

Railroad Grade Beach Nourishment Study

Final Project Report, September 2020
Prepared for the Estuary and Salmon Restoration Program,
Recreation and Conservation Office, and
Washington Department of Fish and Wildlife



Megan N. Dethier, Friday Harbor Laboratories, University of Washington
Jason Toft, School of Aquatic and Fishery Sciences, University of Washington
Hannah Faulkner, Washington Dept of Fish and Wildlife
Frank Leonetti, Snohomish County
Elisa Dawson, Snohomish County

Cover: Aerial image courtesy of Phil Bloch, Confluence Environmental, of Howarth Park captured after shoreline armor removal and restoration (Sept. 1, 2016).



FRIDAY HARBOR LABORATORIES

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2 Executive Summary

Within Puget Sound, ca. 26 miles of shoreline are armored by the supporting structures for the Burlington Northern Santa Fe (BNSF) railroad; this armoring consists of vertical concrete or sloped riprap walls. These walls, the fill behind them, and the railroad tracks built on the fill prevent the alongshore banks and bluffs from eroding, and generally stop sediment from reaching the beach. Prior research on the shorelines of the Salish Sea have demonstrated such armoring can, over time, make beaches narrower, steeper, and composed of coarser sediments. Other documented changes are that armored shorelines have less overhanging vegetation providing cooling shade, and they accumulate fewer logs and less wrack. In turn, there are fewer invertebrates that colonize and degrade the wrack, and fewer insects that fall onto the beach from overhanging vegetation. Some data suggest that fewer forage fish deposit eggs onto armored beaches, and egg survival is reduced on modified shorelines. Ecological impacts are generally reduced lower on the shore, i.e. impacts are clearest the closer the measured parameters are to the armoring itself. Armoring emplaced lower on the shore has more severe impacts on many different parameters.

Beach restoration practitioners face several uncertainties that limit our understanding of the extent to which different types of restoration - such as total armor removal, creation of living shorelines, and/or nourishment of beach sediments - can mitigate degradation associated with shoreline armoring. Do management measures that do not involve complete removal of armoring still allow restoration of ecological functions? We do not have data on longer-term cost-benefit tradeoffs of different types of restoration, e.g., if armored beaches have to be re-nourished frequently, and at a high cost, to retain abundances of fine sediments.

The Snohomish County Beach Nourishment Project (SCBNP) sought to re-supply sediment to shorelines along the railroad grade in Snohomish County by re-using fine-grained clean dredged sediments from the Snohomish River. This was accomplished mostly without removing armoring, although one location at Howarth Park (Site 13) did have armoring removed as well as the placement of sediment size designed specifically for beach nourishment. This report describes a subsequent ESRP “learning project” that built upon the SCBNP, using it as the centerpiece of a monitoring effort to assess the success of nourishment and other treatments in restoring a variety of beach functions.

Both armor removal and nourishment were accomplished in July-August 2016. Beginning in June 2016 (just before construction began), we intensively studied four armored sites along the railroad within Snohomish County, and four nearby reference sites with more natural shoreforms and vegetated beach characteristics. In addition, we surveyed four additional pairs of armored-unarmored sites south of the Nourishment Project region to quantify interannual changes in the same measured parameters at sites without any nourishment intervention. At all 16 study sites we monitored a wide variety of parameters over 4 years including physical measurements of beach morphology and sediment grain sizes (at several elevations), the quantity of logs, wrack, and associated invertebrate communities high on the shore, and the biota of the mid-shore. In the nourishment region we also quantified the sediments appropriate for spawning by forage

fish (Pacific sand lance and surf smelt), as well as actual forage fish spawning events. Movement of emplaced sediments in the nourishment region was tracked in detail throughout the study period.

Overall, we found that rates of drift of emplaced sediments varied highly among sites. Fine-grained sediments moved downdrift quickly where the toe of the railroad grade was lower on the beach, where the beach was steeper and narrower, and where the shoreline was straight or convex with no features to interrupt longshore transport. Wider beaches, those in subtle embayments, and those that had additional sources of sediment such as from small stream deltas all showed slower loss of emplaced sediments. Management decisions about beach nourishment should thus carefully consider these issues of beach morphology and factors that dissipate wave energy.

In general, we found that armored beaches in the nourishment region exhibited lower elevation at beach toe (where the bluff or armoring meet the beach), and therefore greater encroachment onto the beach face, and narrower beach widths. A signal of armor effect on beach slope was less evident. Following the application of beach nourishment, we observed an overall increase in beach toe elevation and width, and a minor decrease in beach slope. Looking within site pairs, we found that changes over time were driven largely by greater transformations measured at armored locations. However, clear and consistent patterns of armor, treatment and temporal effect were complicated by substantial site-specific variation in beach profile.

Within the southern region, the effects of shoreline armor on beach profile were parallel to those at sites in the nourishment region, but with greater differences between armored and unarmored beaches. Because the southern sites were not subject to beach nourishment, these clear distinctions remained over time, despite slight inter-annual variations in profile character. Across all survey years, the beach toe elevation was substantially lower at armored locations compared to unarmored locations. Contrary to beach profiles in the nourished region, the signals of armor effect on both beach width and slope across the southern region were clear and consistent; armored locations exhibited narrower beach widths and greater beach slopes compared to unarmored locations. Even without restoration activities, sites in the southern region still exhibited changes in beach profile over our study timeframe. Some changes paralleled those seen in the nourishment region, e.g., variable changes in beach width and weak response in beach slope. Others differed from observations in the nourishment region, e.g., most locations showed an increase in beach toe elevation.

For some parameters measured in the wrackline, we found nourishment to have an overall positive effect, seen in increases in total percent cover of wrack, depth of wrack, and number of logs. Site 13 showed the most positive responses in wrack and log measurements; this was the site that also included armor removal, placement of logs, and planting of vegetation, as opposed to the other project sites that only had sediment nourishment. However, parameters related to invertebrate responses showed no positive effect of nourishment. The percent of sand at the wrackline ultimately showed a negative response, either because the sandier sediment washed

away post nourishment, or in the case of Site 13, because coarser sediments were emplaced there.

A key goal for beach nourishment programs is to recreate conditions favorable for spawning by forage fish, especially Pacific sand lance and surf smelt. The material used from the Snohomish River was applied to evaluate the potential for beneficial re-use of existing dredged sediment. Though the sediment from this source was appropriately sized for forage fish spawning substrate, it was not deliberately chosen (or designed) for this intended purpose, i.e. it may not be the optimal size composition for either forage fish use or persistence on these shorelines. The sandy sediments added at most of the nourishment sites had the general effect of reducing surface substrate size from the prior pebbly substrate that tends to dominate sediment-starved beaches. This change improved the substrate favorability for Pacific sand lance spawning and appeared to actually support more spawning (based on egg count) at several downdrift locations. No directly nourished sites supported greater egg counts. The increase in sandy substrates resulting from nourishment did not, however, increase substrate size favorability for surf smelt, which prefer more gravelly beaches. Surf smelt spawning was observed only at the Howarth Park site, where nourishment included more coarse gravel in the site design. This change likely contributed to the reduced sand lance spawning at that site. These varied changes all provide insight to forage fish spawning behaviors that are consistent with our interpretation of the role of substrate size.

Sediments and beach biota at Mean Low Water changed in some parallel ways to those in the wrackline. We found a 'signal' of beach restoration in the Nourishment region at Mean Low Water (roughly halfway down the shoreface); some of the emplaced sediments moved down the shore to the mid zone, but then generally did not persist through the duration of the monitoring. No such change was seen at the southern sites where there was no nourishment. In general, unarmored sites had far more sand than armored sites. Accompanying the documented sediment shifts at MLW at the nourished sites were some clear changes in the biota. Overall, biotic communities at this mid-shore elevation are not very diverse, especially when no rocks are present to stabilize the sediment. The surface biota and the infauna at MLW thus tended to be negatively affected after a disturbance such as sand addition, although some taxa such as invasive clam species benefited. There was generally a negative relationship between the amount of sand and species richness at MLW; this pattern was broadly true at the nourished beaches. Thus, as long as these beaches stay sandy, diversity at this elevation may remain reduced.

In conclusion, sediment nourishment along the BNSF railroad can improve some structural and functional aspects of shorelines, but these improvements are unlikely to persist for longer than a few years if they are limited in scale or solely rely on re-use of finer, clean dredged material. Longer term monitoring may be needed to adequately assess these situations, likely along with continued experimental nourishment interventions and maintenance. Restoration alternatives should be explored, such as (1) improving areas where coastal streams are routed under the railroad through culverts that may be undersized or in poor condition, (2) targeting armor removal at the base of feeder bluffs that are updrift of armored sites in order to provide natural

sediment input to beaches downdrift ([ESRP Beach Strategies](#)), and (3) strategic siting of sediment nourishment that constitutes a beneficial re-use of dredged material.

3 Introduction

Within Puget Sound, 29% of the shoreline has been armored (MacLennan et al. 2017), with some sizeable continuous portions of this armoring consisting of the supporting structures for the Burlington Northern Santa Fe (BNSF) railroad. One of the stretches of the BNSF railroad that is directly along the Puget Sound shoreline is ca. 26 miles from north Seattle to Everett, which is built along the upper shore on top of vertical concrete or sloped riprap walls with fill behind them (Figure 1).



Figure 1. Typical double tracked railroad prism at shoreline of bluff-backed beach in Snohomish County

These structures both prevent the alongshore banks and bluffs from eroding, and generally stop sediment from occasional landslides from reaching the beach. Since the majority of the sediment maintaining Puget Sound's beaches are derived from erosion of bluffs (Johannessen and MacLennan 2007), this extensive shoreline armoring means that since the late 1800's when the railroad was completed there has been gradual 'starving' of the beach; finer sediments are winnowed from the shore and carried by alongshore drift into either deeper water or to spits where they are deposited, with no local upland source of new sediment deposition. This, in addition to the direct loss of beach area, affects many shoreline functions as cataloged in Figure 2.

Low Tide Terrace	Beach Face	Beach Berm	Bluff Face
Eelgrass/ macro-algae, detritus-based food web, shellfish beaches, silt/mud	Wave dissipation, variable gravel size, shallow slope, forage fish spawning, infauna, <u>epibenthic inverts</u> , salmonid feeding migration	Driftwood/carbon, dune grasses, terr. prey production, wildlife habitat, marsh (depends on elevation, hydrology, beach barrier, back beach area)	Sediment source, seeps/ hydrology, riparian vegetation, woody debris, terr. prey production/fallout, shading, wildlife habitat

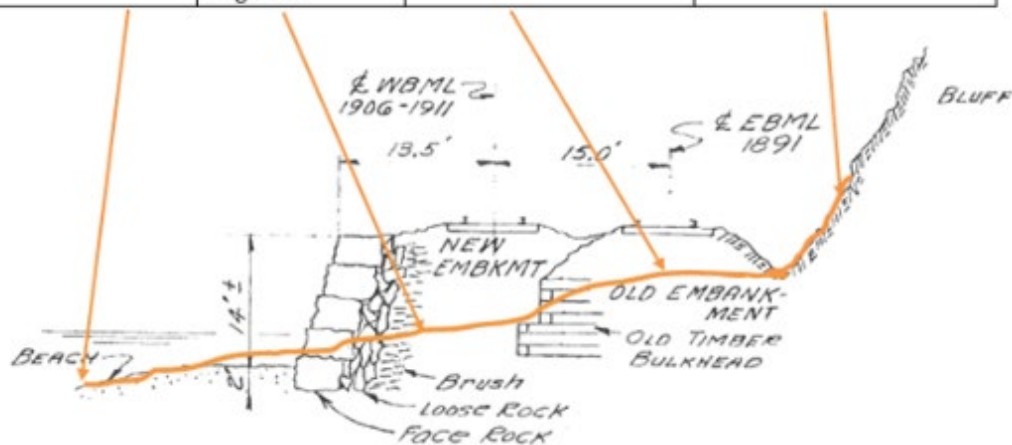


Figure 2. Conceptual historical profile (orange) of bluff-backed beach, as well as key beach characteristics and functions (from Shipman 2008) superimposed upon a cross-section of typical double-tracked railroad prism along Puget Sound (from Great Northern Railway Historical Society 1989).

Prior research on the shorelines of the Salish Sea has demonstrated the diverse and cumulative impacts that such shoreline armoring can have on the geomorphology and ecology of the region's beaches. Armoring can, over time, make beaches narrower, steeper, and composed of coarser sediments (Dethier et al. 2016). Compared with natural beaches, armored shorelines have less overhanging vegetation providing cooling shade, and they accumulate fewer logs and less wrack (Heerhartz et al. 2014, Dethier et al. 2016). In turn, armored beaches have fewer invertebrates that colonize and degrade the wrack, and fewer insects that fall onto the beach from overhanging vegetation (Sobocinski et al. 2010, Heerhartz et al. 2016, Dethier et al. 2016). Some data suggest that fewer forage fish deposit eggs onto armored beaches, and egg survival is reduced on modified shorelines (Rice 2006). Fewer ecological impacts are seen lower on the shore than higher on the shore, i.e. impacts are clearest the closer the measured parameters are to the armoring itself. Armoring lower on the shore has more severe impacts on many different parameters, such as juvenile salmon and other nearshore fishes (Toft et al. 2007).

Our improved knowledge of the negative impacts of shoreline armoring has helped spur increased efforts to restore natural functions to Salish Sea beaches by either removing beach armoring or finding alternative ways to counteract some of these impacts. These restoration efforts include simple removal of armoring, replacement of armoring with 'living shorelines' that incorporate vegetation plantings, anchored logs, and other methods to provide beach stability, 'nourishing' beaches by adding "lost" sediments, or combinations of these methods (Johannessen et al. 2014). Occasionally, nature implements a natural experiment, as was the case along the BNSF railroad with the Woodway slide of 1997. However, beach restoration practitioners face several uncertainties that limit the understanding of how these diverse habitat

enhancements mitigate degradation associated with shoreline armoring. These uncertainties include lack of data on the relative benefits of different design and treatment alternatives, for example the degree of benefits derived from beach nourishment when armoring is not removed, and thus when full ecological and physical processes are not restored. This in turn leads to uncertainty about longer-term cost-benefit relationships, e.g., what are the relative benefits of initial vs. recurring costs if, for example, armored beaches have to be re-nourished frequently to retain abundances of fine sediments. Clearer recommendations based on data collected at implemented sites would lead to more certainty in policy, program and funding directives for beach nourishment.

The Snohomish County Beach Nourishment Project (SCBNP) ([PRISM #13-1106](#)) was implemented to support the Snohomish Basin Salmon Recovery Plan 10-year beach restoration goal of “at least one mile” (SBSRS, 2005, pg. 1-6). As an ESRP portfolio project, this SCBNP sought to re-supply sediment to shorelines along the railroad grade in Snohomish County without removing armoring at most locations. One location, Howarth Park, did have armoring removed as well as sediments nourished, additionally including placement of logs and plantings of shoreline vegetation. A key goal was to determine whether the negative effects of shoreline armoring on forage fish spawning could be mitigated by nourishment rather than complete restoration. This project also sought to implement beach nourishment using dredged sand and gravel from the Snohomish River navigation channel (Figure 3) to evaluate potential beneficial re-use of clean material that otherwise would be dumped in a deep-water disposal site.



Figure 3. Snohomish River navigation channel dredge spoil pile (in Everett, WA). These spoils were used, in part, to implement the Snohomish County Beach Nourishment Project.

The stated goals and objectives of the SCBNP project were to:

- Improve the quantity of potential forage fish habitat along the project reach,
- Initially supply over 18,000 C.Y. of finer sediments (coarse sand and fine gravel) to the system,
- Retain finer sediments in the upper intertidal (+5 MLLW to MHHW) over a reasonable time frame,
- Provide delivery of gravel to adjacent shorelines,

- Increase backshore width to encourage growth of riparian vegetation,
- Remove riprap armoring,
- Minimize adverse effects to key biological communities (particularly eelgrass), and
- Enhance nearshore rearing habitat conditions for juvenile salmonids.

