Research article

Potential long-term disturbance associated with beach nourishment - insights and observations from Pea Island National Wildlife Refuge, Outer Banks, North Carolina

Paul Paris [*], Anya Leach, D. Reide Corbett

Coastal Studies Institute, East Carolina University, 850 NC-345, Wanchese, NC 27981, USA

ABSTRACT

The longer-term ecosystem impacts associated with a beach nourishment project conducted in 2014 were studied on an ocean beach on the Pea Island National Wildlife Refuge on North Carolina's Outer Banks. The unique nature of the project is tied to the study's duration, which spans nine years, and the venue, a national wildlife refuge where human-sourced confounding effects are minimal. Populations for five invertebrates: Emerita talpoida (the Atlantic Mole Crab), *Donax variabilis* (the Coquina Clam), Scolelepis squamata, Ocypode quadrata (the Atlantic Ghost Crab), and indigenous Amphipods were monitored seasonally over nine-years that asymmetrically straddled the 2014 nourishment event. Beach sediments were also monitored in concert with the biodata. Results show that the 2014 nourishment fill sands were finer than those native to the study area beach, however, reworking quickly brought the fill sands on the nourished beach into size parity with native sediments observed on a predefined control site.

Findings from this investigation fail to present evidence to suggest that any type of ephemeral species die-off occurred in association with the 2014 nourishment event. While die-offs are commonplace reported, such outcomes are not inevitable. Other investigators have documented ecosystem resilience against significant disturbances such as beach nourishment—this study appears to corroborate such findings, both at the system and species levels. Many argue that nourishment fill sand characteristics: their fit to the native sediment in terms of size and composition, and their application during construction, are the principal determinants driving the disturbance response and subsequent post-nourishment recovery. This study corroborates this fill-sand/recovery relationship but provides evidence to support a causation argument only circumstantially.

1. Introduction

Beach nourishment is a common response to a beach erosion problem that is affecting an increasing number of communities along sandy beaches worldwide [1,2,3]. Nourishment is the artificial addition of sediment to restore the eroded beach to some prior, or desired, width and elevation [4]. As eustatic sea level rises and beaches continue to erode, nourishment's appeal as a temporary solution continues to grow [5,6,7,8]. Much of the impetus behind this trend is driven by simple economics. Tourism is a major source of revenue and livelihood along many coastlines [9,10], and the loss of those resources can cripple a local economy [11]. Most beach

nourishment projects conducted over the past 5 decades have been and continue to be motivated by the twofold need to provide storm-damage protection to existing coastal properties and to maintain recreational, i.e., economic value [10,12,13,14,15]. Sandy beaches are, however, also recognized as an important ecological resource [6,11,13,16,17,18,19,20]. This recognition has resulted in an increasing number of studies that address ecosystem impact and response from nourishment apart from the economic aspect alone [3,13]. Though many of these studies remain unpublished an increasing number are being issued in peer-reviewed scientific journals (Roscov et al., 2016).

A common criticism of the published scientific literature that addresses nourishment and its impact on beach ecosystems is the lack of studies that span more than a year or two beyond completion of beach reconstruction [18,20,21]. A survey conducted as a part of this investigation looked at 21 relevant peer-reviewed papers from 2000 to 2022 (Paris et al. in review) found that the average duration for beach ecology-nourishment impact studies over the past two decades is 15 months. Many of these short-term studies do appear to address ecological-impact concerns, with most reporting complete system recovery after timespans ranging from only a few weeks up to one to two years [16,22]; Woolridge et al., 2016 [11,18,23,24,25]; Gorzelany and Nelson, 1983 [26]; and the reviews by Speyboreck et al., 2006 and [27]. A smaller number of studies, however, report a failure to recover after one to two recruitment seasons [21]; Peterson et al., 2006; [28]. Further, it is unclear if the recoveries reported are sustained over longer time spans (e.g., >2–4 years) along the nourished beach [18,29]. The objective of present study is to observe longer term species compositions and population abundances and to contrast the variance behavior of these compositions and abundances over a continuous, sustained time period that pre and post-dates a single nourishment event. This study considers a longer-term ecosystem response, encompassing a total of nine recruitment seasons dating from 2012 through 2020, that straddle asymmetrically a nourishment event carried out in 2014. In addition to its longevity, the study is unique in that it was conducted in an environment (a national wildlife refuge) that is largely free of human infrastructure and day to day human use.
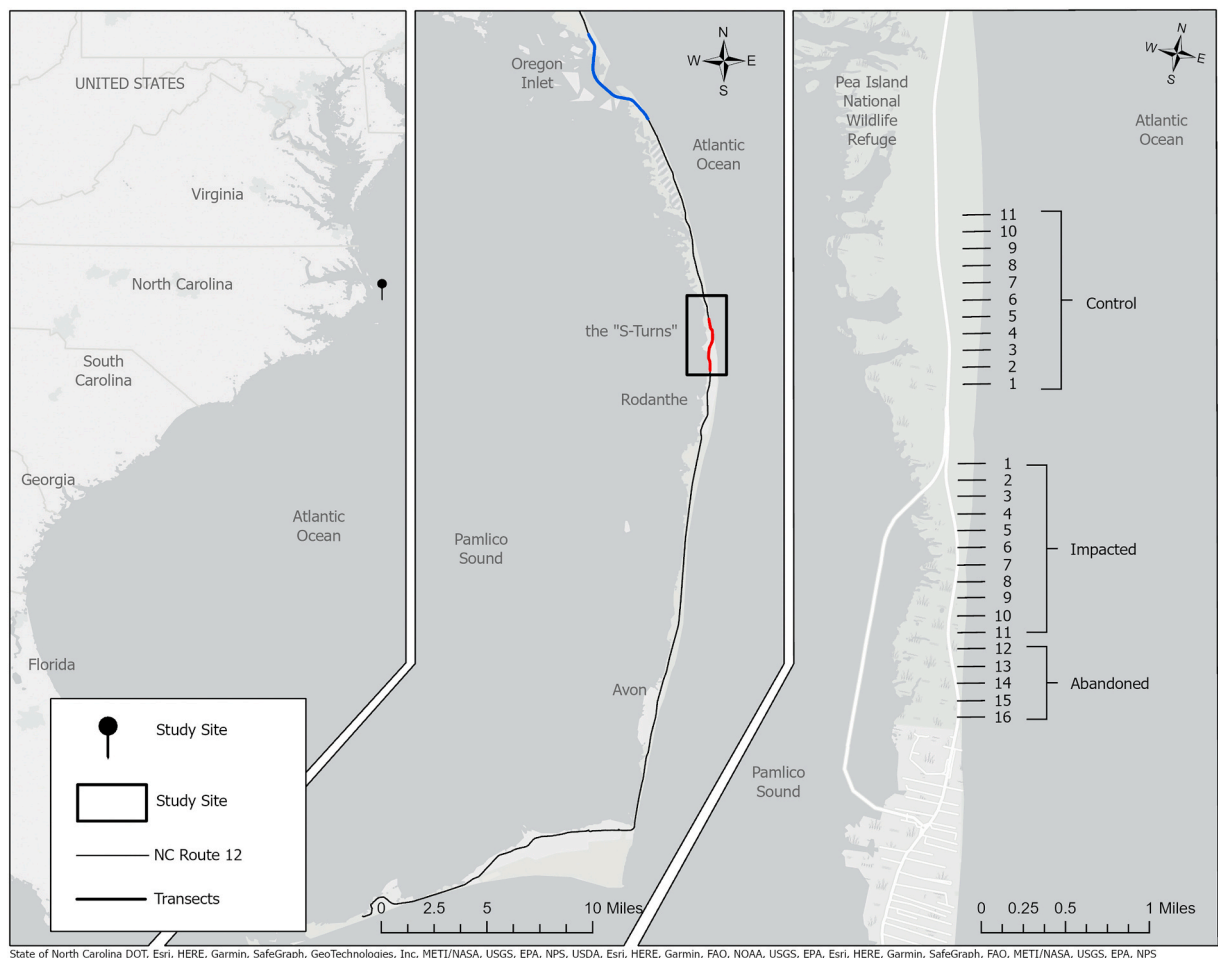

Fig. 1. Location of Pea Island study area along North Carolina's Outer Banks, USA.

