemp et al.,

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2011) and increasingly frequent and intense storms such as hurricanes (IPCC, 2007) are resulting in erosion of beach sediments and flood and storm damage to coastal development. As the threat to coastal properties continues to grow, so too does the demand for coastal engineering interventions (e.g., Valverde et al., 1999; Hanson et al., 2002; Cooke et al., 2012). Beach nourishment, the placement of 'fill' sediments on the beach to elevate and extend it seaward, is a presently favored method of combating beach loss, perceived to avoid the negative impacts of engineered hard structures.

Despite the widespread use of beach nourishment and, in some parts of the world, mandated monitoring of its ecological effects, little is known of its long-term impacts to sandy beach ecosystems (Peterson and Bishop, 2005; Dugan et al., 2010; Leewis et al., 2012; Schlacher et al., 2012). Beaches sustain seasonally dense communities of invertebrates that, in turn, support shorebirds, crabs, and surf fishes (Brown and McLachan, 1990). Ecological monitoring studies of nourishment to date have generally suffered from critical design flaws that limit their utility in management (Peterson and Bishop, 2005; Speybroeck et al., 2006). Among the most notable gaps in these studies is the widespread failure to continue the monitoring beyond a few months after the sediment filling ends (but see Leewis et al., 2012 for a multi-year assessment, achieved by using a space-for-time assessment of duration of impacts). Consequently, basic process-level understanding of how the fauna recovers following this form of disturbance is lacking, delaying development and implementation of mitigation methods to minimize habitat degradation (e.g., Peterson et al., 2006).

Rates of recovery of sandy beach invertebrates following beach nourishment will depend on whether this activity represents a pulse or press perturbation (sensu Bender et al., 1984). At the very least, beach nourishment represents a pulse perturbation because it involves deposition of sediments onto the beach at rates that exceed the capacity of benthic invertebrates to burrow upwards and escape suffocation, starvation, and crushing by burial (Kranz, 1974; Peterson, 1985; Peterson and Black, 1988; Menn et al., 2003; Thrush et al., 2003). Beach filling commonly adds as much as 1–4 m in intertidal beach elevation (Menn et al., 2003; Speybroeck et al., 2006). Many previous studies have demonstrated that along with other physical drivers, such as tidal range, wave energy, and beach slope, sediment grain size plays a major role in determining the community composition of sandy beach invertebrates (Rodil and Lastra, 2004; Defeo and McLachlan, 2005; McLachlan and Dorvlo, 2005). If the sediments used as fill present a close match to the local beach sedimentology, recovery following the pulse disturbance can then begin quickly through secondary succession combined with long-shore transport of colonizing invertebrates into the disturbed area. If, however, the fill sediments are poorly matched to the native beach sediments, longer-term, press impacts may result from the suppression of recovery by modified sedimentology (Nelson, 1989, 1993; McLachlan, 1996; Peterson et al., 2006). Mismatched fill sediments may inhibit burial ability of invertebrates, interfere with the behavioral habitat selection of dispersing larvae, and modify invertebrate feeding and predator avoidance (Peterson et al., 2006; Viola et al., 2014; Manning et al., in press). Yet, with most studies failing to monitor for longer than several months following nourishment, and some showing clearly incomplete recovery (e.g., Adriaanse and Coosen, 1991; Peterson et al., 2006), it remains unclear by how long nourishment with mismatched sediments may delay recovery (Schlacher et al., 2012). This concern may be especially critical for the coarsening of beach sediments because coarse materials are not as readily eroded and transported away by waves and currents as fine sediments (e.g., Komar, 1998). Furthermore, recognition of this basic sediment transport principle motivates informed consulting engineers to advocate intentional beach sediment coarsening to enhance durability of the nourishment project and thereby reduce long-term costs.

Here, we test the hypothesis that deposition of coarse shell hash on an ocean beach will produce long-lasting modifications of the sedimentology, benthic invertebrate densities, and shorebird foraging use of the sandy beach habitat. We conduct this test by re-sampling, to provide up to four years of response data, on control beaches and nourished beaches where deposition of unnaturally coarse shell hash was previously shown to have modified sandy beach ecology for nearly a year after nourishment (Peterson et al., 2006). Although, in that previous short-term study, *Scolelepis squamata* (Muller 1789) polychaetes were unaffected by filling and mole crabs (*Emerita talpoida* (Say 1817)) displayed only a short-term suppression, abundances of bean clams (*Donax* spp.) and direct-developing haustoriid amphipods exhibited an average depression in abundance of 93–95%, with no trend toward recovery (Peterson et al., 2006). These impacts to invertebrates were matched by their predators, with ghost crabs (*Ocypode quadrata* Fabricius 1787) half as abundant and foraging shorebirds, dominated by sanderlings, 60–95% lower on nourished than control beaches, a pattern that was evident throughout the warm season (Peterson et al., 2006). Our new study provides the results of an additional three years of post-nourishment monitoring and three years of monitoring another replicate nourishment project to provide the longest available post-nourishment monitoring of a sandy ocean beach ecosystem. Given that most sandy beach invertebrates have a life span of 1–2 years (Diaz, 1980; Ansell, 1983), our study extending for up to 4 years post-nourishment assesses the capacity for recovery over multiple generations.

2. Methods

2.1. Study sites

We assessed physical and biological impacts of beach nourishment that deposited high levels of coarse shell hash on the intertidal beaches of Bogue Banks, North Carolina, USA. Bogue Banks is a 34 km-long barrier island that runs east to west, with an ocean beach facing due south and with extensive development. Our study assessed impacts of two beach nourishment projects, each using sediments from offshore borrow sites in similar geological outcroppings. During the first, from early December 2001 to early April 2002, 1.3 million m^3 of sediment was deposited along 11 km of beach covering the beaches of Pine Knoll Shores through Indian Beach (Fig. 1). During the second, extending from mid January to late March 2003, 1.4 million m^3 of sediment was deposited along 9.5 km of beach in Emerald Isle, westward of the first nourishment project (Fig. 1). Fill sediments contained up to 13 times more gravel and nine times more coarse sand than native beach sediments, but also double the low percentage (<1%) of silts and clays (Peterson et al., 2006). The volume of sand placed on the beach was engineered with intent to provide adequate protection to coastal property for ~10 years. Previously (Peterson et al., 2006), we used a "Beyond-BACI" (Underwood, 1994) design to identify and quantify impacts of the first nourishment event on sediment granulometry, macrobenthic invertebrate abundances, and shorebird foraging for nearly a year following the beach filling. Here, we present results of further sampling from 2002 to 2005 to: (1) extend the sampling period to determine the temporal duration of and recovery trajectory from impacts resulting from the nourishment project; and (2) provide analogous sampling to document impacts and their duration after the second nourishment, thereby providing replication from a separate event using similar sediment sources placed on similar but different beaches of the same island.

To assess the duration of impacts of these beach filling activities on beach habitat sedimentology and ecology, we sampled at nine locations (Fig. 1): three control locations outside of the area of each beach filling (C1, C2, C3); three locations nourished in 2001–2 (N1-1, N1-2, N1-3); and three locations nourished during the 2002–3 fill event (N2-1, N2-2, N2-3). The control and nourished treatments were not interspersed because beach filling occurred along continuous stretches of shoreline (Fig. 1). Pilot studies, however, revealed that there was not a pre-existing east–west gradient in any of the variables sampled, prior to