Our ESRP learning project (PRISM #14-2305) built upon the SCBNP, using it as the centerpiece of a monitoring effort to assess the success of nourishment and other treatments in restoring a variety of beach functions. This effort also includes a space for time substitution, by including the Woodway slide site of 1997 among our sample locations (Deer Creek unarmored), which we believe can help inform restoration uncertainties related to scale and time, neither of which can readily be included in monitoring studies. This report summarizes results from the learning project and from a portion of the SCBNP project objectives above.

Both armor removal and nourishment were accomplished in June-August 2016. Beginning in June 2016 (just before nourishment and Howarth Park construction began), we intensively studied four armored sites along the railroad within Snohomish County, and four nearby reference sites with more natural shoreforms and vegetated beach characteristics. In addition, we surveyed four additional pairs of armored-unarmored sites south of the Nourishment Project region to quantify interannual changes in the same measured parameters at sites without any pre-related nourishment intervention.

Based on prior data from comparisons of armored and unarmored beaches, we hypothesized that project treatments such as beach nourishment would change beach textures and profiles, in particular making beaches wider, less steep, and with more sand. Following other results, we hypothesized that these changes would result in increases in logs, wrack, and abundances of insects and benthic fauna, especially on the upper shore. These physical changes and increases in beach-dependent biota in turn should encourage forage fish spawning and provide trophic support for organisms such as juvenile salmonids feeding along shore. Our data gave us the opportunity to explore the relationship between substrate characteristics and forage fish spawning events. Although adding beach sediments in front of the railroad is an artificial process, we hypothesized that the creation of more natural beach textures and morphology would allow enhanced (nourished) beaches to become intermediate in their functional responses compared to armored (the BNSF railroad) and natural (unarmored) beach site. An example of this on a large scale is the Woodway slide of 1997, where natural bluff material overran the railroad to change an armored beach to an essentially unarmored beach (Figure 4).



Figure 4. Oblique aerial image of deep-seated landslide at Woodway, WA (left image) taken May 1997 by E. Harp. Reprinted from USGS Bulletin 2180 (Savage et al. 2000). Woodway location in 2017 (right image), with vegetated buffer between beach and railroad. Image date 5/10/2017 from Pictometry by Eagleview.

Our sampling consisted of combined and coordinated efforts from Snohomish County, the University of Washington, Washington Dept. of Fish and Wildlife, and other groups, resulting in a comprehensive collection of data. Parameters monitored include beach substrate size characterization, benthic infauna, beach wrack (detritus to driftwood), beach zonal widths, riparian composition and cover (where present), topographic surveys, and forage fish spawning. Measurements are primarily transect-based. Fieldwork tasks included biological and physical sampling each summer (2016 through 2019), and forage fish egg and substrate sampling (selected winters). Three sites at SCBNP were previously sampled in July 2013 as part of the [Puget Sound UW Armoring Study](#), and WDFW sampled a subset of the parameters at two of the sites in 2015, so there are some additional pre-restoration data for those locations.

The results from this study are intended to inform future restoration site selection, design and anticipated functional responses. They should ultimately directly inform capital project sponsors and will help ESRP determine if projects focused on beach nourishment are worth funding in selected “Enhancement-High” strategy locations (ESRP 2012).

4 Implementation and Monitoring Sites

We conducted sampling at pairs of sites in eight locations (for a total of 16 study sites): four armored and restored (nourished) sites and nearby unarmored (reference) sites within the SCBNP region to the north (hereafter, Nourishment Region), and four additional pairs of armored and unarmored sites south of the nourishment project area (hereafter, Southern Region (Figure 5). This sampling design enables us to interpret observed changes both at treatment locations relative to paired untreated transects in the Nourishment Region, and between unaltered paired sites in the Southern region. Most analyses are conducted separately for the Nourishment Region and the Southern Region. The updated “Beach Strategies” report now considers there to be 3 separate drift cells along this shoreline, all going south to north, with breaks at Edmonds and Mukilteo.

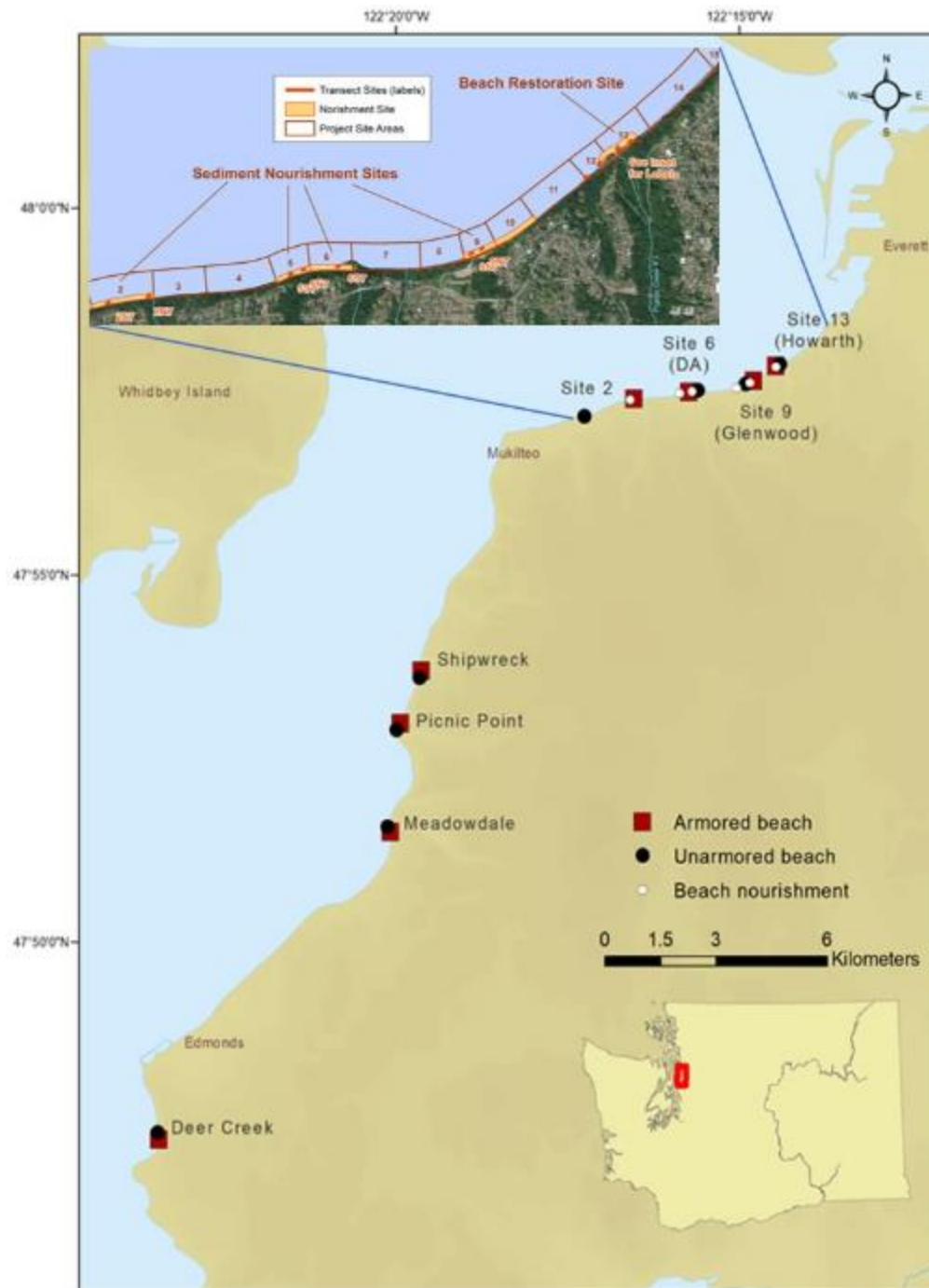


Figure 5. Map of all 16 study sites sampled 2016-2019. Armored and nearby unarmored (reference) beaches are shown, along with the locations where beach nourishment (sediment addition) occurred (all near the 8 northern study sites [inset; expanded in Figure 6], in Snohomish County).

Restored sites within the SCBNP area (shoreline process unit 8055), consisted of five sediment nourishment sites between Sites 2 and 10 (Figure 6) and more involved restoration actions at Howarth Park (Site 12-13, Figure 6). The beach nourishment applications did not involve

grading or finished specifications, and material used was clean dredge spoils from the Snohomish River predominantly composed of sand and some pea-gravel.

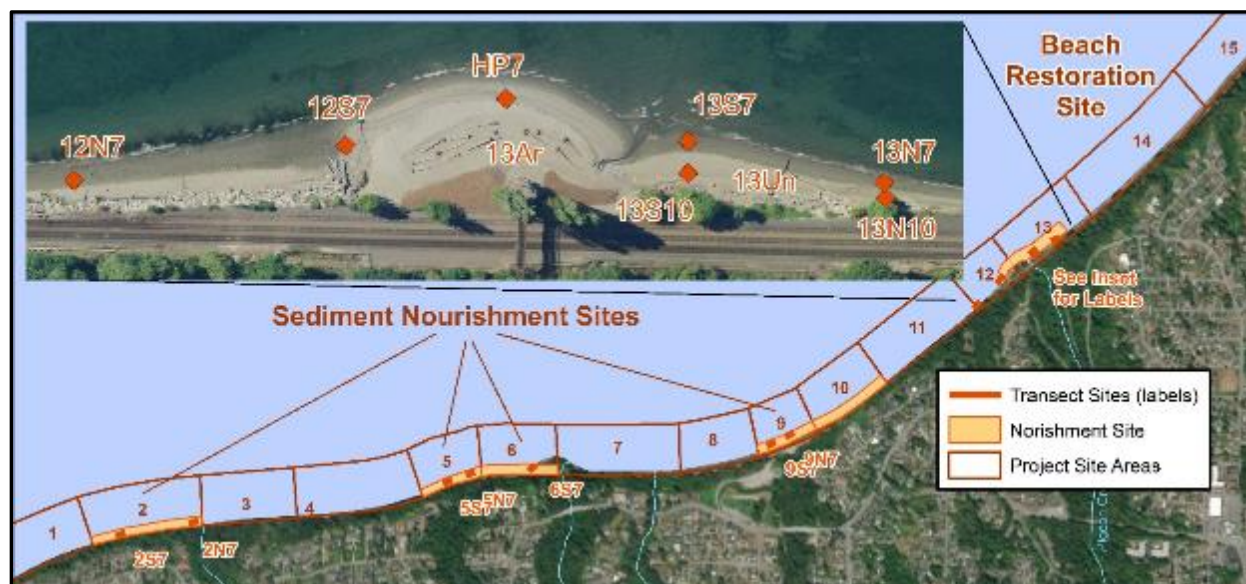


Figure 6. Nourishment and restoration sites along the Everett shoreline (process unit 8055) showing all the site numbers used for the SCBNP project, some of which were sampled for our learning project. Inset photo of Howarth Park is oriented +40 degrees from North. Points are center of forage fish sample sites. 13Ar and 13Un are also shown. 13Ar was not sampled post-restoration.

The plan for the five SCBNP nourishment sites called for a minimum use of 11,000 cubic yards of material. However, the [project completion report](#) indicated 16,879 cubic yards were used to nourish these five sites, each of which covered similar lengths of beach (range, 270-310 feet). Each of the sites varied in appearance, direction to fetch, initial substrate size, degree of armoring, beach slope, shoreline encroachment by the railroad, and degree of back beach with driftwood and vegetation, among other characteristics. Thus, real treatment replication was not possible. In some cases, beach nourishment was placed at pre-project forage fish sample locations. These forage fish sample sites are referred to as “Nourishment” sites. Other adjacent down-drift forage fish sample sites became “Drift” sites in our analyses. The relative location, site type, and naming conventions for sample sites are denoted in Table 1. Appendix Table A1 details what types of sampling were undertaken in each year and location.

Table 1. Summary of drift cell sample sites by UW or Snohomish County site ID. Armored¹ locations are shaded. Treatment locations and cubic yards of nourishment material emplaced at each site are indicated. Drift cell drift direction is from Site 2 (south) to Site 13 (north).

Drift Cell Drift Direction	UW Site ID	SnoCo Site ID	Nourishment or Drift	Placement (Date) ²	Length As- built (feet)	Estimate of Nourishment (cubic yards) ³
	2Un		None			
	2Ar	2S7	Nourish	Shoreface (7/11/2016)	305	2284
		2N7	Drift			
		5S7	Nourish	Shoreface (6/27/2016)	292	2967
		5N7	Drift			
	6Ar		Nourish	Shoreface (7/4/2016)	270	2903
	6Un	6S7	Drift			
		9S7	Nourish	Subaerial (6/28/2016)	310	4553
		9N7	Drift			
	9Un		Nourish	Subaerial (6/28/2016)	310	4173
	9Ar		Drift			
		12N7	Drift			
		12S7	Nourish	Profile (7/25/2016)		
	13Ar	HP7 ⁴	Nourish	Profile (7/25/2016)	320	9888
	13Un	13S7, 13S10	Drift			
		13N7, 13N10	Drift			

1 - Armored means that railroad armoring meets the beach face and no shoreline vegetation is present.

2 - Terms used in Clancy et al. 2009. Shoreface is lower elevation than subaerial. Profile contains sediment spread over the entire beach profile.

3 - From contractor estimates of quantities by site.

4 - HP7 was the unarmored post-restoration site at the 13Ar pre-restoration location.

Nourishment material was off-loaded from a barge by conveyor belt boom between construction staking and emplaced on the beach at a height of approximately 2 feet above existing grade. Figures 7-11 highlight the pre-project and as-built appearance of these locations. Other detailed site descriptions and photos of SnoCo sites (column 3 in Table 1) are available from the [Snohomish County Marine Resources Committee SCBNP](#). Material was immediately subject to movement by waves, making documentation of the “as-built” condition challenging. Howarth Park was engineered and constructed with much greater quantities (described below) of larger gravel-sized material (in addition to sands) that also overlapped sample site 12S7.



Figure 7. Site 2 shore pylon (left photo) demarcating limit of sediment placement left of pylon (center photo) and initial dispersal beach-ward (center photo) and updrift west of pylon (right photo).

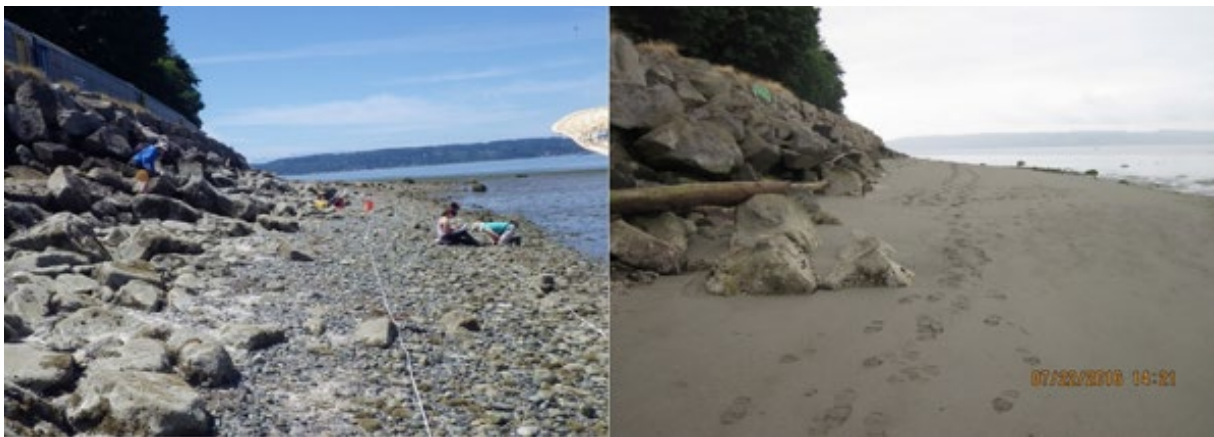


Figure 8. Site 2S pre-project (June 2016, left) and as-built (July 2016, center). Depth of nourishment cover is up to 2 feet based on design specifications.