2. Study area

The Pea Island National Wildlife Refuge is located along North Carolina's Outer Banks, at the northern end of Hatteras Island (Fig. 1). The refuge is uninhabited and largely undeveloped. A series of shore-parallel dunes built in the 1930s by the Civilian Conservation Corps, and behind them, North Carolina (NC) Highway 12, are the only notable human infrastructure currently present along this section of Hatteras Island.

The study area sits along the ocean beach at the southern end of the Pea Island Refuge. This section of the refuge is locally referred to as "S-Turns", or "S-Curves" (Fig. 1), monikers referencing the sinuous track followed by highway NC 12 in this area. The site has long been impacted by storms pushing water and sand over NC 12's paved surface, leaving the roadway damaged and increasingly often in need of costly repairs [30]. NC 12 is the only thoroughfare connecting the populated villages along Hatteras Island to the northern mainland beaches making the area a vital corridor to the residents and visitors to Hatteras Island. In 2013, emergency funds were allocated to nourish the beach along this two-mile stretch of ocean shoreline to temporarily mitigate the persistent NC12 storm-damage problem. The project's design lifespan was 3 years. In the summer of 2014, 1.6 million cubic yards (1.22 million cubic meters) of sand were placed along almost 2 miles (3.22 km) of ocean shoreline (Fig. 2), approximately 80% of this sand was placed within the refuge.

The ocean beach at the study site is a semi-diurnal, micro-tidal, with a dominant range of approximately 1m (REF). Wave energies vary somewhat along the length of Hatteras Island north of Cape Hatteras, with average annual significant wave heights of about 1.1m ([30]. The greatest amount of energy is delivered to the beach during the cooler months from November through March with predominate winds from the north and northeast [30] augmenting larger incident North Atlantic-sourced ocean swell. During the warmer months the dominate winds, much lighter in intensity, shift to a southerly or southwesterly direction.

The geomorphology of the beach and nearshore along the study area is one that varies from reflective [60] during the quiescent summer season to dissipative [60] during the Fall, Winter, and early Spring when both mean wave energies are higher and storm-wave conditions are commonplace.

3. Methods

3.1. Field methods

Field work and sampling for this study adopted an approach identical to that used by the U.S. Fish and Wildlife Service (USFWS) for a prior USFWS/Coastal Studies Institute (CSI) 2014–2017 short-term study [22]. This approach is based on a Before-After-Control-Impact (BACI) experimental design [31,32] which partitioned the 3.2 km (~2 mi) long Pea Island study beach into two experimental units, one a control beach site where baseline conditions were established and defined, and the second, the region that received nourishment sands, the impacted (i.e., nourished) beach site. In each area, a series of fixed-position cross-shore transects were placed (Fig. 1) with an alongshore spacing of 160 m (0.1 mi). The control and nourished transect groups were separated by an 800 m (~0.5 mi) buffer. This separation was intended to minimize cross-contamination risk to the control beach. Though field

Fig. 2. Aerial view of the 2014 nourishment underway along the southern end of the Pea Island National Wildlife Refuge on the northern end of Hatteras Island. The populated Village of Rodanthe is set in the background.

surveys continued over the 27 transects originally established, storm-damage and subsequent reconstruction interventions by the North Carolina Department of Transportation (NCDOT) as part of on-going efforts to maintain nearby North Carolina Highway 12, necessitated the abandonment of the five southernmost transects, 12 through 16 on the nourished beach (Fig. 1). Thus, while the fieldwork continued to visit and sample all 27 transects (i.e., 11 controls and 16 nourishment sites), all analyses described below use only the first 11 of the transects on the nourished beach. All geomorphic and biological data collected per transect were later aggregated to the experimental unit level (i.e., control or nourished beach sites, respectively) for analysis.

The biological sampling protocol consisted of abundance (counts) for a select set of indigenous invertebrates previously established for taxonomic identification by the USFWS and the NCDOT and based on prior monitoring studies [33,34,35]. Taxa included four site-common invertebrate species, Emerita talpoida (the Atlantic Mole Crab), Ocypode quadrata (the Atlantic Ghost Crab), Donax variabilis (the Coquina Clam), and the Polychaete annelid Scolelepis squamata. In addition, observations were included for swash zone invertebrates of order Amphipoda (undifferentiated by species). These species were selected for this study both for the group's relative commonplace occurrence as indicator species along Outer Banks ocean beaches but also in order to maintain consistency with the prior 2014–2017 USFWS study (Corbett and Walsh, 2017) and on-going beach survey work being conducted by the NCDOT. Maintaining consistency in sampling made possible the inclusion of the latter's beach survey data to augment data collected as part of this research.

Swash zone abundance results represent pooled counts from 3 shallow 10 cm-diameter (0.26 L) cores collected in the lower, middle, and upper swash zones at each of the original 27 transect locations (Fig. 3). Each core sample was passed through a 305 mm diameter 1 mm mesh sieve, and those specimens captured in the sieve were counted (Fig. 4). Biological specimens were not retained, all sample material and specimens were returned to the swash. Ocypode quadrata abundance was gathered via a fixed-area proxy, where crab dens observed within a 1-m square quadrat randomly "tossed" along the transect between the mid and upper beach (Fig. 3) were tallied for 3 locations and summed. Pooled abundances were converted to relative per-species abundance densities by dividing the pooled experimental unit counts by the number of sampling units (transects) used in the survey.

Surface beach sediment (including sand and carbonate shell debris) was sampled at cross-shore positions (Fig. 3) along each transect. At each sample location approximately 250 g of sediment material was collected using a hand trowel from the top 10 cm (4 in) of beach surface for later laboratory analysis. Sampling protocols included 4 cross-shore positions: lower swash (S1), middle swash (S2), upper swash (S3), and dune toe (S4). Beginning with the January 2016 survey, a fifth backshore (mid beach) sample (S5) was also added (see Fig. 3).

3.2. Laboratory methods

Sand samples were mechanically sieved using standard composite sieve techniques [36,37] at ½ φ intervals from 3.5 φ (0.88 mm) to −2 φ (4 mm). Within the medium sand size group (1 φ to 2 φ; 0.25–0.5 mm), the separation interval was ¼ φ. Grain size and distribution statistics were computed using GradiSTAT [38] in Microsoft's Excel.