Figure 9. Site 10 as-built condition one month post beach nourishment shows concentric deposits (right side of left photo) of material placed from barge-based conveyor boom and initial drift (right photo, black line) in up-drift direction from the nourishment material (back of photo).



Figure 10. Site 6 beach nourishment location pre-project (left photo) and post-nourishment (right photo). Note that the forage fish sample site was downdrift (front of photo) from this nourishment location.



Figure 11. Site 9 beach nourishment location pre-project (left photo) and post-nourishment (right photo) still showing concentric deposits from conveyor boom prior to wave action.

The Howarth Park site construction included the removal of approximately 300 feet of shoreline armoring (riprap), retention of buried shoreline stabilization for park protection, and placement of coarse substrate and sand in a delta formation to specific design composition, slope and elevation specifications ([Project snapshot](#)). The toe of shoreline armor (where the waterward terminus of riprap meets the beach face) was measured at 2.4 to 2.6 m +MLLW. This site was sampled pre-restoration as “13Ar”. The total volume of placed material was designed to be 6,000 cubic yards, though the project completion report states that 9,888 cubic yards of material was used for construction. Twelve pieces of large woody material were placed in the backshore, which was also planted with native beach vegetation and fenced. The large footprint of the Howarth Park beach construction also overlapped with the existing forage fish sample site 12S7 (Figure 6 and 12). After Howarth Park restoration a new forage fish sample site was added (HP7, in Figures 6 and 12).

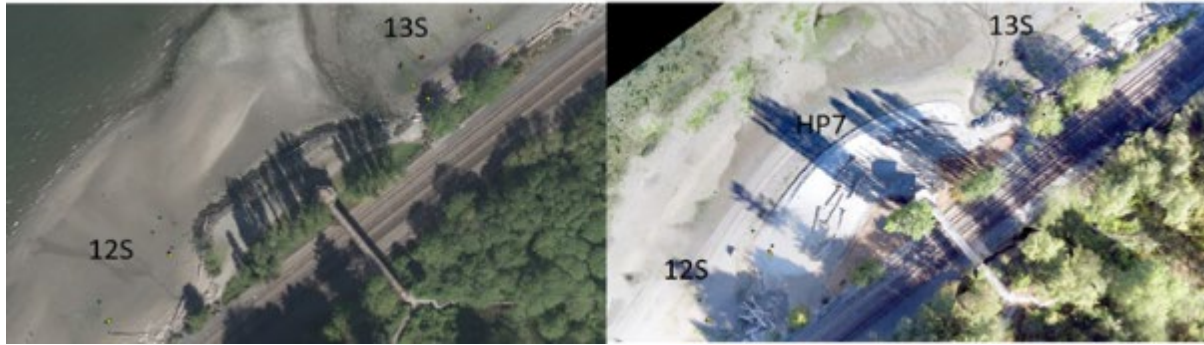


Figure 12. Aerial photo view of Howarth Park in 2015 and post-restoration in 2016 with forage fish sample sites labeled.

Figures 13-14 show pre-project and post-construction shoreline views of Howarth Park. Actual site designs and basis of design reporting can be found here:

<https://secure.rco.wa.gov/PRISM/Sponsor/Project/Brief/Index/13-1106>



Figure 13. Howarth Park showing some of the 300 feet of shoreline armoring in 2013, and in 2016, one month post-construction. Beach access is from the pedestrian overpass in the background.



Figure 14. Howarth Park looking west from the pedestrian tower (left photo, 2013) and nearly two years post-restoration (right photo). Shoreline armoring in left foreground was removed.

Most of the prior research on armoring impacts on Salish Sea beaches was done at nearby, paired, armored and unarmored comparison locations (Dethier et al. 2016). This selectivity in prior research necessarily excluded the railroad grade where there are no genuinely unarmored sites. However, there are areas, usually associated with small stream deltas, where the railroad is far enough back from the shoreline that relatively natural terrestrial vegetation develops at the upper beach, and logs and wrack accumulate similarly to/on unarmored stretches of shoreline. Such sites, including Site 13 (Figure 15) and Deer Creek unarmored (Figure 16) were used for ‘unarmored’ reference comparisons in the current study, especially since they were expected to approximate the potential outcomes of restoration in front of the railroad prism.



Figure 15. Example of beach with vegetation, beach wrack, and log line maintained between railroad prism and beach face (Site 13Un) that is part of creek (lower left) delta. In contrast, back of photo shows all shoreline armoring.

Among the Southern sites, in particular, we selected Deer Creek unarmored because it was the site of the Woodway slide in 1997. Here, the remnants of slide material have persisted for more than 20 years, having formed their own delta with higher-elevation erosion face, back beach and fan-like slope and contours, all waterward of the railroad. Even though the original slide extent (Figure 4, above) has retreated back toward the railroad, the rate has been slow enough, given the extent and the size of the slide volume (>100,000 cy), that the early site colonization by red alder has left remaining trees >30cm diameter. With persistent erosion of the slide material, these are recruited to the shoreline to contribute to drift logs and wrack. Thus, the scale of the introduced material has likely generated many functional characteristics at this railroad location that are intermediate between truly natural beaches and armored sites. This site thus contributes information to what we have learned about the importance of spatial scale (of treatment or effect) and amount of time until achieving restoration of goals.



Figure 16. Deer Creek unarmored, site of the Woodway slide, 20 years post-slide. Left to right are railroad prism, back beach with dune grass, 30 cm diameter red alder trees, beach berm and log line, beach wrack, beach face, leading to beach terrace (out of photo).

5 Methods

Subsets of the scientific methods applied during the [Puget Sound UW Armoring Study](#) (e.g., Heerhartz et al. 2014, Dethier et al. 2016) were used to collect data on sediment grain sizes at MHHW (Mean Higher High Water) wrack tidal elevations, beach profiles, wrack composition, wrack invertebrates, mobile wrack invertebrates and insects, and riparian vegetation and logs (most protocols are also detailed in the [Shoreline Monitoring Toolbox, with applicable data uploaded to the Shoreline Monitoring Database](#)). Transects parallel to shore were 50-m long at each site (overlapping or in addition to forage fish egg transects); perpendicular beach profiles extended from the backshore to MLW (Mean Low Water: +0.85m) or MLLW (Mean Lower Low Water: 0.0m) using laser level and stadia rod methods or RTK-GPS. All methods are described in detail below. Sites were relocated each year using GPS coordinates or measurement from shore monumentation. Site 2A (Appendix Fig B4.) transect locations varied among years because of inaccurate or mis-recorded coordinates; thus, some of the inter-annual change at this site may be due to different exact locations having been sampled.

Beach profiles and topography. Beach surface elevations were collected at each meter tape distance along profile length, extending from beach toe (e.g., armor, bank) to MLW, or lowest accessible beach. At least one profile was collected at center transect, and up to three profiles at right, center or left transect. Number of survey profiles within a transect varied by site and survey year. Within the Nourishment Region, profiles were collected at most sites each year 2015 – 2019; except for 2015 surveys at sites 2A and 2U, and 2017 surveys at sites 9A and 9U.

Within the Southern Region, profiles were collected at all sites, each year 2016 – 2019. Profile data was collected using a Trimble Geo XH 6000 Centimeter Edition RTK GPS unit (2-10 cm vertical accuracy), or laser level and stadia rod in limited years when the RTK GPS was unavailable. Elevation data was collected in North American Vertical Datum 1988 (NAVD 88) and converted to MLLW for analysis using Vertical Datum Transformation (VDatum), a NOAA software package designed to transform coastal elevation data based on input and desired output vertical (datum) and horizontal (coordinate system) information (NOAA 2012). For profiles collected with survey level and rod (i.e. RTK unavailable), elevations were referenced against water level at predicted tide elevations. VDatum was also used to calculate site-local elevations of MHHW and MLW for profile analysis. As expected, tidal datums differed only just within and between North and South sites. On average, at North sites MHHW is 3.37 m +MLLW and MLW is 0.85 m +MLLW, and; at South sites MHHW is 3.33 m +MLLW and 0.85 m +MLLW.

From each beach profile, we derived: elevation at beach toe (m above MLLW) where the beach face meets the waterward terminus of upland armored or unarmored shoreline; beach width (m), measured as the linear distance from beach toe to MLW; beach slope (m), measured as the absolute gradient from beach toe to MLW, and; relative encroachment (m MLLW), measured as the waterward encroachment of beach toe on MHHW.

We characterized beach surface topography at each transect by exercising a photogrammetry technique, Structure from Motion (SfM), that uses digital imagery with modeling software to create high resolution 3-D models. We collected a series of overlapping oblique convergent imagery on-site using a compact digital camera either hand-held or fixed to an extendable pole. Prior to image collection, we established a network of ground control points (GCPs), where we collected location and elevation data using the RTK GPS. This enabled real-world projection of 3-D models. We processed photos using computer software AgiSoft Metashape Professional to derive point clouds and build digital elevation models (DEM) of beach surface.

Sediment tracking from nourishment sites. Snohomish County personnel tracked the movement of emplaced sediment on a monthly basis after project implementation using GPS and walking the perimeter of the sediment. Photographs were taken by Snohomish County Staff from consistent photo points to visualize change over time as highlighted above. Figure 17 is a generalized schematic from the Snohomish County monitoring plan (Snohomish County 2012) that shows some of the sampling efforts within a given site, including sediment tracking methods.



Figure 17. Generalized schematic of some of the parameters quantified at each location within Snohomish County (Snohomish County 2012).

Quantifying sediment grain sizes. Grain sizes, which are critical to forage fish spawning and other biological processes, were quantified at different elevations and with slightly different methods.

1. At MHW (or highest accessible location), two samples were collected at transect center at both surface and subsurface. Surface sediments were collected from the top most layer to a depth of approximately 5 cm below surface, and subsurface sediments were collected to a depth approximately 10-15 cm below surface (Toft et al. 2013). Sample volume varied according to observed grain-size at site, where at least 100x the largest dominant grain-size was collected. Bulk sediment samples were spread in shallow trays and dried in the oven overnight. Dried samples were then passed through progressively smaller sieves by hand and standard RoTap sieve shaker, every half-Phi -6.0 through 4.0 ϕ ; where Phi(ϕ) is calculated as $-\log_2(\text{particle diameter in millimeters})$. For each bulk sediment samples, we calculated percent total weight (g) by cobble (> 6 cm), pebble (6cm - 4mm), granule (1 – 4 mm) and sand (< 2 mm).
2. At the wrackline, cores that were taken for invertebrates (N=5, see below) were also processed for sediments, using the RoTap methods detailed above.
3. At MLW, sediments were sampled at MLW to seek the lower extent of changes occurring after upper-shore restoration efforts. Beach sediment composition was estimated in two ways: surface cover of 3 size categories (cobble, pebble, and sand) in 10 large quadrats, and surface plus subsurface cover of 5 categories (cobble to mud, plus shell hash) in 3 small quadrats.
4. Sediment suitability for forage fish. We were interested in whether optimal substrate size for each target species (surf smelt (SS) and Pacific sand lance (PSL)) changed as a result of beach nourishment, whether that varied among sites (directly nourished and down-drift), and whether those changed conditions persisted. We also analyzed data for whether changes in substrate

size characteristics due to beach nourishment influenced forage fish spawning (as measured by egg count).

Seasonal beach sediment size characterization was evaluated monthly (October-February) for four years at 13 targeted sites (SnoCo Site ID, Table 1) prior to beach nourishment (2011-2015) and for four years post-nourishment (2016-2020). Bulk sediment samples (1368 grams, on average) were collected at each site along a consistent transect and used to both quantify grain sizes and detect the presence of forage fish spawning activity (Moulton and Penttila 2001). In conjunction with bulk sampling, still images were collected at each site to characterize substrate size.

Substrate size characterization was based on calculating the forage fish spawning suitability from each beach sample collected. Gravel samples were dried, sieved and weighed using standard Tyler series sieves. The spawning suitability substrate size range used for Pacific sand lance was quantified with sieve sizes 0.152 – 0.599 mm, and for surf smelt with sieve sizes 1.2 – 9.525 mm (Penttila 2007). These size ranges do not specifically correspond to those described in Penttila (2007, i.e. 0.2-0.4 mm for sand lance; 1.0-7.0mm for surf smelt). Our differences are partly due to the sieve sizes available at Snohomish County for sediment processing and partly due to inconsistency in the literature on fish size preferences. For example, the weight retained on sieve size 0.4 mm actually represents sediment that has passed through the next largest sieve size (0.8 mm in Penttila 2007). Therefore, the size range should be restated as 0.2-0.8 mm. Thus our range is expanded from the 0.2-0.4 mm but still reflects the apparent favorable size range highlighted in Penttila (2007).

The substrate favorability was calculated as the sum of weights from the suitable size classes (sieves) divided by the total sample weight – the percent suitable size composition. Figure 18 shows an example of the sieve size analysis for the month of October for one site pre- and post-nourishment. In this case, the post-nourishment quantity retained (as %) on the smaller sieve sizes in 2016 and 2017 is greater than the other years which contributes to the calculation (and interpretation) of higher substrate size suitability for Pacific sand lance, for example. Similar data were summarized for 365 samples for all dates and sites. Substrate size favorability for Pacific sand lance and surf smelt are evaluated by site, by year, by pre- and post-nourishment (pooled results), and by site type (“Nourishment” or “Drift” as described above).

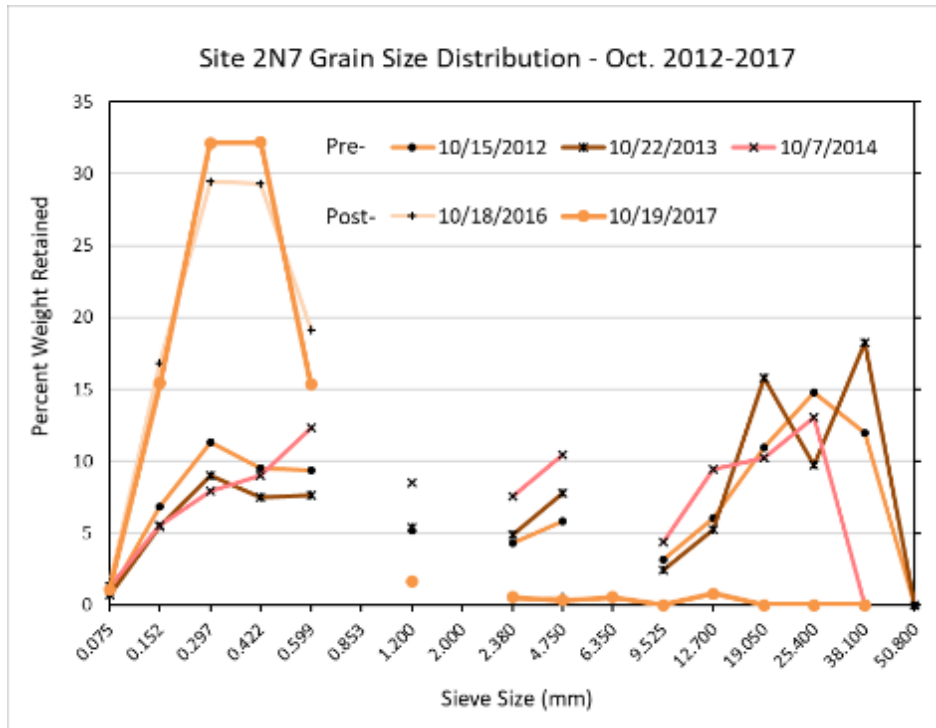


Figure 18. Example of beach gravel sample weight by sieve size during October spawning month for years pre- and post-nourishment.

Forage fish sampling. Snohomish County Surface Water Management and the Snohomish County Marine Resources Committee collected sand lance and surf smelt egg presence/absence data at 13 sample locations (Table 1 and Appendix C) in support of the SCBNP. Sand lance and surf smelt are important forage fish species which deposit eggs on upper intertidal sand-gravel beaches with certain characteristic grain-size spectrum. Forage fish are typically found spawning along this Everett shoreline in August-February. This critical habitat is vulnerable to various impacts from human shoreline development, particularly armoring. The sites in this study have been heavily impacted by the railroad embankment and the subsequent cessation of erosional inputs of sediment for the maintenance of fine-grained beaches.

To assess the impact of nourishment to improve forage fish habitat and response, 13 forage fish sample sites were designated along the 4.5 mile stretch of the SCBNP project. Forage fish sampling sites either overlapped or were spatially shifted from beach nourishment locations sampled for all other parameters, in part due to their initial selection in 2011, prior to the ESRP project (this report) and exact knowledge of nourishment siting at that time. However, forage fish sampling sites were located either with nourishment or downdrift from nourishment, so we designated sites as either “Nourish” or “Drift”. Three sites matched (or were slightly shifted from) unarmored locations in this study (6S, 9N, 13S). Only one location (2S) matched an armored location. The armored/unarmored, nourished/downdrift designations are included in Table 1. Samples were taken monthly at each site from approximately August-February in 2011-2015 (pre-project) and monthly from approximately August-February in 2016- 2020 (post-project).

Forage fish spawning surveys followed protocols developed by WDFW (Moulton and Penttila 2001). This protocol requires that 1.5-2 liter of sediment is collected along a 100-foot designated transect that is parallel to shore at the 7' tidal elevation (Moulton and Penttila 2001). Tidal elevation was re-established annually and sometimes varied in horizontal distance from shore-based monumentation. Four scoops of approximately .5 liters of sediment are taken at the 0-foot, 33-foot, 66-foot and 100-foot locations along the 100-foot transect (Moulton and Penttila 2001). Samples for sites 2-12 occurred at the +7' tidal elevations (MLLW), while site 13 had samples taken at the +7' and +10' tidal elevation (MLLW) (Figure 19). This additional sample location was added at site 13 due to favorable habitat at higher elevation. The sediment samples were washed through a standard series of progressively finer sieves. Egg extraction throughout the sampling season for all years was done using pan winnow methods – the Standard WDFW Winnow Protocol adapted for the Snohomish MRC (Appendix C). Surf smelt and Pacific sand lance egg extraction, identification and enumeration for the 13 transect sites was completed by Dan Penttila of Salish Sea Biological from the inception of the project. Confirmation of egg presence was based on the presence of 2 eggs or more within a 1.5-2 liter sample from one location.

Substrate size and forage fish egg count were evaluated monthly (October-February) for four years at 13 targeted sites prior to beach nourishment and for four years post-nourishment. Substrate size favorability for Pacific sand lance (PSL) and surf smelt are evaluated by site, by year, by pre- and post-nourishment (pooled among years), and by site type (Nourish or Drift).



Figure 19. Sampling sediments for forage fish eggs at Howarth Park (HP) post-restoration - tidal elevation here is approximately +7'. Hence, sample site name is HP7.

Wrack and logline sampling. We measured wrack percent cover of algae, eelgrass, terrestrial, and human debris sources deposited on the beach on an ebbing tide, using a 0.1 m² quadrat at

ten random points along a 50 m transect parallel to the beach. At each quadrat, we also measured wrack depth (cm), and overall width of the wrack-line (m). We used a benthic core (15 cm diameter, 2.5 cm depth) to sample invertebrates and sediments at five random points along the same transect in the wrack. Core samples were frozen so that invertebrates and sediments could be processed in the laboratory. Invertebrates were separated from the samples and sorted at the microscope for taxa and number. Sediment sizes were determined using a standard RoTap shaker, by sieving dried sediments and weighing the amount collected in each sieve. We counted the number of logs (driftwood) and the width of the log-line perpendicular to shore at the same five random points that benthic cores were collected. Pitfall traps were used to sample mobile invertebrates and insects in the wrack. Five traps were placed randomly along 50-m transects at both the high and low wrack lines. When armoring was so low that there was no high wrack line, traps were placed in the riprap. Each trap consisted of a 473-ml (16-oz) plastic drinking cup filled with ~3 cm of filtered seawater mixed with a small amount of biodegradable soap to break the surface tension. Trap contents were collected after 1 hour, preserved in 70% isopropanol, and taken back to the laboratory for sorting and counting.

WSU Snohomish County Extension Beach Watchers volunteered to gather additional data on wrack abundance starting in June 2017 post-nourishment at Site 13 (Howarth Park), and to continue that sampling across months to document seasonal patterns not visible in UW sampling. One of us (JT) trained a group of Beachwatcher volunteers (organized by Scott Calhoun) in wrack surveys at Howarth Park in June and July 2017, with continued training in March and June 2018, and June 2019; they subsequently continued sampling during most months, and data through October 2019 are included here.

MLW biotic sampling. Biotic sampling at this level used [SCALE](#) methods (Dethier and Schoch 2005) to quantify surface macroflora and fauna abundance in ten 0.25 m² quadrats, and infauna in ten 10-cm diameter cores inserted to 15-cm depth and sieved to 2mm.

5.1 Statistical analyses

Our analytical techniques are similar to those used in previous studies of our peer-reviewed research (Dethier and Schoch 2005, Toft et al. 2013, Heerhartz et al. 2014, Toft et al. 2014, Dethier et al. 2016), i.e. standard univariate linear model techniques for analyzing physical and biological responses, plus multivariate techniques (NMDS, PERMANOVA, DISTLM) to link community responses of biota to measured physical parameters under the supra-categories of armored and unarmored. Where appropriate, we use Before-After Control-Impact (BACI) techniques, to compare parameters measured before and after nourishment. For BACI analyses, fixed factors were site, strata (armored-unarmored), period (before-after nourishment), with year a random factor. The interaction term of strata*period indicated whether nourishment had an effect. For forage fish egg counts in the Nourishment Region we used the interaction term of treatment*period, where treatments were nourished and drift sites. The pitfall traps had an additional fixed factor and interaction term for the two elevations. To improve normality, wrack percent cover and sediment percent data were arcsine-square root transformed, and invertebrate densities and forage fish egg counts were log-transformed.

Analyses at the four Nourishment sites were assessed as compared to analyses at the four southern sites with no nourishment. Post-nourishment monthly sampling June 2017 - October 2019 at Site 13 by the Beach Watchers was analyzed separately for strata and month. We used this monthly sampling to assess how representative our extensive June sampling was to yearly patterns.

Ultimately, sediment location and drift were documented by analyzing changes in the shape of beach profiles and sediment sizes across transects over time, with supporting evidence of changes captured by delineation of drift and at photo points. Results from this experimental design are useful for evaluating beach nourishment success and developing quantitative and conceptual drift cell management goals and objectives in the future.

6 Results

6.1 Nourishment region: SCBNP sites

6.1.1 Beach profiles

Armor effect. Beach profiles across the Nourishment Region differed by site, presence of shoreline armor and treatment effect. We observed some interannual variability (Appendix Figs. B21-B23.), with at least four and up to five years of surveys, but no clear trends emerged over time due to the wide range of beach conditions. Overall, we found that armored beaches exhibited lower elevation at beach toe, and therefore greater encroachment on MHHW, and narrower beach widths. However, a signal of armor effect on beach slope was less evident (Table 2).

At armored locations across the Nourishment Region, beach toe elevation was lower (i.e. more waterward) (mean=3.1 m +MLLW) with a wider range (range= 1.2 to 4.2 m +MLLW) than at unarmored locations (mean = 4.0, range 3.4 to 5.0 m + MLLW) (Table 2). This armor effect was consistent within individual sites, but with clear differentiation observed only at south-most Nourishment sites 6 and 2 (Figure 20). Expectedly, the widest within-site range of toe elevation, across time, was observed at Site 13 armored, where shoreline armor was removed in complement with beach nourishment.

Table 2. Average, minimum and maximum values of beach profile parameters measured across Nourished Region sites 13, 9, 6 and 2, in Snohomish County, WA. Values are averaged across all years sampled and summarized by strata (armored or unarmored). Site total is the average across all years and sites. Toe (m above MLLW) is the measured point where the upper beach face meets the waterward terminus of armored or unarmored shoreline; relative encroachment (m MLLW), is measured as the waterward encroachment of toe on MHHW; beach width (m), is measured as the linear distance from toe to MLW; and beach slope (m), is measured as the absolute gradient from toe to MLW.

		Armored	Unarmored	Site total
Toe (m +MLLW)	Average	3.11	4.01	3.58
	Minimum	1.24	3.36	1.24
	Maximum	4.18	4.96	4.96
RE (m +MLLW)	Average	0.27	-0.64	-0.20
	Minimum	-0.80	-1.59	-1.59
	Maximum	2.14	0.01	2.14
Width (m)	Average	35.50	45.98	40.91
	Minimum	4.56	22.52	4.56
	Maximum	61.13	72.12	72.12
Slope (m)	Average	0.07	0.08	0.08
	Minimum	0.03	0.04	0.03
	Maximum	0.13	0.13	0.13

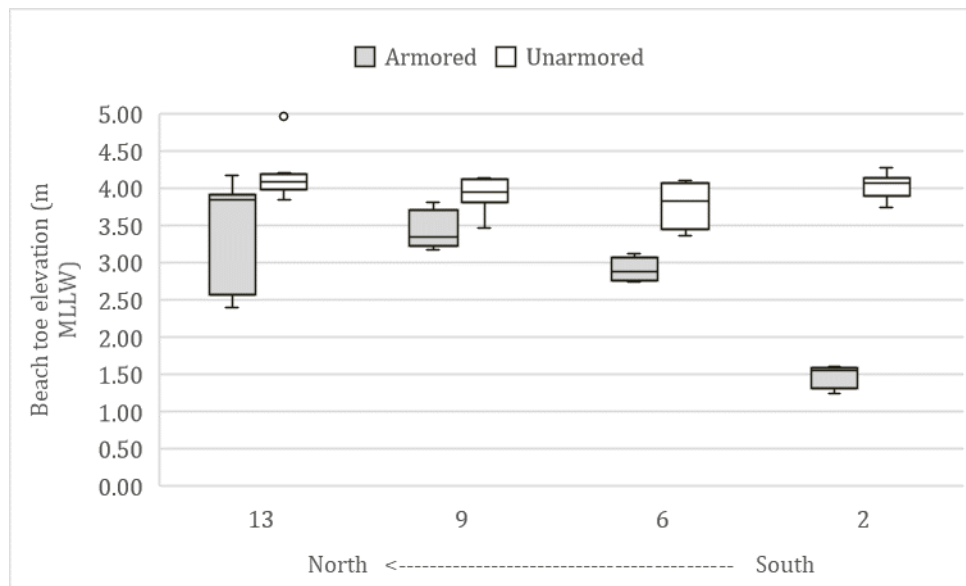


Figure 20. Range of beach toe elevations (m +MLLW) measured at each Nourishment site 13, 9, 6, and 2 in Snohomish County, WA. Values are averaged across all years sampled, 2015 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair. Arrow indicates direction of drift.

As a whole, relative encroachment (RE) of beach toe on MHHW was minimal in the Nourishment Region (mean=-0.2 m) (Table 2). Similar to the effect of armor on beach toe, RE

was greatest at armored locations (mean =0.3, range -0.8 to 2.1 m), with the strongest contrast observed at south-most Nourishment sites 6 and 2 (Appendix Fig. B18.). This similarity to the beach toe data was expected as RE is a calculation relative to toe elevation, and tidal datums do not differ greatly within this small spatial framework.

Within each Nourishment Region pair, beach width was consistently greater at the unarmored location compared to armored location (Figure 21); widths overall at unarmored locations averaged 46.0 m compared to 35.5 m at armored locations (Table 2). However, both armored and unarmored locations exhibited a wide and overlapping range of widths across the Nourishment Region, which appeared to be driven by other site-specific beach characteristics. For example, mean beach width at site 2 was less (19.0 m) than site 6 (60.8 m); however, looking within site pairs, site 6 armored was wider (59.0 m) than site 2 unarmored (25.7 m) (Figure 21). The wider beach at both portions of site 6 potentially contributed to the longer persistence of nourishment material here and at the downdrift location (see below).

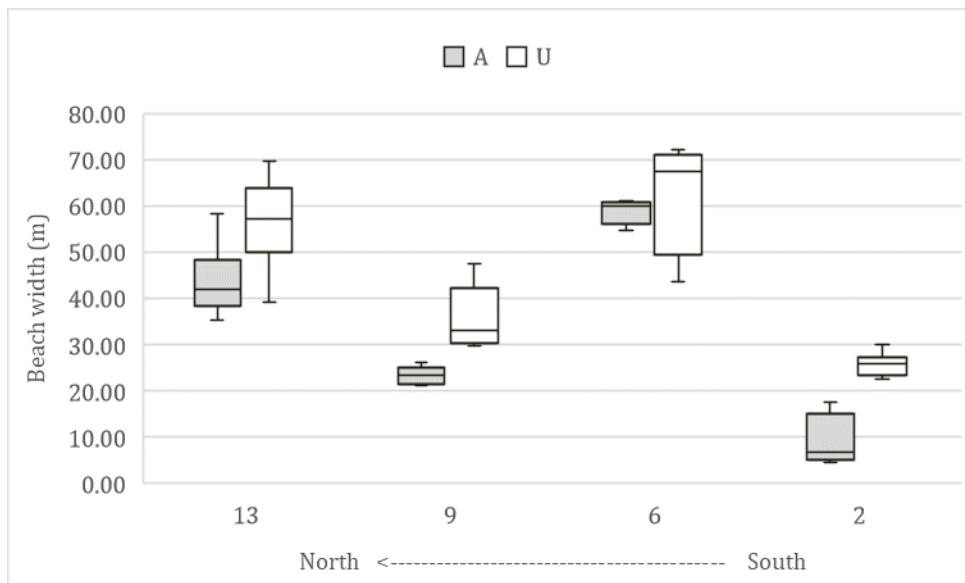


Figure 21. Range of beach width (m) measured at each Nourishment site 13, 9, 6, and 2 in Snohomish County, WA. Values are averaged across all years sampled, 2015 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair. Arrow indicates direction of drift.

Profile data did not detect a clear signal of armor effect on beach slope, and summaries were similar between strata (armored mean = 0.07, range 0.03 to 0.13 m, unarmored mean = 0.08, range 0.04 to 0.13 m) (Table 2). The predicted effect of armor to lessen beach slope was evidenced only in sites 2 and 6 (Appendix Fig. B20.).

Nourishment treatment effect. Following the application of beach nourishment across the Nourishment Region, we observed varying degrees of positive and negative responses of beach profile and could not identify a clear signal of treatment effect for all sites. Averaged across all Nourishment Region sites, we observed an increase in beach toe elevation and beach width,

and a decrease in beach slope. Looking within site pairs, we found that broad changes were driven largely by greater changes measured at armored locations. Overall, we found that measures of beach profile character averaged across post-treatment survey years (2017 to 2019) were less distinct between strata of those averaged across pre-treatment survey years (2015 to 2016), i.e. closer means and greater range overlap. However, this pattern was not always consistent within individual sites and profile parameters.

Averaged across all sites and treatment status, the elevation of beach toe (where beach sediments meet the armoring or bank) increased only slightly after nourishment (before and after mean = 3.5 and 3.6 m +MLLW, respectively), although range of values expanded in both minimum and maximum extent (range = 1.6 to 4.3 and 1.2 to 5.0 m, respectively) (Table 3). However, this overall change was driven singularly by an increase in toe elevation at Site 13 armored, where shoreline armor was removed in conjunction with beach nourishment. Contrary to expectations, apart from Site 13 armored, all Nourishment sites, armored and unarmored, eventually showed a decrease in beach toe elevation following treatment (Figures 22, 23).