Durable shells along with shell fragments of varying sizes and shell hash, present in many of the samples collected, were not
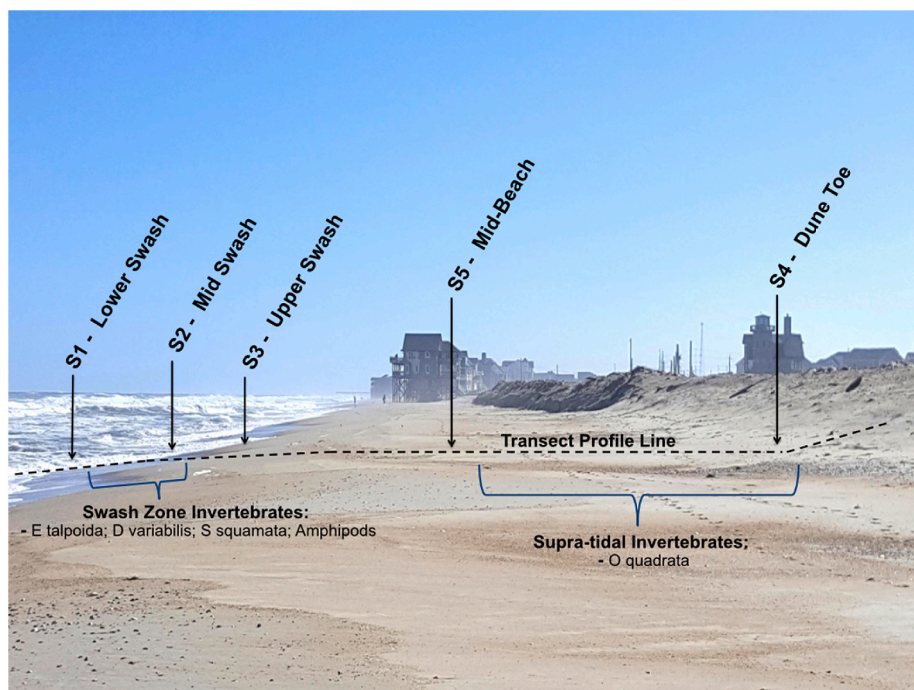

Fig. 3. Typical sampling transect used for field data collection.

Fig. 4. Survey team members during invertebrate counts in the swash zone. Counts were carried out by sifting a sediment sample collected in the beachface swash through a 1 mm wire-mesh sieve to remove the smaller sand-sized particles then skimming through the remaining material searching for the five indicator invertebrates, counting and recording the number of each seen in the sieve. This process was done three times (3 replicated) at each of the 22 control and impacted transect locations.

separated from the total sample and so a carbonate contribution to the sample, aside from noting presence or absence, was not estimated. When shell was present in a sample its constituent weight is included undifferentiated as part of the total weight of each size fraction.

Heavy mineral constituents (mineral densities (ρ) » 2.65 g/cc) such as hornblende, ilmenite, magnetite, rutile and garnet, all commonplace species found along Hatteras Island Ocean beaches [33], were determined as percent of total sample weight for each sand sample collected. Percent of total weight was estimated based on a semi-automated digital recognition technique that relies on grain color intensity and opacity as a proxy for traditional microscope-based visual species identification. The method, first developed by Ref. [35] consists of a microscope outfitted with a high-resolution digital camera and the image analysis software suite ImageJ [39]. Heavy mineral content in a sample was determined by placing a small 15-g dried and homogenized subsample on the microscope stage under uniform illumination. Image frames captured from the camera were then processed through ImageJ using an in-house built script that partitioned the grain images based on RGB pixel intensities and intensity thresholds. Grains were identified and classed by the script as either silica-based quartz or non-silica dark sands. Given each grain class total count and the ratio of the dark to light grains, a percent dark mineral content was computed. This process relies on the assumption that the true heavy mineral composition in each sample is suitably represented by the dark, opaque particle content in that sample.

4. Results

4.1. Native beach sediment characteristics

The native sediments along the Pea Island Ocean beach (native sands were observed on the control beach for the duration of the

Table 1
Mean Sediment Particle Diameters (mm) by Beach Position, Before and After nourishment. Period averages consider time prior to nourishment (2012–July 2014) and time following nourishment (Sept. 2014–2020) Note: values in parentheses are computed from observations during the immediate post-nourishment field survey in September 2014 and are representative of characteristics for the fill sands used in the project. No samples were collected at the S5 beach position until January 2016.

Area	Control Beach		Nourished Beach	
Epoch	pre-nourishment (sediment particle diameters in mm)	post-nourishment (sediment particle diameters in mm)	pre-nourishment (sediment particle diameters in mm)	post-nourishment (sediment particle diameters in mm)
Sample				
S1	1.041	1.154 (1.311)	1.083	1.053 (1.026)
S2	0.631	0.709 (0.658)	0.677	0.668 (0.513)
S3	0.454	0.475 (0.457)	0.45	0.444 (0.281)
S4	0.388	0.376 (0.446)	0.413	0.412 (0.390)
S5	–	0.368 (–)	–	0.463 (–)
Period Averaged Mean	0.628	0.653 (0.718)	0.656	0.627 (0.552)
Period Averaged Median	0.452	0.483 (0.557)	0.485	0.476 (0.425)
Period Averaged Std Dev	0.426	0.418 (0.374)	0.387	0.368 (0.332)

study, and along the nourished beach prior to the 2014 nourishment event) are composed almost entirely of quartz sands (2.65 g/cc). Medium and coarse particle sizes (0.5–2.0 mm) dominate the group, collectively making up as much as or more than 80% of the weight fraction (Table 1). The remainder is composed of lesser amounts of mixed fine gravels (2–8 mm) and fine sands (0.25–0.50 mm), with varying amounts of interspersed carbonate shell fragments and shell hash. Finer sediments (sizes≤0.125 mm) were quartz sands mixed with varying amounts of dark-colored minerals. Dark mineral fractions were consistently fine grained (≤0.125 mm), and while they sometimes constituted the majority by weight percent of the fine fraction, they only rarely exceeded 5% of the total sediment (Table 2).

Beach site sediment grain size distributions for both the native and nourishment fill sands are shown in Fig. 6. Fig. 6a shows sand size distributions immediately before and after nourishment on the nourished beach. Fig. 6b shows the sediment size distribution immediately before and after nourishment for the Control Site. Fig. 6c and d depict the time-averaged distribution of sediment grain sizes on the Nourished and Control Sites for the periods 2012–2014 and 2014–2020, respectively. Native sediment particle sizes on the control beach for the period prior to nourishment (April 2012–July 2014) averaged 0.628 mm (median = 0.452 mm; std = 0.426 mm). Sediments on the pre-nourished beach were slightly coarser overall (mean 0.656 mm, median = 0.485 mm; std = 0.387 mm). The largest effective sand grain diameters were consistently seen in the swash zone, where gravel and coarse sand content was highest. The lower swash (identified in Fig. 3 and designated S1 in the data tables) has the largest overall grain size. It is the only beach zone where the mean size exceeded 1 mm (Table 1). Zone S1 is also the only location, save for a single exception on the control beach at S2, where beach-site averaged gravel content exceeded 10% of the sample by weight, reaching a maximum average in excess of 40% along the control beach and 34.9% on the pre-nourished beach (Table 2). The dominant particle size in S1 is coarse sand (Table 2).

Moving shoreward onto the swash S2 and S3 zones the native sediment characteristics shift toward finer grain sizes. In contrast to that observed in S1, gravel content in S2 was always, but with a single exception, below 10%, and less than 5% in S3 (Table 2). Coarse and medium sands are the dominant sediment size groups across the beachface (S1, S2, and S3), typically comprising greater than 90% combined of the total sample. Fine sand was less than 1% of the content in the swash zones (S1–S3).

For zone S4, the backshore beach, medium sands make up the largest fraction of the native sediment, approximately 60% (Table 2) followed by coarse sands which comprise 20%–35% of the average. Gravel content on the backshore control beach was consistently much less than 5%. Fine sand made up between 1 and 2% on average (Table 2) on the backshore beach.

Table 2
Summary Mean Particle Size Fraction Distributions for Native and Fill Sediments observed at each of the 5 beach sampling positions and the overall position-averaged particle size. Values in parentheses are from measurements collected during the immediate post-nourishment field survey in September 2014. No samples were collected at the S5 beach position until January 2016 survey.