Table 3. Average, minimum and maximum values of beach profile parameters measured across Nourishment sites 13, 9, 6 and 2 in Snohomish County, WA. Values are summarized by treatment status (before or after nourishment) and strata (armored or unarmored). Site total is summarized by treatment status, and averaged across all sites. Toe (m above MLLW) is measured point where the upper beach face meets the waterward terminus of armored or unarmored shoreline; relative encroachment (m MLLW), is measured as the waterward encroachment of toe on MHHW; beach width (m), is measured as the linear distance from toe to MLW; and beach slope (m), is measured as the absolute gradient from toe to MLW. See Figure 22 below for standard error.

		Before (2015 - 2016)			After (2017 - 2019)		
		Armored (n=10)	Unarmored (n=10)	Total (n=20)	Armored (n=22)	Unarmored (n=24)	Total (n=46)
Toe (m +MLLW)	Avg	2.92	4.10	3.51	3.21	3.97	3.61
	Min	1.56	3.78	1.56	1.24	3.36	1.24
	Max	3.80	4.27	4.27	4.18	4.96	4.96
RE (m +MLLW)	Avg	0.46	-0.72	-0.13	0.16	-0.59	-0.23
	Min	-0.43	-0.89	-0.89	-0.80	-1.59	-1.59
	Max	1.81	-0.40	1.81	2.14	0.01	2.14
Width (m)	Avg	30.68	47.81	39.25	38.04	45.10	41.75
	Min	6.09	25.75	6.09	4.56	22.52	4.56
	Max	59.75	72.12	72.12	61.13	68.39	68.39
Slope (m)	Avg	0.08	0.08	0.08	0.07	0.08	0.07
	Min	0.03	0.05	0.03	0.03	0.04	0.03
	Max	0.13	0.13	0.13	0.10	0.13	0.13

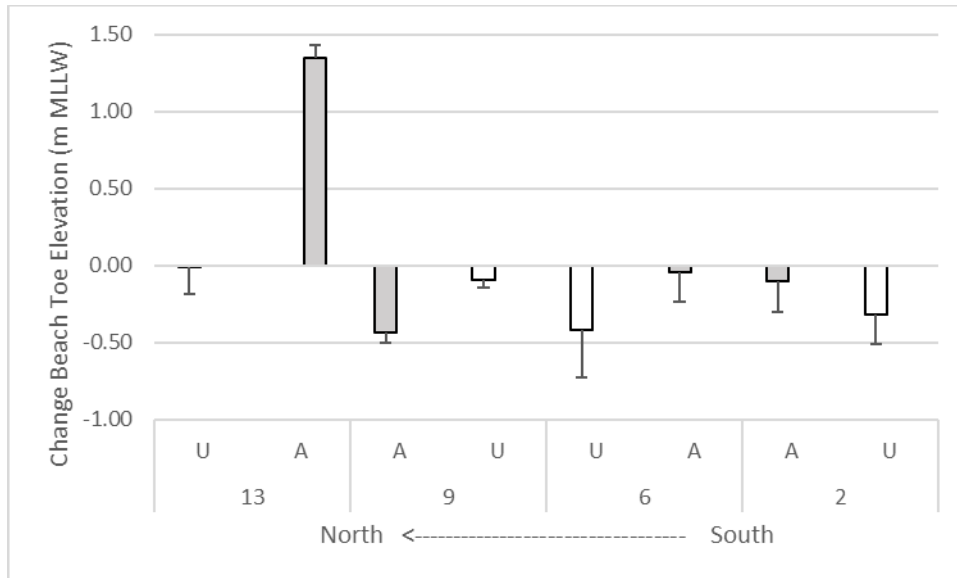


Figure 22. Change from pre-treatment to post-treatment in beach toe elevation (m + MLLW) (+/- SE) in response to beach nourishment measured at each Nourishment site 13, 9, 6 and 2, in Snohomish County, WA. Values are averaged across pre-treatment (2015-2016) and post-treatment (2017-2019) survey years. Arrow indicates direction of drift.

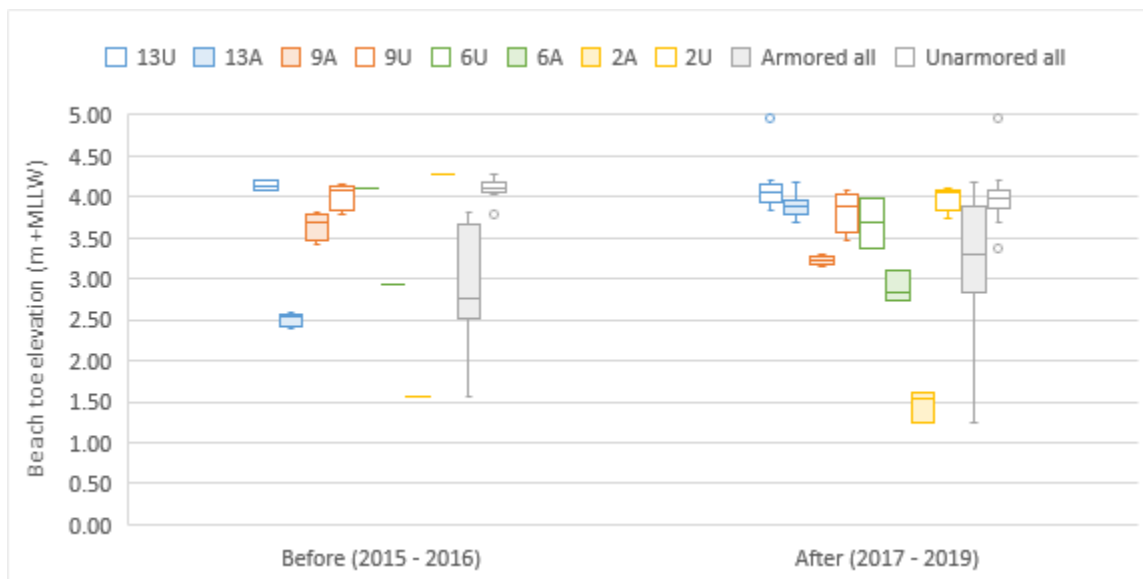


Figure 23. Range of beach toe elevations (m + MLLW) measured at each Nourishment site 13, 9, 6 and 2 in Snohomish County, WA. Profiles were surveyed before (2015 to 2016) and after (2017 to 2019) beach nourishment, at armored, A, locations (shaded plots) and unarmored, U, locations (open plots).

Similar to broad patterns of toe elevation, beach width averaged across all Nourishment sites increased after nourishment (before mean = 39.3 m and after mean = 41.8 m) (Table 3), but direction and magnitude differed between sites and strata (Figure 24, 25). For the most part, we

found that beach widths increased at armored locations and decreased at unarmored locations. The only exception was site 6, where both the armored and unarmored location decreased in beach width; however, the armored pair decreased by a much lesser amount (Figure 24). At Site 6 the sediments may have drifted to lower on the shore (Figure 11) than our beach width measurements, which only ran to MLW.

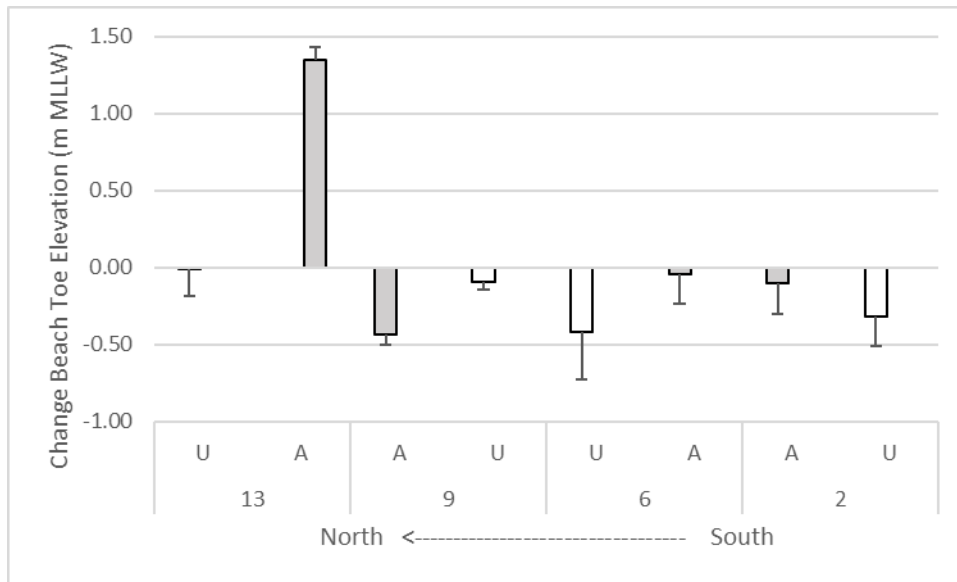


Figure 24. Change in beach width (m) (+/- SE) in response to beach nourishment measured at each Nourishment site 13, 9, 6 and 2, in Snohomish County, WA. Values are averaged across pre-treatment (2015-2016) and post-treatment (2017-2019) survey years. Arrow indicates direction of drift.

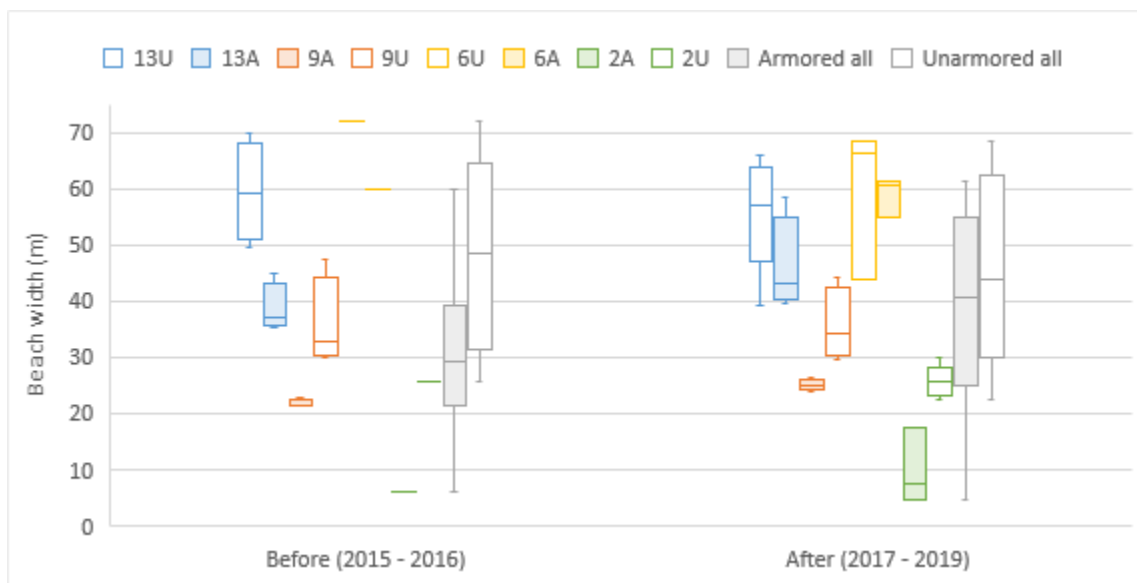


Figure 25. Range of beach width (m) measured at each Nourishment site 13, 9, 6 and 2 in Snohomish County, WA. Profiles were surveyed before (2015 to 2016) and after (2017 to 2019) beach nourishment, at armored, A, locations (shaded plots) and unarmored, U, locations (open plots).

We found that beach slope exhibited the weakest response to beach nourishment (before mean = 0.08, range 0.03 to 0.13 m, and after mean = 0.07, range 0.03 to 0.13 m) (Table 3), and similar to other profile parameters, varied by both site and strata (Appendix Fig. B19). Change in beach slope was not consistent by strata, but instead changed unilaterally within a site, e.g., site 13 armored and unarmored decreased and site 9 armored and unarmored increased (Figure 26). However, greater change in either direction was most often observed at armored locations; site 6 being the only exception.

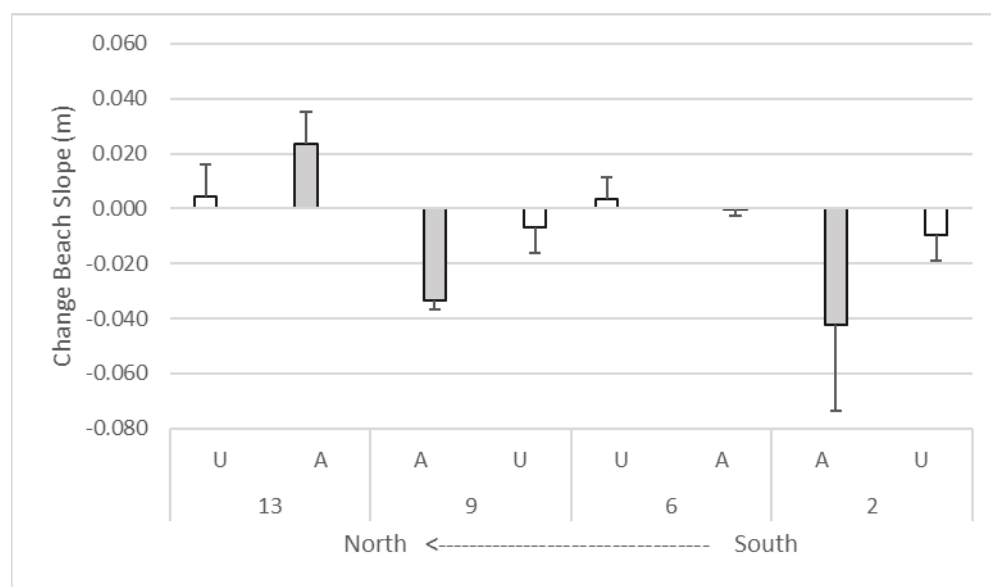


Figure 26. Change in beach slope (m) (+/- SE) in response to beach nourishment measured at each Nourishment site 13, 9, 6 and 2, in Snohomish County, WA. Values are averaged across pre-treatment (2015-2016) and post-treatment (2017-2019) survey years. Arrow indicates direction of drift.

Change over time. For most profile parameters in the Nourishment Region, we did not observe substantial changes within the post-treatment time frame 2017 through 2019. The initial patterns documented post-treatment (in the as-built 2017 surveys) remained consistent over time, with slight inter-annual variation in rate of change (Appendix Figs. B21-B23). However, at select sites we observed relatively large inter-annual change in profile character post-treatment. For example, yearly surveys at site 2 armored identified a severe flattening of beach slope and increase in beach width in the first year following treatment (2017), and a slow rebound toward steeper and narrower conditions in successive years 2018 and 2019 (Appendix Figs. B21 and B22, respectively). However, differences at this site may be a reflection of slight variation in survey profile location rather than a true reflection of beach character (Appendix Fig. B4).

6.1.2 Sediment tracking from nourishment sites: drift and persistence

For restoration projects, such as beach nourishment, important questions for managers are: 1) is there a sustained effect of treatment over a longer timeframe; and 2) can we differentiate initial system reactions from lasting responses? In-depth monitoring of sediment drift and persistence at nourishment sites informs these questions.

The footprint of placed material was delineated in the field for selected nourishment locations using mapping-grade GPS to identify the limits of initial placement and subsequent boundary of down-drift movement of sand. The geospatial data consists of individual lines delineating the boundary between fine sediment (sand, likely deposited by beach nourishment efforts) and coarse sediment (small gravel to small cobble size sediment typical for Puget Sound beaches that have limited fine sediment sources). In conjunction with geospatial data, still images were collected at each site to also describe the movement of sediment. This boundary between emplaced and native substrate was most easy to distinguish at the updrift margin of the beach nourishment boundary but was readily discernible at the downdrift margin as that moved alongshore. As time passed and drift material thinned and dispersed alongshore and downshore, these delineations were less obvious.

Site 2. Figure 27 shows Site 2S (aka 2A-armored) in the pre-project condition, immediately after nourishment, and 16 months post-nourishment after much material had moved downdrift (back of photo. Also see [SCBNP](#) for photo series of Site 2S7). In this case, the transport of nourished sand was so rapid that monthly sampling of the fixed 2S7 forage fish sampling location “missed” documenting the obvious change in substrate size at this site.



Figure 27. Site 2S Pre-project (June 2016, left), As-built (July 2016, center), and 16 months post-project (October 2017, right). Note that there is a small sand delta persistent at the back of the October 2017 photo.