	Area	Control Beach		Nourished Beach	
	Epoch	pre-nourishment (sediment particle diameter in mm)	post-nourishment (sediment particle diameter in mm)	pre-nourishment (sediment particle diameter in mm)	post-nourishment (sediment particle diameter in mm)
	sample				
% gravels	S1	25.94	33.874 (41.977)	25.964	26.058 (34.863)
	S2	7.566	10.612 (4.297)	7.236	7.681 (4.006)
	S3	3.066	3.356 (0.706)	2.143	2.141 (0.300)
	S4	0.766	0.662 (0.635)	0.947	1.248 (1.584)
	S5	–	1.162 (–)	–	2.222 (–)
	Overall	7.924	7.239 (11.904)	6.415	4.212 (10.188)
% coarse sands	S1	40.083	41.615 (56.133)	45.253	47.436 (51.382)
	S2	43.566	49.225 (65.404)	50.39	52.906 (43.331)
	S3	28.12	32.568 (37.850)	30.416	33.660 (7.866)
	S4	23.523	22.701 (35.807)	26.258	26.783 (30.953)
	S5	–	20.780 (–)	–	35.097 (–)
	Overall	35.245	39.916 (48.799)	39.13	43.920 (33.383)
% medium sands	S1	24.174	19.249 (1.788)	22.786	20.358 (11.458)
	S2	39.964	33.962 (28.061)	35.322	33.779 (41.843)
	S3	55.288	52.689 (55.203)	55.426	53.724 (53.774)
	S4	60.212	59.505 (54.317)	62.693	58.927 (44.748)
	S5	–	57.992 (–)	–	54.749 (–)
	Overall	44.92	44.059 (34.842)	42.662	42.980 (37.956)
% fine sands	S1	0.924	0.245 (0.030)	0.512	0.400 (0.160)
	S2	0.299	0.279 (0.301)	0.586	0.234 (0.452)
	S3	1.139	0.558 (0.168)	0.96	0.445 (2.423)
	S4	1.994	1.495 (0.886)	1.009	1.509 (3.988)
	S5	–	1.226 (–)	–	0.784 (–)
	Overall	1.063	0.761 (0.346)	0.69	0.620 (1.756)
% "dark" minerals	S1	3.12	3.96 (5.276)	3	2.83 (3.752)
	S2	2.72	2.88 (3.426)	2.3	2.80 (2.699)
	S3	2.69	3.16 (2.969)	2.73	2.91 (3.287)
	S4	5.12	5.09 (5.014)	4.08	3.98 (2.323)
	S5	–	4.39 (–)	–	3.63 (–)

In the swash and backshore beaches, dark minerals comprised on average 2–4% and 4–5%, respectively (Table 2), of the fine fraction. The largest average percentage of dark minerals, 9.3%, was measured at the S5 backshore beach position in the Summer of 2017 (see Appendix).

4.2. Nourishment sands

Quantitatively, the mean grain particle size for the sands used as nourishment fill, as observed from the September 2014 beach survey (along the nourishment beach transects) immediately following completion of beach reconstruction and listed in Table 1 (data in parentheses) was 0.552 mm (median = 0.425 mm; std = 0.332 mm). In the swash zone the largest grain sizes were observed in the lower swash (S1). Here, sediment mean size of the fill sand was 1.026 mm (from Table 1) with fine gravel and coarse sand dominating the fractional distribution at 35% and 51%, respectively (Table 2). Size declined progressively up the swash, dropping to 0.513 mm at S2, and reaching a minimum of 0.281 mm in the upper swash at S3 (Table 1) for the September 2014 post-nourishment survey. At S2 the gravel content was 4% while coarse and medium sands were represented in approximate equal measure, 43% and 42%, respectively. At S3 the gravel fraction had all but disappeared (0.3% per Table 2) while coarse sands had dropped to less than 8% of the total. Here at S3 medium sands were the dominant group (54% per Table 2). On the upper beach at S4 medium sands dominated samples averaging 0.39 mm (Table 1) and making up on average about 60% of the total sample, followed by coarse sands (31%) (Table 2). Gravels represents less than 2% of the nourishment fill, while fine sands were more common, making up on average approximately 4% of the samples by weight. An immediate post-nourishment mid-beach (S5) sample was not collected during the post-nourishment September 2014 survey.

4.3. Differences between the native and nourishment fill sediments

The differences observed between the nourishment fill and the native sediments can be seen in the density plot of Fig. 6a. Fig. 6a compares the sediment grain-size distribution density for native beach sediments observed on the nourished beach prior to the nourishment event (the July 2014 survey shown in blue) with the fill sediments placed on that same beach as observed during the immediate post-event survey in September 2014, shown in orange. The fill sands used are finer, though not significantly so, than the native materials that were replaced. Table 1 quantifies the differences seen in Fig. 6a. Here, the pre-nourishment fill sediments (mean = 0.522 mm) contrast against the native sands observed for the same September 2014 survey on the control beach (mean = 0.718 mm). Coarse and medium size sand are the dominant size fractions in the nourishment fill, making up more than 70% of the averaged content by weight (Table 2). For the native sediments, coarse and medium sands make up more than 80% of the average fraction (Table 2). Gravel was only slightly less common in the fill sediments (10.2%) versus native sediment (11.9%) observed on the nourished beach prior to the nourishment event (Table 2). On the other hand, gravel content in the native sediment observed on the control beach averaged <8% for both the pre- and post-nourishment epochs (Table 2). Gravels, where present, were largely confined to S1 while medium sands comprised most of the sediment in S2 and S3 on both the control and nourished beaches. Medium sands dominated on the backshore mid-beach at S4 (~45%) at both beach sites (Table 2). Gravel was seen only in very small quantities at S4 (~1.6%) along both beaches, before and after nourishment (Table 2). Fine sands were found in greatest quantities on the backshore nourished beach at S4 (~4%) for the September 2014 survey (Table 2). Fine sand was greater in the fill by more than five times the fraction by weight (1.8% versus 0.3%) relative to the native sands on the nourished beach prior to replenishment, but the overall contribution of fines to the total distribution is small, resulting in little influence on the overall mean.
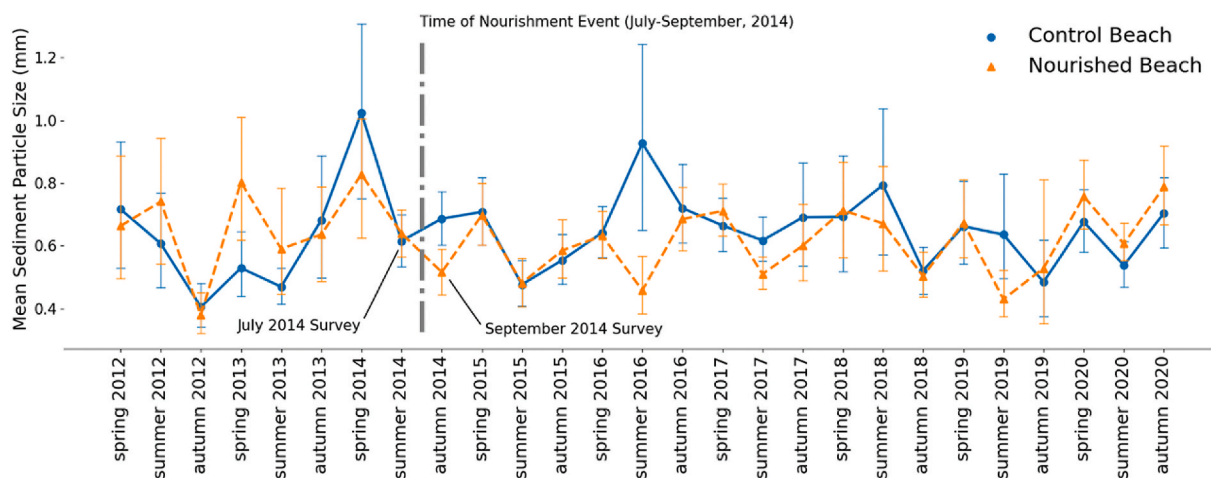

Fig. 5. Mean seasonal sand particle size for the control and nourished beach sites, before and after nourishment in 2014. Vertical bars represent 95% confidence intervals. While the two distributions track closely there are notable departures from congruence (no confidence interval overlap) during autumn 2014 and summer 2016. The autumn 2014 difference is attributed to sediments pumped on the beach.
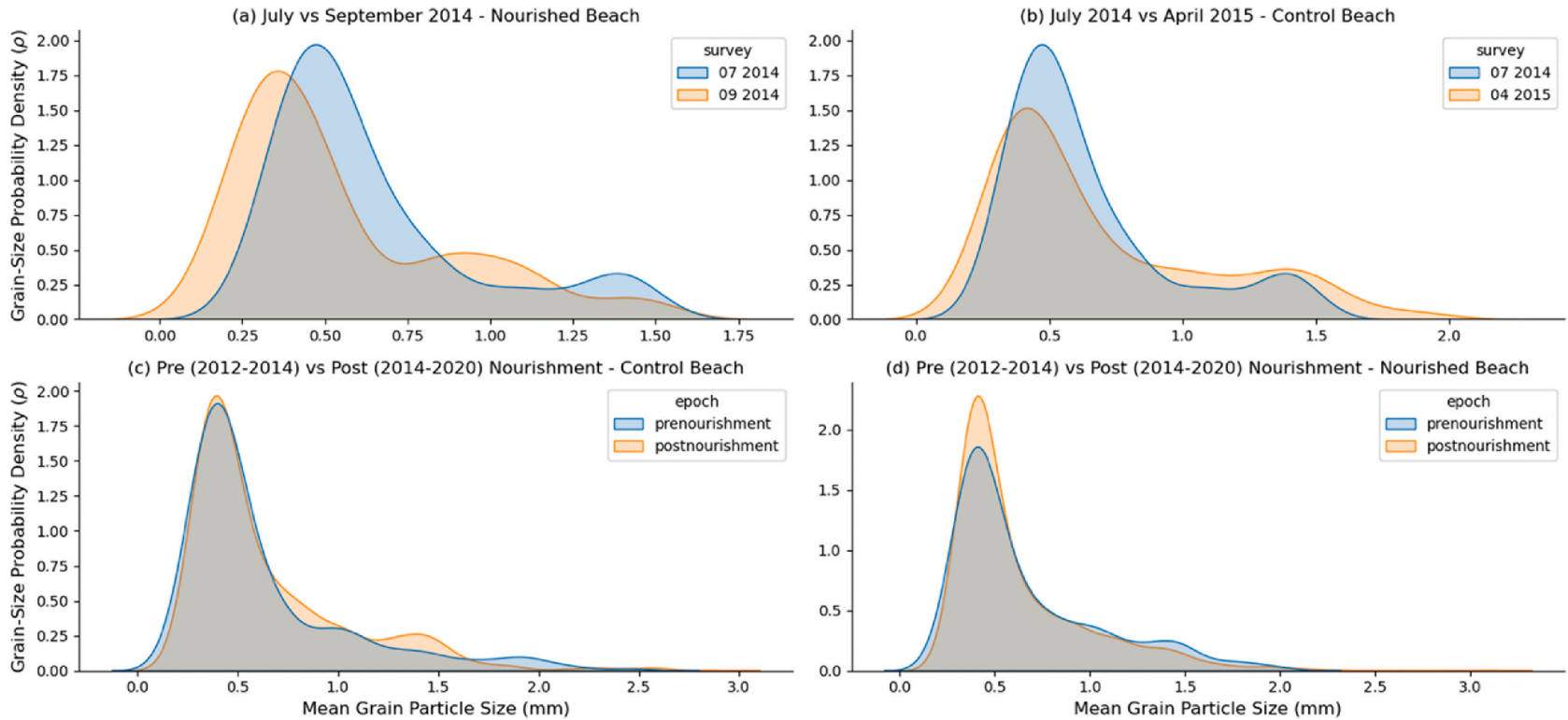
Fig. 6. ad: Kernel density estimators (probability densities) for native (blue shaded curve) and nourishment fill (orange shaded curve) sand distribution contrasts: A.) fill sands observed on the nourished beach (immediately following project completion in September 2014) to the native sands observed on that same beach in July 2014, prior to project startup; B.) fill sediment on nourished beach observed in September 2014 to sands on same nourished beach in April of the following year (2015); control beach (native) sands averaged prior to nourishment and control sands averaged post-nourishment; D.) nourished beach (fill) sands averaged prior to nourishment and nourished beach sand averaged post-nourishment. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Dark mineral content in the fill sediment occupying the swash zone at S1 observed during the post-nourishment September 2014 survey was approximately 3.8% (Table 2). During that same September 2014 survey, the dark mineral constituent in S1 on the control site was 5.3%. Similarly, at S2 dark minerals in the fill sands were around 2.7% which was less than that observed on the control site beach (3.4%). Only at S3 did the fill sands exhibit an excess in dark minerals versus their counterpart on the control beach, 3.29% versus 3%, respectively (per Table 2). On the upper beach dark minerals accounts for slightly more than one-half (2.3% versus 5%) of that observed in sediments from the control beach. Overall, dark minerals were most abundant on the backshore beaches at S4 for both the control and nourished sites but were generally less prevalent in the nourishment fill sediments relative to the native sands on the control beach.