The drift of material and delineation of our observations for site 2S is shown in Figure 28. The initial as-built condition (labeled Aug 2016) had already spread out from the construction limits of initial nourishment. By October 2016, nourishment material was positioned both downdrift and down slope. As mentioned above, surveys at site 2 identified a severe flattening of beach slope and increase in beach width in the first year following treatment (as in Figure 27, center), and a slow rebound toward steeper and narrower conditions in successive years 2018 and 2019, reminiscent of the pre-project condition. At site 2, nourishment material was completely evacuated out of the original placement area by February 2019 (labeled).

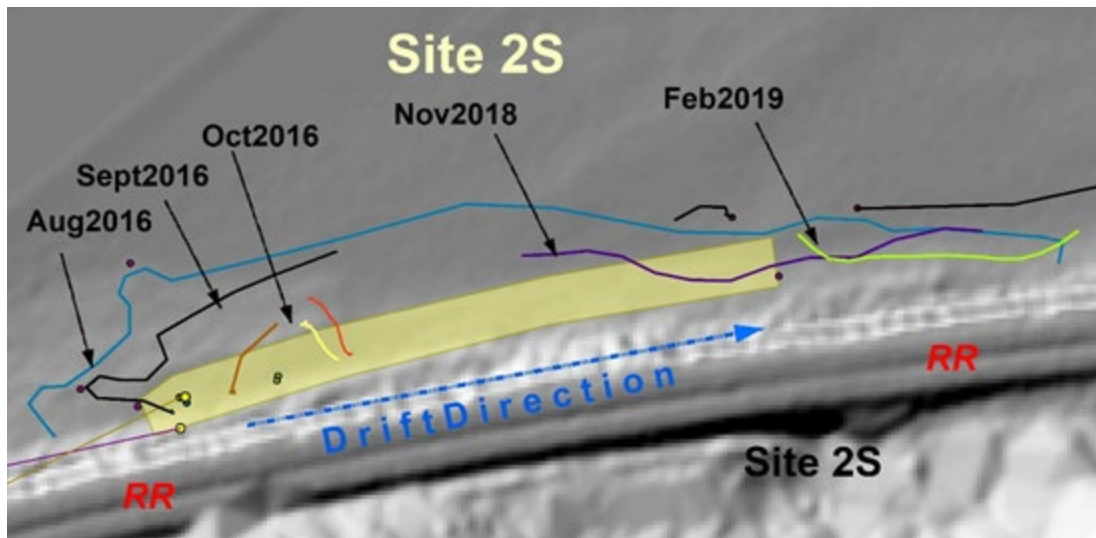


Figure 28. Site 2S showing beach nourishment placement area (yellow polygon) and shifting nourishment boundary from left (west) to right (east) with the shoreline process unit drift direction. Railroad prism is labeled (RR). Not all months are shown or labeled.

Hence, the estimated 2284 cubic yards (cy) was fully transported downdrift in approximately 29 months, or an average rate of 95 cy/month. Immediately downdrift at Site 2N, Figure 29 highlights that drifting sand reached the site by September 2016, two months post-nourishment. Here, the edge of the drifting material is partially retained by the elevated Powder Mill Creek alluvial fan which sustained this persistent edge of the drift lines.

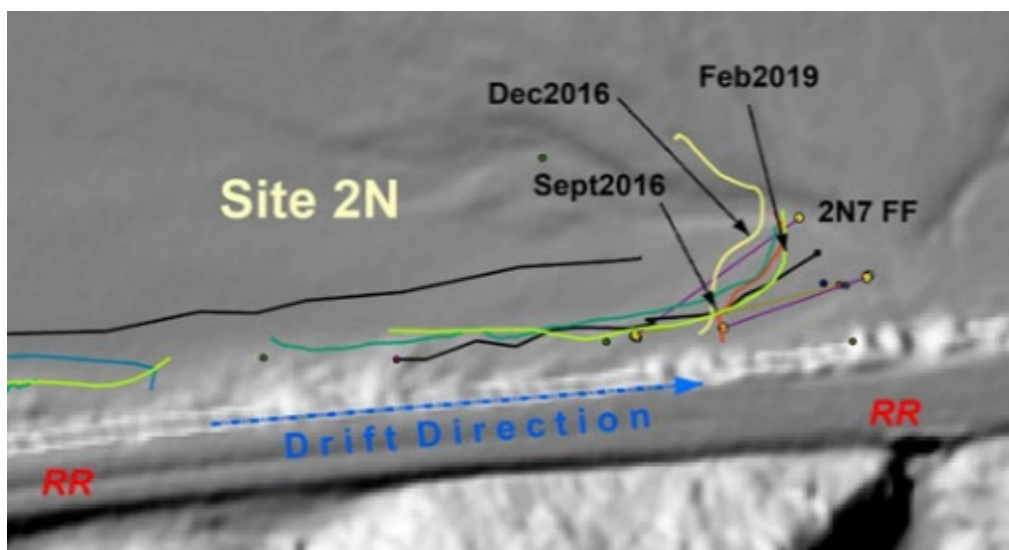


Figure 29. Site 2N, downdrift from 2S, shows persistent beach nourishment drift boundary at tributary delta between September 2016 and February 2019. Railroad prism is labeled (RR).

The pre- and post-nourishment favorability for forage fish spawning and sediment persistence over time (at Site 2N7) is illustrated below in Figure 30 using monthly substrate samples. For the nourishment site 2S, the rate of drift was so rapid between August and October 2016 that

the designated forage fish sampling site (2S7) hardly reflects any change in substrate size (favorability) over time compared to 2N7. In order to report some beach nourishment composition associated with placement at 2S, two sediment samples were collected on the minor delta formed downdrift of 2S7 (photo in Figure 27). This sandier material is part of the total drift contributing to the change in 2N7 substrate favorability for Pacific sand lance spawning compared to the pre-project condition, and also highlights the flattening of the placed material described above. Other results for substrate size favorability are reported in section 6.1.6.

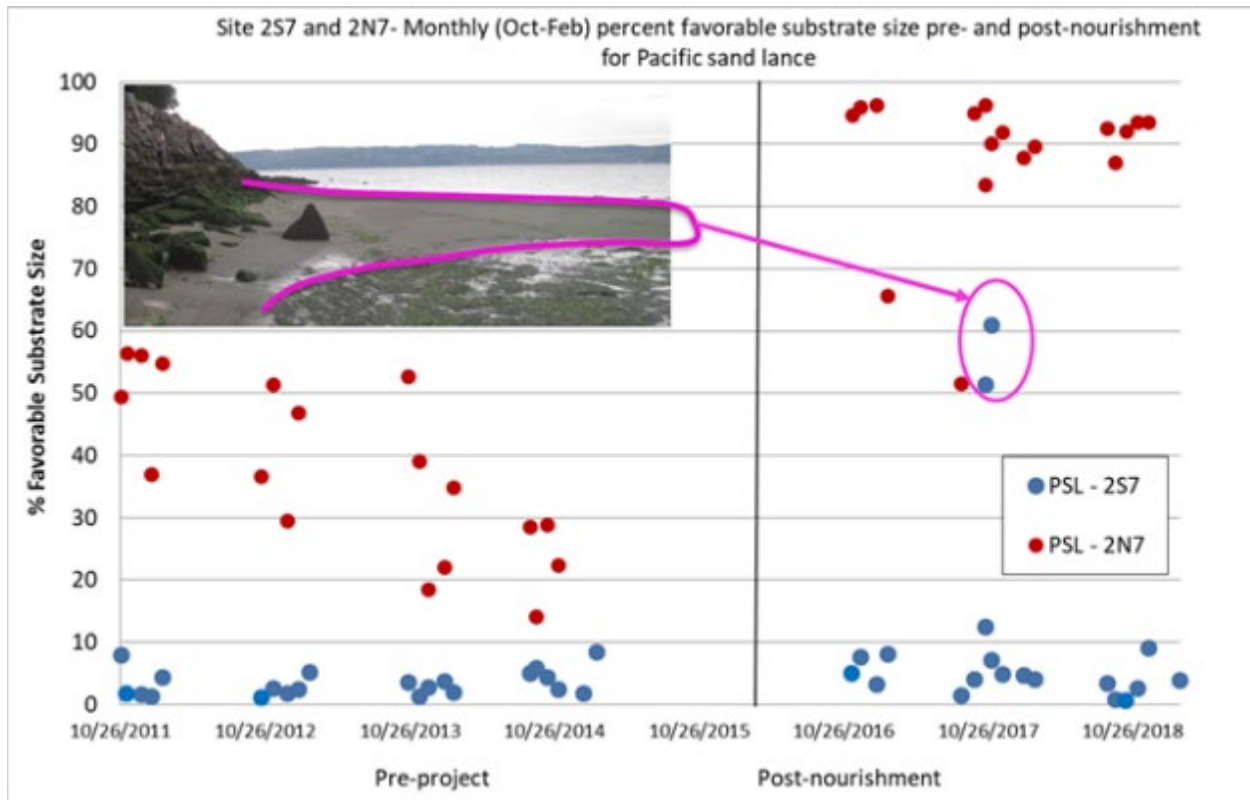


Figure 30. Monthly PSL substrate size suitability pre- and post-nourishment at sites 2S7 and 2N7 based on sieve sampling of core samples. Supplemental sampling of substrate size (and forage fish eggs) on the drift delta (outlined in embedded photo and circled data points) are also shown. The inset photo does not cover data points.

At forage fish sample site 2N7, drifting beach nourishment material arrived within two months of emplacement and was still persistent in thin patches after 36 months (Figure 31). Although beach nourishment material rapidly evacuated the majority of the initial placement area within 24 months, sand from beach nourishment continued to support relatively higher PSL substrate favorability (as in Figure 30).



Figure 31. Site 2N at tributary delta downdrift from beach nourishment. Photos show before nourishment (left photo), with nourishment (center photo), and year three post-nourishment. After three years, patches of finer nourishment material remain.

Site 5. Figure 32 shows the as-built condition at Site 5S, with the sand boundary easily delimited relative to existing cobble and angular beach substrate. Figure 33 illustrates the change in surface substrate composition over time (from the updrift construction limit of beach nourishment) due to the drift of substrate from the placement location. Smaller patches of sand were sometimes separated from the main drift, which is not shown in the drift maps.



Figure 32. Initial up-drift boundary of beach nourishment at Site 5S. Black line delimits the boundary for Jul2016 shown in Figure FL23. Note the angled log in the center back of photo also shown in Figure FL22.



Figure 33. Site 5S two months post-nourishment (left photo) showing placed sand taken from the south edge of nourishment, then at six months (center), and 15 months post-nourishment.

At Site 5 beach nourishment material first moved updrift (Aug2016 and Sep2016, Figure 34). This was followed by continued drift to the east, but with persistent retention of material on the creek delta near site 5N. By December 2018 all beach nourishment material had evacuated the original placement limits, suggesting the drift rate was approximately 102 cy/month.

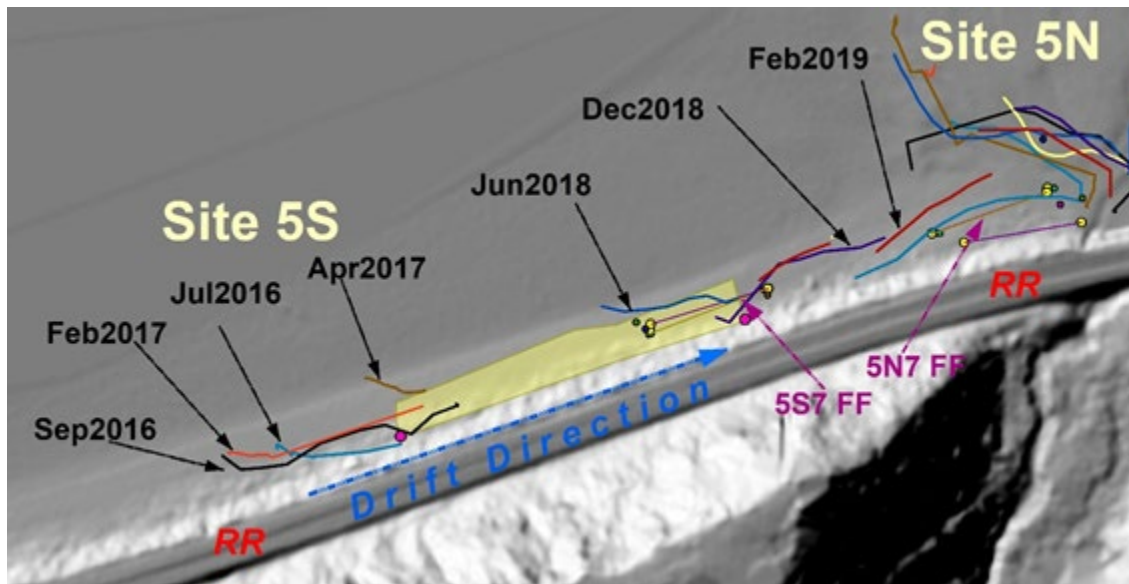


Figure 34. Sites 5S and 5N, beach nourishment yellow polygon area, initial drift delineation (Jul2016) and drift from left (west) to right (east) by date. The downdrift boundary persists on the tributary delta at forage fish sample site 5N7. Sample site 5S7 is also shown. Railroad is labeled (RR).

The retention and persistence of drift material at Site 5N7 is illustrated in Figure 35 and was greater than at Site 2N7 after three years.



Figure 35. Site 5N at tributary delta downdrift from beach nourishment. Photos show before nourishment (left photo), with nourishment (center photo), and three years post-nourishment. Beach nourishment material is widely persistent over the area after three years.

Site 6. Figure 36 highlights the changes at Site 6 over time in substrate size before project implementation, after beach nourishment, and 35 months post-nourishment. The beach nourishment was placed here between two creek deltas where the beach had a low slope and was contained within a subtle embayment with a very wide beach terrace, but high encroachment from the railroad. Immediately downdrift from this location, finer beach sand entered sampling Site 6S7 (Figure 37) two months post-nourishment. Unlike sites 2S and 5S, beach nourishment material was still retained within the placement area (back of right photo) at the end of the study period (44 months); a transport rate of less than 66 cy/month. Nourishment drift line mapping is shown in Figure 37.



Figure 36. Site 6S/6Ar nourishment at armored location at toe of railroad - pre-project (left photo), two months post-project (center), and 35 months post project (right photo). Some drift material is still retained on the creek delta in background after 35 months.

At Site 6S, the prominent boundary downdrift from beach nourishment was the apex of the creek delta where drifting material arrived by September 2016. Interestingly, the boundary mapped in December 2018 was closer to the nourishment suggesting an early wave of drifting material subsided; followed by another wave that extended the drift boundary again, to February 2019, as shown. By that time, some drift appeared to be arriving from Site 5.