The finer overall size distribution recorded in the fill sediments initially during the September 2014 post nourishment survey relative to baseline control was no longer present by the start of the following recruitment year (i.e., 2015). This is seen in Figs. 5 and 6b, where mean grain-size parity has been approximately reached for the spring 2015 survey. Moreover, based on the post-nourishment time series curves for both the impacted and control beaches (Fig. 5), this parity is maintained, apart from the
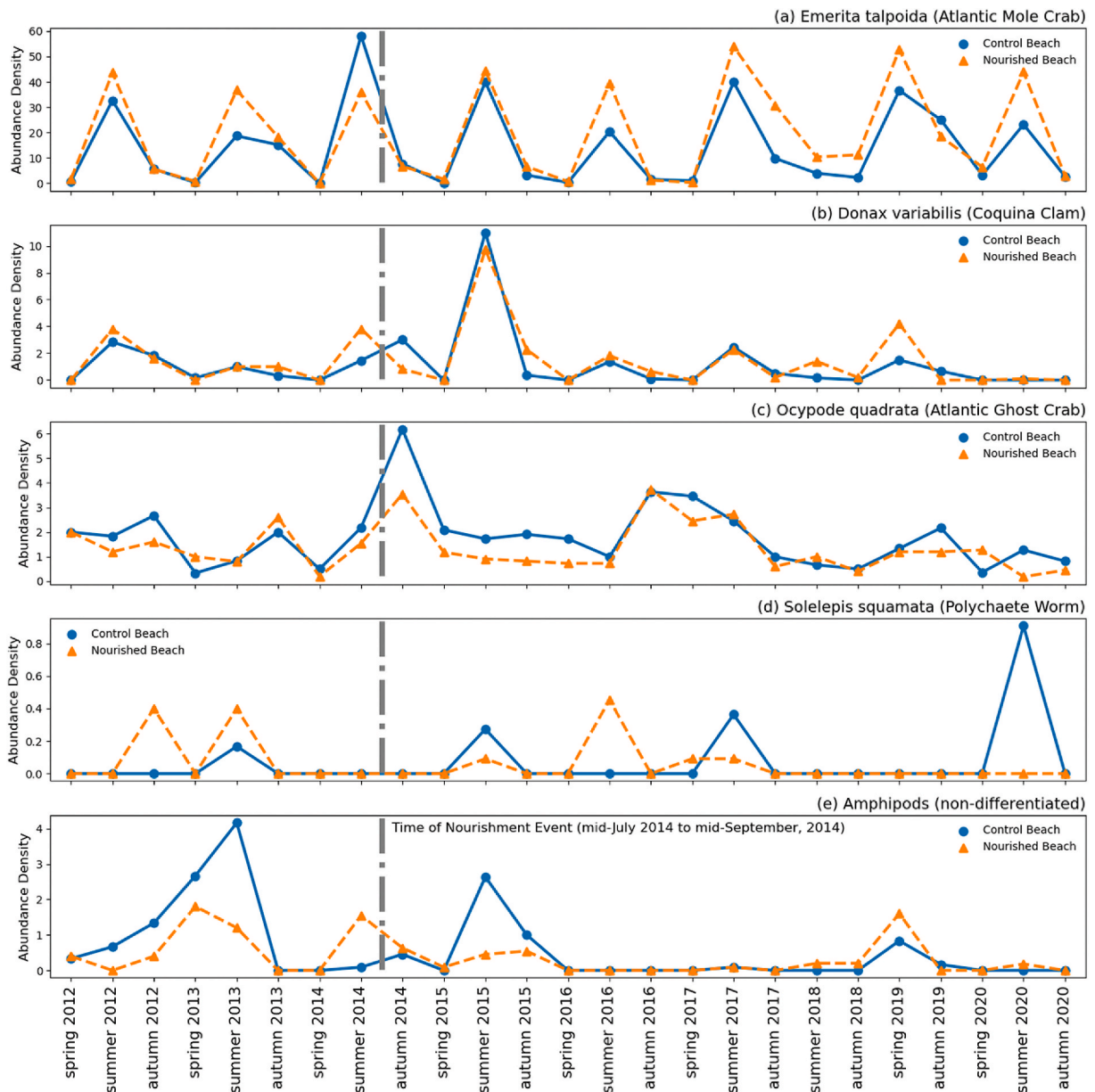

Fig. 7. a–e: Time series of species abundance density comparing the baseline and nourished beach abundance densities, before and after the 2014 nourishment project. The data points represent mean densities computed as the pooled number of specimens counted along all 11 transects in each beach site (control vs impacted) divided by the number of transects (11). This yields an abundance density in units of specimens/transect.

summer 2016 survey, for the duration of the study. Overall, the sediment grain size distributions between the control and nourished beaches, both for the periods before (2012–2014) and after (2015–2020) nourishment are identical along both sites (per Fig. 7c and d). For both the baseline control and fill sand distributions, medium and coarse sands dominated the content (typically ~40% per Table 2) in approximately equal measure. Coarse grain materials dominated the swash, with the greatest quantities of gravels seen at S1, coarse sands greatest at S2, and medium sands dominate at S3 (Table 2). The backshore beach, which after 2016 included a fifth mid-beach sand sample (S5), was dominated by medium sands (~60% of the total sample). Gravels and fine sands were both limited at S4 and S5, typically 2%. Dark minerals were also in greatest abundance on the backshore beaches (control and nourished) at S4 and S5 (Table 2).

4.4. Species abundance

Individual per survey abundance densities for each of the five taxa: Emerita talpoida, Donax variabilis, Ocypode quadrata, Scolelepis squamata, and indigenous Amphipods for each sampling beach (i.e., control vs nourished experimental units), computed for each seasonal survey, are provided in data table A2 (see Appendix). Taxa densities are temporally summarized in Table 3. Following nourishment during the September 2014 survey, E. talpoida were observed at a density of about 7.7 specimens on the control beach and 6.7 specimens on the newly nourished beach (Table 3). Abundances for D. variabilis and O. quadrata were similarly observed to be less in the fill sands on the nourished beach relative to those in the native sands on the control beach. The differences per Table 3 were 3 vs. 0.8 and 6.2 vs. 3.6 specimens/transect for the two species, respectively. Again, from Table 3, Amphipod abundance was greater on the nourished beach (0.64) than along the control (0.45). Abundance density for S. squamata was 0 between the July and September 2014 surveys, on both the control and nourished beaches (Table 3).

During subsequent recruitment seasons E. talpoida abundance was consistently greater than 20 specimens/transect during the warm-season surveys (Fig. 7a) both on the control and nourished beaches. For the July 2015 survey, median abundance between the control and nourished sites was at parity (16.7 vs 16.0, respectively, as referenced from data table A2, see Appendix). In 2016, 2017, and 2018, densities for E. talpoida were higher on the nourished beach (22.4, 22.2, 10.4) relative to the control (11.3, 15.2, 4.0), although it was observed that the 2018 recruitment season was markedly lower than that measured during the two prior years. This seeming anomaly for the 2018 recruitment season should, however, be viewed with the knowledge that there was no spring survey conducted for that year. Abundance for 2019 was once again higher relative to the prior 2018 season. Overall, E. talpoida abundance on the control beach before and after nourishment declined from 16.4 before to 13.0 after (Table 3). On the nourished beach the numbers were higher (17.8 before to 19.6 after per Table 3).

The most notable result for D. variabilis is the anomalous spike in abundance (Fig. 7b) along both beach sites for the 2015 recruitment year. Here, densities were approximately 4 specimens/transect (referenced from data table A2, see Appendix). Abundance for Donax prior to nourishment in July 2014 was 1.4 specimens/transect on the control beach and 3.8 specimens/transect on the pre-nourished beach (Table 3). Following nourishment, in September 2014, Donax abundance on the control beach (3.0) was more than 3 times that observed on the nourished beach (0.8) (Table 3). Donax abundance did decline on the nourished beach but there is no evidence to suggest that the species experienced complete mortality as a result. Overall, D. variabilis abundance observed after nourishment was higher on the nourished beach (1.4) than from those measured on the control beach (1.2). Donax is seen to have declined on the control beach but remained stable on the nourished beach (Table 3).

O. quadrata populations increased in the immediate aftermath of nourishment (Fig. 7c) but were lower compared to abundance on the control beach. Pre-nourishment abundance for the species on the pre-nourished beach was 1.6 specimens/transect from the July 2014 survey. Immediately after the nourishment event in September 2014 abundance increased to 3.6 (Table 3). On the control beach abundances for the same surveys were 2.2 and 6.2 specimens/transect, respectively. During subsequent recruitment years, quadrata populations were lower (Fig. 7c), but regained parity with the control beach by 2016 or 2017 where they remained through the end of the study in 2020. Overall, mean abundance densities for O. quadrata increased on the control beach between the pre- and post-nourishment recruitment years (1.9 after vs 1.5 before). Along the nourished beach populations remained stable before versus after (Table 3).

The undifferentiated Amphipod species counted during the study were sparsely represented in comparison with their counterparts (i.e., Donax and E. talpoida and O. quadrata). Only S. squamata densities were lower (Fig. 7d). Abundance for the Amphipods was also variable with some seasons presenting relatively larger numbers while for others the animal is absent from both the control and

Table 3

Overall pre- and post-nourishment, and immediate before and after (July 2014 and September 2014) nourishment, comparative invertebrate abundance densities (specimens/transect).

	Area	Amphipods	D. variabilis	E. talpoida	O. quadrata	S. squamata
Jan 2012–July 2014	Control Beach	1.16	0.95	16.44	1.54	0.02
	Nourished Beach	0.67	1.4	17.85	1.37	0.1
July 2014 Survey	Control Beach	0.09	1.45	58.18	2.18	0
	Nourished Beach	1.55	3.82	36	1.55	0
September 2014 Survey	Control Beach	0.45	3	7.73	6.18	0
	Nourished Beach	0.64	0.82	6.73	3.55	0
September 2014–October 2020	Control Beach	0.3	1.24	13.03	1.9	0.09
	Nourished Beach	0.24	1.39	19.55	1.36	0.04

nourished beaches (Fig. 7e). Abundance density only once exceeded 4 specimens/transect on the control beach (summer 2013 per Fig. 7d) and never reached 2 specimens/transect on the nourished beach. Populations on the pre-nourished beach, nevertheless, represented a global maximum for the investigation at 1.6 (Table 3). After nourishment, based on results returned from the September 2014 survey, abundance had declined on the nourished beach (0.6) but remained greater than that seen on the control beach (0.4) per Table 3. Over the longer-term of the study Amphipod group abundances decline following nourishment on both the control and impacted beaches (Table 3) with populations lower along the latter (nourished) site.

5. Discussion

A pulse disturbance likely did adversely impact the Pea Island beach ecosystem as a result of the 2014 nourishment event, but the magnitude of this disturbance is difficult to ascertain from the field-collected data. The lack of compelling evidence in these data suggest that any such disturbance event was short-lived for most of the invertebrates tracked during the study. Ephemeral extinction of the indigenous fauna along an impacted beach is commonplace reported and often anticipated following nourishment [18,20] though it's not universally seen [26,40]. Invertebrate populations observed in the immediate aftermath of the 2014 Pea Island nourishment event investigated here indicate that, while declines in species populations might have been seen, no such large-scale ephemeral extinction event occurred. Abundances for E. talpoida, D. variabilis, O. quadrata, and the undifferentiated Amphipods were each lower but by differing amounts on the nourished beach relative to the control after nourishment, but in all cases, populations were non-zero (ref Table 3). None of these differences were statistically significant. Only S. squamata was absent (abundance = 0) after nourishment. It was, however, also absent from both beaches prior to nourishment and so can offer no insight into immediate impacts on the species. Complicating the interpretation of the reduced abundances that were recorded following nourishment is the timing of the nourishment event itself. The completion of the project in mid-September made it difficult to discriminate any potential nourishment disturbance impacts residual in the survey data from changes associated with seasonal oscillations in abundance. The declines observed may reflect as much natural change as any imposed by the nourishment event itself.

The taxa tracked as a part of this study, E. talpoida, D. variabilis, O. quadrata, S. squamata, and the undifferentiated Amphipod group, each yielded a post-nourishment response that was unique to the species. For E. talpoida, the data support the conclusion that the 2014 nourishment had little immediate and no discernible lasting impacts. Populations for the 2015 recruitment season are aligned with those observed on the control beach (Fig. 7a). During subsequent seasons, 2016 to 2019, abundance densities on the impacted beach following nourishment exceeded baseline control populations, but a similar pattern is also seen for the two seasons prior to nourishment (2012–2013 ref Fig. 7a), suggesting that the temporal patterns observed are as much or more so associated with natural variability as any type of press disturbance linked to nourishment. PERMANOVA [41,42] testing results provide further support for this conclusion as only a seasonal main effect is seen to be significant (F = 41.6; Pr>(F) = 0.001 per Supplementary Table A1a in the Appendix). E. talpoida has shown an ability to evade harm during beach nourishment operations [26]. The species is also known to be tolerant of a wider range of stressors and substrate conditions than many other species that occupy the surf and swash zones along a sandy beach [21,43]. These attributes may offer explanation for why the species survived the 2014 replenishment event seemingly unscathed.

Donax variabilis' vulnerability to disturbance events (e.g., human trampling, storms, beach nourishment) has been documented both as a part of short term [44,45] and longer-term studies [21]. Of particular importance is the species' observed greater sensitivity to substrate composition relative to more adaptive species such as Emerita [46]. Coarser grained sediment distributions affect burrowing perhaps more so for Donax than some other swash zone invertebrates [46] with larger average particle sizes corresponding with reduced burrowing rates [47]; [58] Wilson, 1999; MacLachlin et al., 1996) and concomitant delayed recovery following disturbances such as those resulting from beach nourishment [21]. In this instance, however, the swash zone sediment distribution profile for the nourishment fill sands skewed finer (Fig. 6a). This finer material may have proven advantageous to Donax, at least in the short term. The resultant short-lived sedimentary environment might have been useful to explain the anomalous single-year abundance maximum observed for Donax during the 2015 season (Fig. 7b). Here, the increase in abundance density more than doubles over that from the prior (2014) or subsequent (2016) recruitment years. Tempering this idea, however, is the similar magnitude response observed simultaneously for the species resident along the control beach (Fig. 7b). This would suggest that an explanation for the peak is just a likely to be attributable to drivers independent of the prior year nourishment event as to that event itself. Beyond the 2015 recruitment season Donax abundance densities were stable on the impacted beach before versus after nourishment, while they rose slightly on the baseline control beach. These differences were not significant. D. variabilis' large temporal variation in abundance both before and after nourishment is accounted for largely by seasonal main effects (F = 25.72; Pr>(F) = 0.001 per Supplementary Table A1b) and associated seasonal/annual interactions). Little other evidence in the data exists to suggest that nourishment impressed any lasting impacts on the species.

For O quadrata abundances were lower on the nourished beach relative to the control baseline for the 2015 season (Fig. 7c). A similar low abundance density for the species may have extended into the 2016 season before the nourished site regained parity with the baseline control. Though it was not modeled specifically (via PERMANOVA) results for the entire data set do suggest that 2015 and perhaps 2016 abundance densities differed (Year: F = 10.55; Pr>(F) = 0.054 from Supplementary Table A1c) in some important way, thus identifying a potential nourishment event impact of 1–2 recruitment seasons duration. After the 2016 recruitment season O. quadrata recovery is interpreted to be complete. O. quadrata almost certainly did experience mortality due to burial and suffocation in association with the 2014 nourishment event. However, there is nothing in the data to suggest that an ephemeral extinction event occurred. In fact, the data show that O. quadrata populations were higher, almost doubled in abundance density, in September 2014 versus that seen during the prior pre-nourishment July 2014 survey on the nourished beach (Fig. 7c). Evidence of impact only comes

when a comparison is made between densities observed along the nourished beach versus the control where we see (Fig. 7c) that latter to be almost twice that of the former. This difference, (at a lesser magnitude) between densities on the nourished versus control beaches would continue through 2015 and into the 2016 recruitment season and marks the temporal extent of the interpreted impacts on quadrata resulting from nourishment.

One possible explanation for O quadrata's seeming survival on the nourished Pea Island beach may be attributed to fill sand placement, which may have been concentrated more along the intertidal sections of the beach. Less sand may have been placed along the upper beach and dune surfaces where burrow densities are highest, thus preventing large-scale burial [45] Reilly and Bellis (1983) observed such a post-nourishment circumstance on Bogue Banks, North Carolina beaches and proffered a similar explanation [18,45]. They also suggest upward burrowing as a potentially viable explanation for species survival during beach nourishment if fill layer thickness does not exceed about 1 m—a possibility if the backshore beach received less fill than did the foreshore. In addition, the species has often been observed by the authors across and immediately behind the primary dune field at the Pea Island study site, areas not impacted by the nourishment event. Rapid opportunistic recolonization of the newly reconstructed beach immediately following nourishment in September 2014 by quadrata in residence landward of the impacted beach may provide the most plausible explanation for the populations observed on the beach in the nourishment event's immediate aftermath.