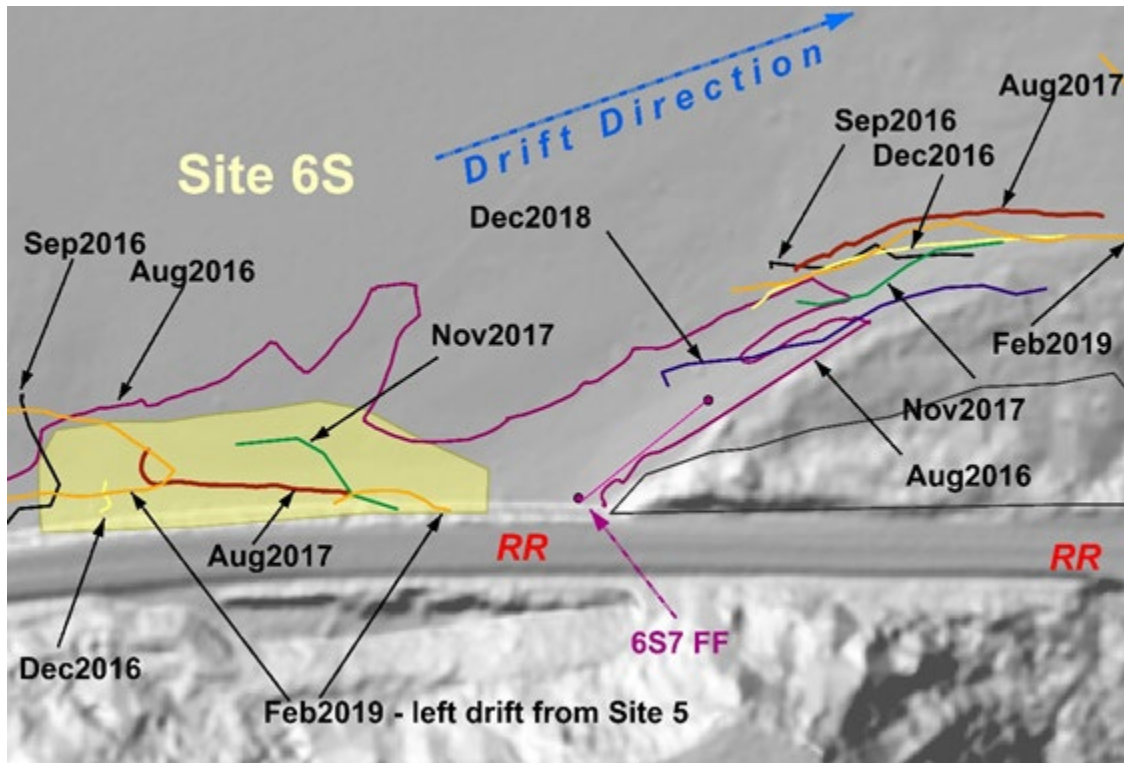


Figure 37. Site 6S, beach nourishment yellow polygon area, initial drift delineation (Aug2016) and drift from left (west) to right (east) by date. Forage fish sample site 6S7 is also shown. Railroad is labeled (RR).

Figure 38 highlights the change in substrate size near sample site 6S7. Here, finer beach sand has entered site 6S7 two months post-nourishment at the location of forage fish sampling. This location, at a large tributary delta has natural vegetation, log line and prominent accretionary shoreform waterward of the railroad. Unlike sites 2S and 5S, beach nourishment material was still retained within the placement area at the end of the study period. Figure 38 shows a relatively high degree of beach nourishment persistence.



Figure 38. Site 6 at tributary delta downdrift from beach nourishment near forage fish sample 6S7. Pre-project (left photo), two months post-project (center), and 36 months post-project (right photo) shows drift material having entered the site and remaining persistent.

Site 9. Figure 39 highlights the changes over time at nourishment Site 9 in substrate size before project implementation, after beach nourishment, and 35 months post-nourishment. This beach nourishment was placed within sample site 9S7 and was immediately updrift from Site 9N7. Unlike sites 2S, 5S, and 6, this site contained a limited amount of upper beach area where beach nourishment material was retained longer. More notably, immediately downdrift from the placement location, the beach was wider and was shaped by a small creek delta fringed by some riparian vegetation.



Figure 39. Site 9 beach nourishment before project implementation (left photo), beach nourishment (as-built), and in 2019, 35 months post nourishment.

Figure 40 shows the location of Site 9 and initial delineation of beach nourishment material in July 2016. At this time, sand had already drifted right (east) toward the tributary delta right of site 9N7. The persistence of drift material within the bounds of the beach nourishment (polygon) lasted until December 2019, albeit in thin layers. After 42 months (Jan 2020), nourishment material had evacuated the original placement footprint though was still very persistent immediately downdrift on the creek delta. As the estimate of total beach nourishment material placed at this site was greatest, our estimate of the rate of drift was 103 cy/month and relatively similar to other sites.

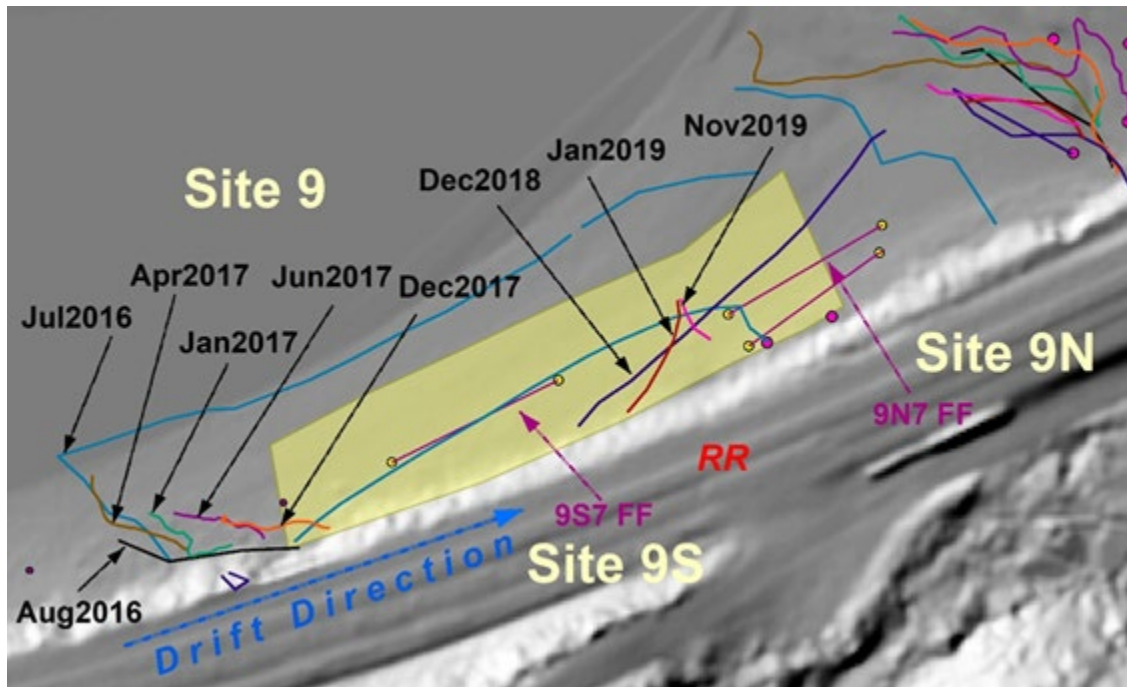


Figure 40. Sites 9S and 9N, shows beach nourishment placement area, initial drift delineation (Jul2016) and drift from left (west) to right (east) by date. Drift material boundary persists on tributary delta fan at right near forage fish sample 9N7. Forage fish sample 9S7 is also shown. Railroad prism is labeled (RR).

Site 9N was unique among all locations in that the drift from beach nourishment (at 9S) added to the back beach extent of the site immediately updrift from the tributary delta and up-slope from forage fish sample site 9N7. Although our observations are anecdotal, the back beach became wider, with greater storage of drifting sand, a higher beach elevation, and greater storage of beach logs as shown in Figure 41.



Figure 41. Site 9N at tributary delta downdrift from beach nourishment near forage fish sample 9N7. Pre-project (left photo), two months post-project (center), and 36 months post project (right photo) shows drift material having entered the site and building up the back beach.

Digital elevation models of beach surface at UW Site 9 (aka SnoCo Site 10), downdrift of Sites 9S and 9N and updrift of Sites 12N and 12S, revealed that following nourishment beach surface decreased in the upper-most regions, at and just waterward of MHW, and increased in the mid and lower regions, down to MLW (Appendix Figs. B12 and B13). Observed elevation decreases

along the upper beach expanded waterward over time (i.e. year three post-nourishment), consistent with slight decrease in overall beach surface from 2018 to 2019. This observation was less exaggerated at Site 9 unarmored and particularly in the most up-drift areas. At this location we note that there was no tributary delta east from Site 10. Sediment, therefore, may mostly have drifted downslope and downdrift to mid and lower regions. Drift line mapping was not conducted at Site 10.

Howarth Park. Howarth Park restoration was unique among beach nourishment sites in terms of scale, treatments, design, and construction. Consequently, changes post-restoration were unique. Results below include photo documentation, monthly delineation of drift, beach profile changes and a depiction of delta-wide changes in elevation post-project using structure from motion (SfM) photogrammetry techniques. The photo panel in Figure 42 shows the pre-project (with rip rap) and as-built conditions. The beach nourishment material has been placed in a delta-like configuration and included large wood placed on top of the beach nourishment. Finer beach nourishment material in the foreground has already been mobilized and dispersed onto the beach terrace and downdrift.



Figure 42. Howarth Park pre-project and as-built (August 2016). Riprap is removed and beach nourishment and beach wood has been placed in delta configuration as shown in Figure 13.

Three years post-restoration, the photo (right) in Figure 43 (June 2019), shows that the delta has eroded landward and large wood has settled from placement on top of the delta (left photo in 2016) onto the eroded beach face.

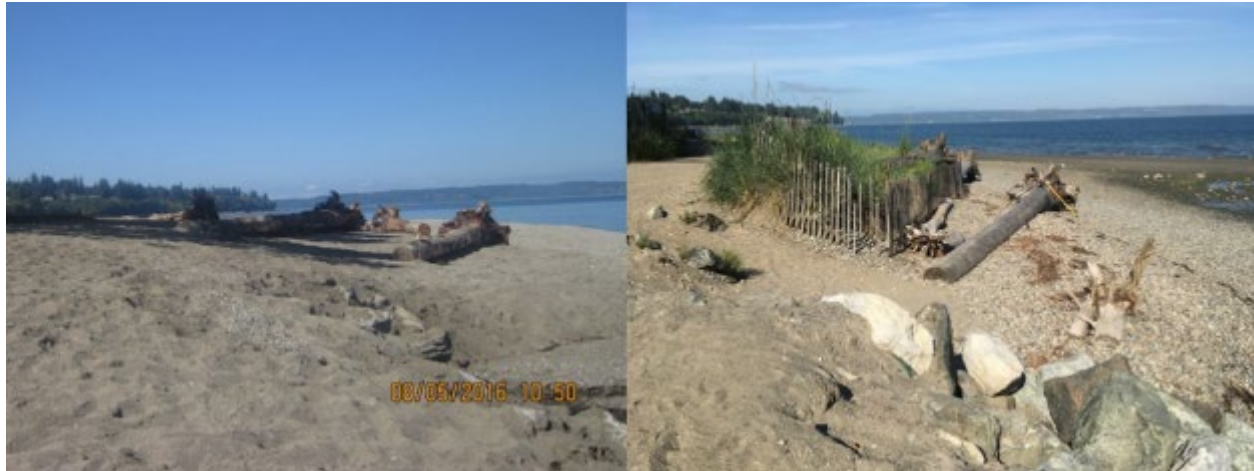


Figure 43. Photo taken from top of creek culvert of as-built (left) and three years post-nourishment (right).

The landward retreat of the beach nourishment at Howarth Park is highlighted in Figure 44. The drift lines show the semi-circular boundary of the delta from the initial nourishment in 2016 (Aug 2016) to 2020 (Feb 2020). As wave action mobilized the beach nourishment material, the delta both flattened onto the beach terrace and retreated landward from an erosion scarp (the delineation) as material was evacuated and moved downdrift from its as-built configuration.

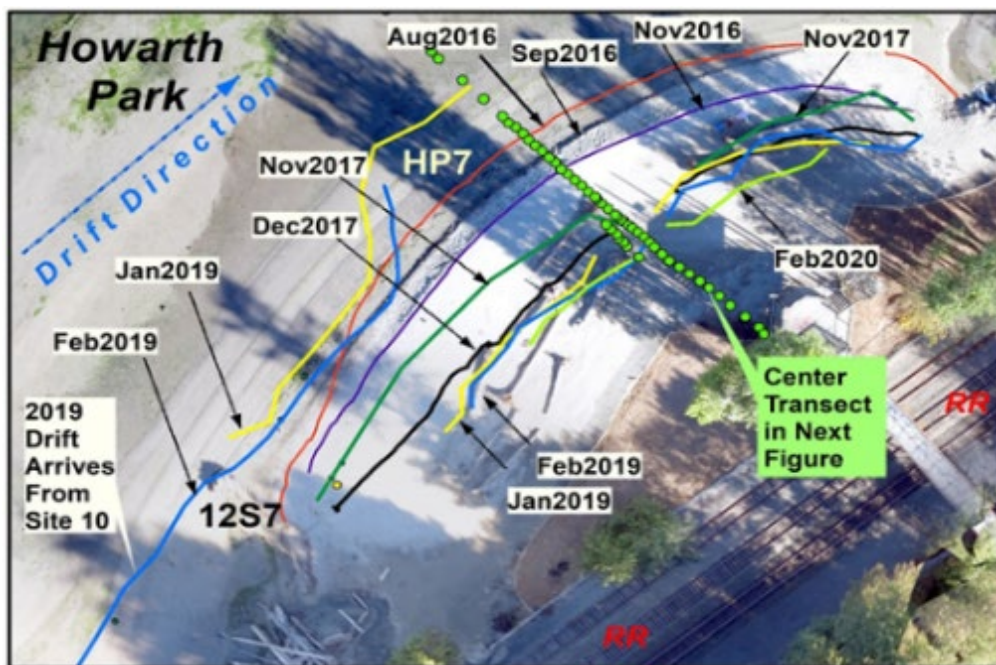


Figure 44. Howarth Park beach restoration and delineation of shifting erosion scarp (by date). The erosion scarp can be clearly seen in the September 2016 photo. By January 2019, new lines were delineated representing supplemental drift from farther updrift, likely from Sites 9 and 10. The center transect showing the beach profile in Figure 45 is shown. HP7 is the location of forage fish sampling post-restoration.

The change in the beach profile due to landward erosion of the delta is confirmed in Figure 45, showing the change in beach profile prior to beach nourishment (2015 and 2016) and post-nourishment (2017). The 2015 and 2016 beach profile measurements highlight the steep riprap beach face at zero (x-axis), as well as the toe of the rip rap in 2016. In 2017, the beach profile shows the placement of beach nourishment material, which by the time of the beach survey had already retreated landward and flattened in a down-beach direction. The position of the erosion scarp and likely elevations are also shown for other dates prior to June 2017, as also shown in Figure 44 above.

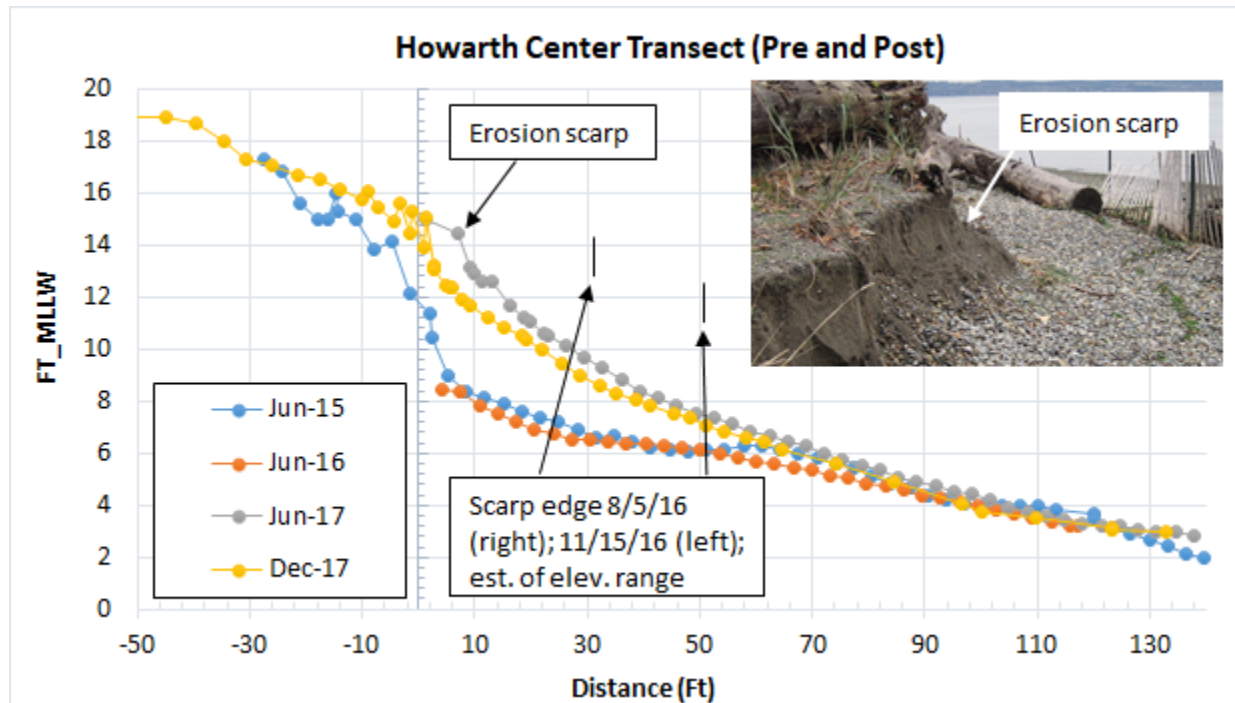


Figure 45. Howarth Park center transect by date, pre-project and post-nourishment.