Lowered abundances and a concomitant delay in recovery observed during subsequent years for quadrata could then reflect an overall reduction in population brought on by sand placement and distribution during the nourishment event and the associated constraints on recovery that prevented complete recolonization for the 2015 and 2016 seasons. Unlike E. talpoida, and perhaps D. variabilis, who are thought to be able to exploit longshore currents to potentially escape and so survive a large-scale disturbance such as beach nourishment [26,45] quadrata must rely on burrowing and/or overland ambulation as a means of retreat. During recovery similar pathways must be exploited to return populations to pre-event levels.

Contributing to the observed delay in recovery for O. quadrata may be the initial differences between the fill and native (control) sediments. The finer fill sands may have had some effect on this recovery. The peaks in fine sediment recorded for seasons 2014 (~4% of total sample) and 2015 (~5.5% of the total sample) at S4, albeit relatively small in terms of their overall contribution to the typical total sample, did nonetheless coincide with the two seasons where O. quadrata populations are low relative to abundances measured against the control beach baseline. This association is, however, difficult to convert into explanatory causation. More likely, recovery for O. quadrata populations were driven by a combination of factors, to include population loss due to partial burial and crushing during nourishment construction operations, followed by limitations associated with the species' ability to naturally recolonize after nourishment was complete.

While the results seen for the three primary species (E. talpoida, D. variabilis, and O. quadrata), classed as primary by their relative abundances, present patterns of temporal variance that permit analysis-based interpretation, results for the remaining groups, S. squamata and the undifferentiated Amphipods present a greater challenge. Amphipod group abundances do suggest a nourishment response. This suggestion comes from the low density observed for the 2015 recruitment season (Fig. 7e) combined with the subsequent almost total decline in post-nourishment beach abundance observed at least through the abbreviated 2018 season. PERMANOVA modeling comparing the pre and post event epochal differences were found to be non-significant at the 0.5 alpha level (F = 3.96, Pr (>F) = 0.0540 per Supplementary Table A1e). The elevated abundance measured during the spring 2019 survey is likely the mechanism that reduced the PERMANOVA result to insignificance. It is also, for its congruence with values seen along the pre-nourished beach, a sign that if a nourishment-associated impact was experienced by the Amphipods, it is during this 2019 season that recovery for the group might have occurred. Nevertheless, these differences account for only about 5% of the total variance seen in the data (Supplementary Table A1e). Explanation for almost 60% of the variance observed for the Amphipod group remains unaccounted for in the models. Complicating this interpretation further is the fact that the control baseline abundance also declined in equal measure from 2016 through 2018. Control beach density after 2014 remained much below that observed during 2013. It is possible that the 2013 season was an anomaly–one that does not represent an accurate baseline for the behavior of the indigenous Amphipods populations over the longer term. Unfortunately, no data prior to 2012 exists to test this hypothesis.

For S. squamata the results appear even more puzzling in their interpretation than that seen for the Amphipods. Prior to the 2014 nourishment a seasonal trend in population density is noted (Fig. 7d), and modeling indicates that it accounts for more than 25% of the total variance observed in the data (Supplementary Table A1d). It is a significant main effect in the data (F = 27.87; Pr(>F) = 0.001). However, if this seasonality assumption made here is true it inexplicably fails to carry over into 2014, either prior to or following nourishment. For the 2014 recruitment season there were no S. squamata observed during any survey (ref. Fig. 7d). The complete absence of the species for 2014 cannot be explained by the nourishment event of that same year, nor can the reappearance of the species in 2015 and 2016 (Fig. 7d) be attributed to any lingering nourishment effects, though again, this must be viewed in context that abundance on the Pea Island Refuge beach was consistently very low over the nine-year duration of the study. Abundance densities on both the control and nourished beach only once exceeded 0.4 specimens/transect. These results suggest that the species is not a commonplace resident along the Pea Island Ocean beach and observations accurately reflect this absence. This result is seen in contrast to the assertion that S. squamata is a ubiquitous opportunistic species found in abundance elsewhere in the region (Petersen et al., 2014 [48,49,50]; and one that can endure to survive a broad range of stressor conditions [51,52].

6. Conclusion

For all the invertebrate species included in this study temporal abundance variation as observed over the entire 9-year time span of the present study is dominated by natural seasonal oscillations. There is, perhaps surprisingly, little evidence in the survey data collected to indict the nourishment event as playing any significant role in short or longer-term changes in system populations, nor

changes in the behavioral patterns (the variance) of these populations through time. This contrasts with expectation, where most investigators report some type of definite disturbance impact associated with nourishment operations. This impact is often seen both in the immediate aftermath of the disturbance as well as for some finite time period subsequent. The dearth of longer-term (>2 year) studies makes it difficult to define the full-scope duration of impacts for many of these earlier investigations, but several authors do report some form of recovery having been observed before the study itself was concluded. Others, however, do not.

This study was an attempt to explore possible longer-term impacts (>2 years) associated with beach nourishment operations. As the placement of more than 1.5 million cubic yards (1.15 million cubic meters) of new fill sand on an extant beach surface is recognized in the literature as representing a large-scale pulse-type disturbance to the pre-existing ecosystem, it is assumed here that some type of disturbance must have occurred along the nourished Pea Island Ocean beach following nourishment in 2014. Further, that disturbance must have in some way altered the local invertebrate ecosystem. With the possible exception of the species O. quadrata and the undifferentiated Amphipod group, there is nothing to suggest unequivocal impact and subsequent recovery tied to the 2014 Pea Island nourishment nor that any such changes were in any way deleterious. All that might be stated is that most of the evidence for these changes, if such change did occur along the beach as a result of nourishment, falls below the effective detection limits of this study's experimental design. A structural limitation of the design is tied to the sampling interval employed. Apart from the two immediate before and after event sampling surveys (July 2014 and September 2014), further field survey work was performed only on a quarterly schedule. At this frequency even natural seasonal and sub-seasonal variation in the ecosystem is under-sampled. Higher frequency sampling (e.g., monthly) might have shed some additional light on disturbance impacts tied to the 2014 nourishment.

The findings from this study thus suggest a tripartite conclusion. First, ephemeral extinction of indigenous populations along the nourishment-impacted beach, while perhaps commonplace, is not a foregone conclusion. As some other investigators have demonstrated, and this study appears to corroborate, an ecosystem can endure a significant level of disturbance (in this case beach nourishment) during a vulnerable part of the recruitment season (mid-summer) and survive with little obvious change. As stated earlier, some type of alteration invariably did occur, but the lack of clear evidence for such change over the longer-term (6-recruitment seasons) suggests that it was neither large in scale nor adverse, and/or our sampling scheme was unable to detect any evidence for impacts that might have been present. Second, the indigenous faunal response to a nourishment disturbance is at least somewhat species dependent. Some animals can seemingly endure such disturbances with little or no [detectable] change (e.g., E. talpoida, D. variabilis), while others (e.g., Q. quadrata) may experience potentially significant, albeit short-term, reductions in abundance. How the fill sands are applied and distributed during beach reconstruction operations likely is an important determinant in this regard. Third, there exists little direct evidence to explain the recovery observed. Many point to the choice of fill sands as the key factor that drives resultant ecosystem response to nourishment—the closer the native and fill sands agree in terms of size and sorting the more favorable the resultant outcome—but, despite the well-matched fill sands applied to the Pea Island beach studied here, the evidence uncovered to suggest is that this close match supplies a cogent argument for causation is at best circumstantial.

Author contribution statement

Paul Paris: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Anya Leach: Performed the experiments; Analyzed and interpreted the data; Wrote the paper. D. Reide Corbett: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e12816.

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