The beach profile shown in Figure 45 only depicts a cross-section of the vertical change, as the volume of material has been displaced over time. Separately, using photogrammetry we measured surface elevation in 2015 through 2019 at Howarth (Site 13 armored), and downdrift at Site 13 unarmored. Using high resolution digital elevation models, we measured change over time in overlapping beach surfaces. After one year post-nourishment, i.e. 2017, we found that the beach surface increased in elevation across Site 13 armored, with the greatest increase (>2 m) observed along the upper beach and a waterward migration of MHW (Figure 46). Three years post nourishment, i.e. 2019, we found that the increase in beach surface lessened and MHW migrated back up-shore slightly - coupled with a decrease in surface elevations along the lower outer beach (Figure 47). This aligns with observed decreases in beach surface in years after nourishment, i.e. 2017 to 2019 (Appendix Fig. B11).

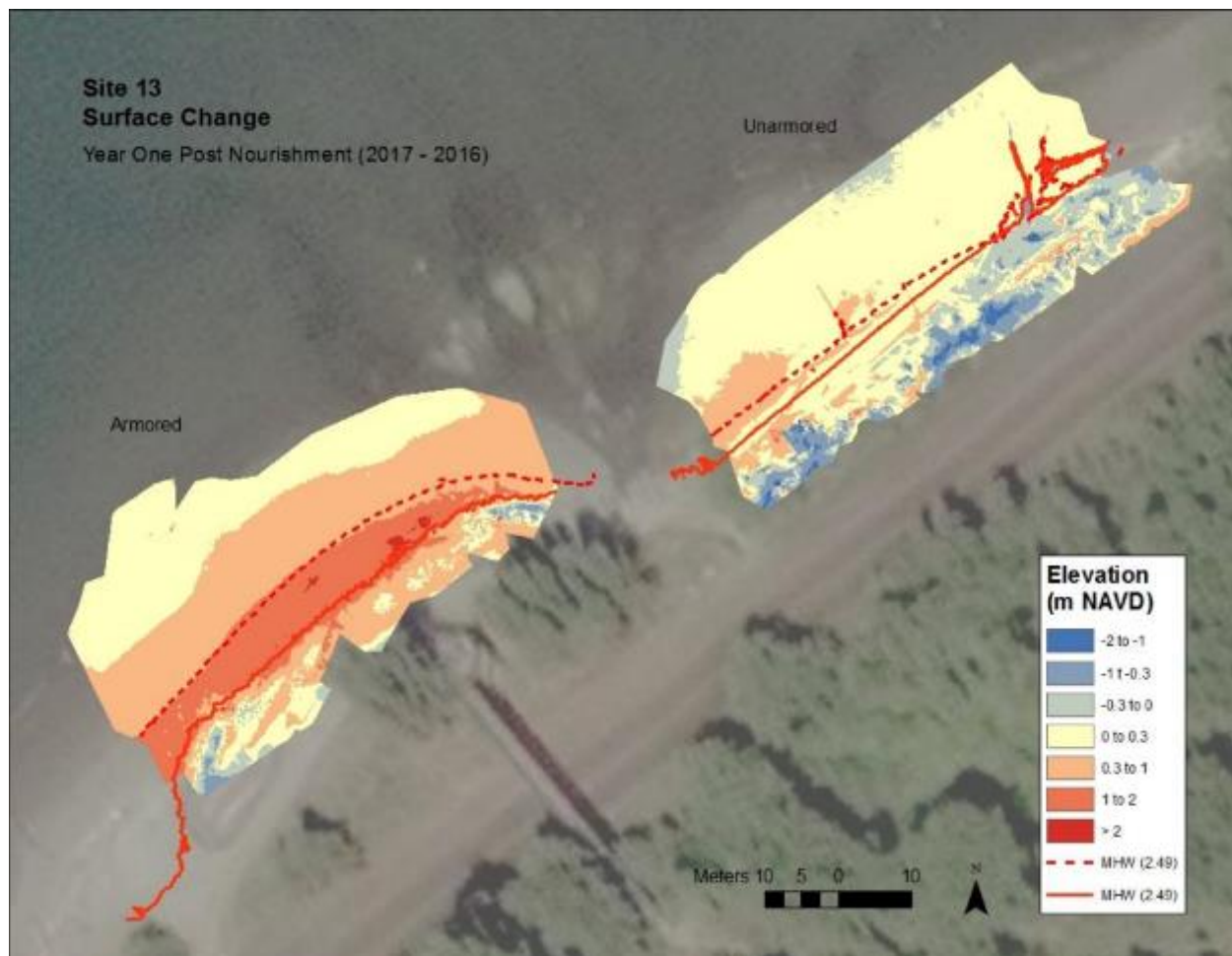


Figure 46. Change in beach surface elevations year one post-nourishment at site 13, in Snohomish County, WA. Change is measured as difference in elevation (m NAVD) $t_{2017} - t_{2016}$. MHW is denoted as a solid line before nourishment, i.e. 2016, and a dashed line after nourishment, i.e. 2017.

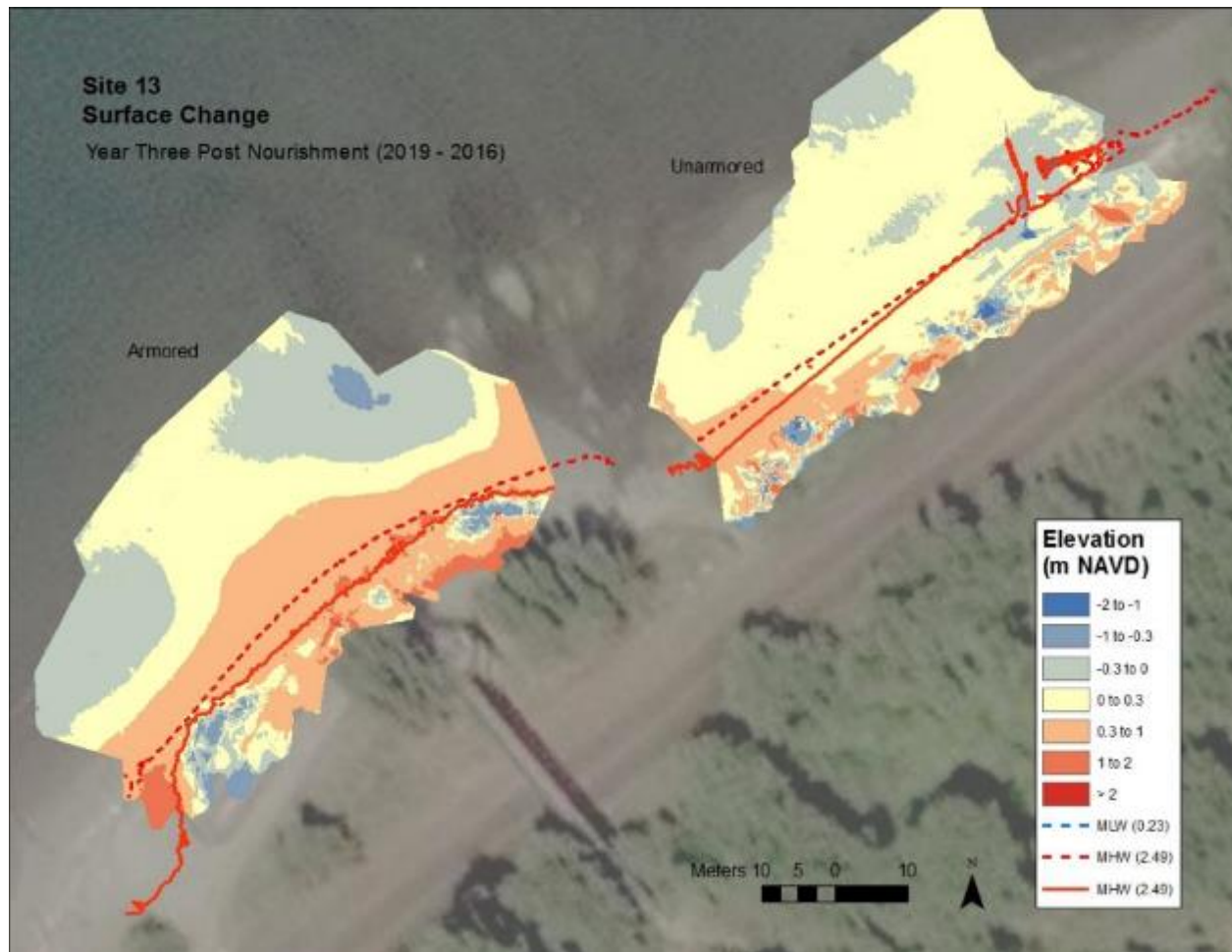


Figure 47. Change in beach surface elevations year three post-nourishment at site 13, in Snohomish County, WA. Change is measured as difference in elevation (m NAVD) $t_{2019} - t_{2016}$. MHW is denoted as a solid line before nourishment, i.e. 2016, and a dashed line after nourishment, i.e. 2019.

The drifting substrate from Howarth Park (aka Site 13 armored) moved toward site 13 unarmored, which in addition to Figures 46 and 47 is seen in a beach profile of Site 13 (Figure 48). This highlights the initially higher beach elevation in 2017 post-nourishment, which is followed by a subsequent reduction in beach elevation by December 2017.

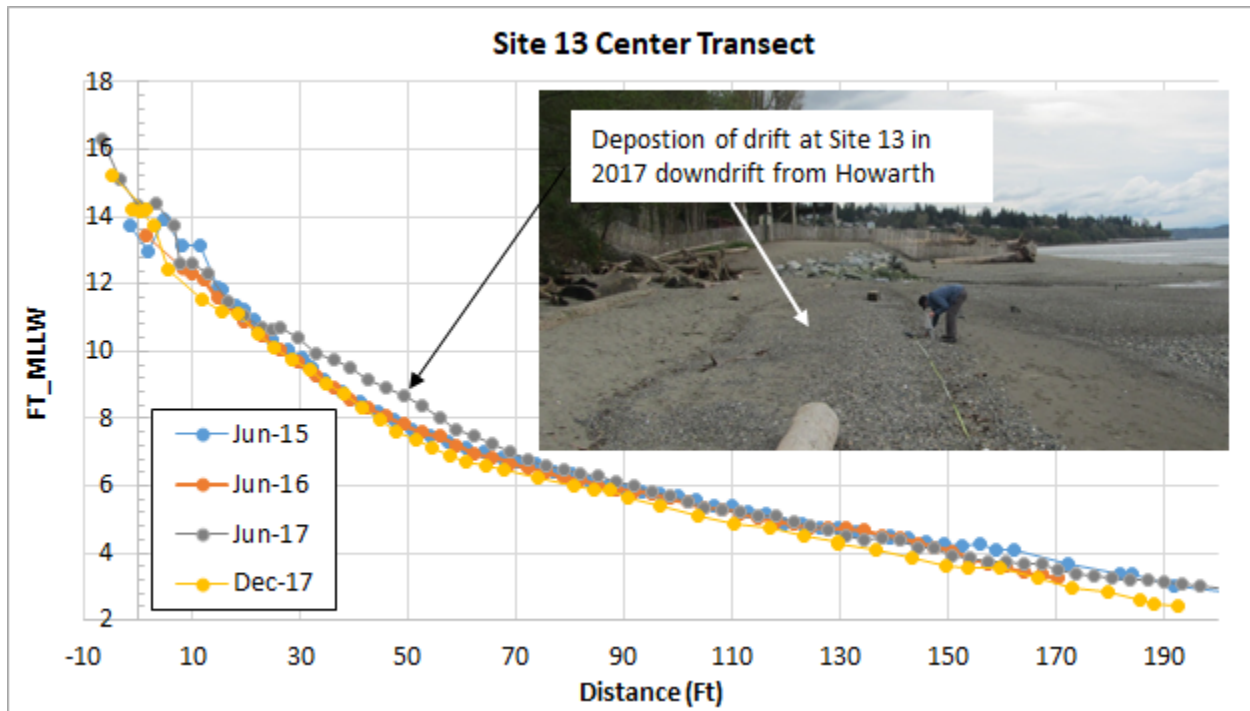


Figure 48. Site 13 center transect downdrift from Howarth Park shows subtle deposition of drift in 2017. Photo is from April 2017, as the June 2017 photo (date of survey) is darkly shadowed.

Site 13, prior to restoration at Howarth Park, was primarily composed of coarse gravel (Appendix Figs. C2 and C3). The mobilization and transport of nourishment material from the restoration footprint changed the surface elevations as noted above, but also delivered much finer substrate downdrift to Site 13 (Figure 49, center photo). However, unlike the other sites (2, 5, 6, 9) discussed above, Site 13 contained no natural accretion shore form to aid retention of nourishment material at Site 13 (refer to Figures 13 and 16). Hence, substrate size in year three (2019) post-restoration was substantially coarser again (Figure 49, right photo).



Figure 49. Site 13S showing the pre-project Howarth Park armored shoreline (in background and updrift of left photo) and post-restoration at Howarth Park (as-built, center) showing drift material. Beach material is substantially coarser after 35 months (right photo).

Identifying the migrating limits of the emplaced material allowed us to map the beach nourishment, track the drift of substrate and estimate rates of drift for some sites, allowing qualitative characterization of persistence of nourishment material in conjunction with site

photos. Among nourishment sites (2, 5, 6, 9, 10 in Table 1), the drift rate of sand varied. We estimated this based on the total loss of sand from the emplacement location over the number of elapsed months. Drift was fastest at Site 2 followed by Site 5, Site 9, then Site 6 and appeared to be an interactive function of shoreform, beach width, beach slope and the elevation of drift placement - determined by the elevation of the beach armor present (Figure 20).

Site 2 had a low elevation of existing beach armor, narrow beach width, higher slope and convex shoreline. Site 5 had higher beach toe, intermediate beach width, intermediate slope, and straight shoreline conducive to longshore transport. Site 6 had lower beach toe and existing armor, but had a wider beach, low slope, and a subtle embayment shoreform (between stream deltas) that may have reduced sediment movement by waves. Site 9 was unique in terms of the more up-beach placement of nourishment. Here the toe of shoreline armoring was higher, the beach was wider, slope was intermediate, and there was some limited back beach area that may have slowed the mobilization and drift over time. Drift data was not collected for Site 10, nor did this site have forage fish or substrate samples.

Persistence of nourishment material over the ensuing three years at downdrift locations, particularly sites 2N7, 5N7, 6S7, and 9N7 was affiliated with small tributary deltas that changed the shape and elevation of the beach face. Site 13 had no accretionary shoreform and hence did not retain finer sediments in the same manner. Our estimate of relative drift rate and persistence are summarized in Section 6.1.6.

6.1.3 Sediment grain sizes

Mean high water. Sediment samples in the upper intertidal were collected for only Nourishment sites 13 and 9. We found that, averaged across sediment samples and survey years, MHW beach sediments were composed mostly of sand (52.2%), followed by pebble (43.8%), granule and cobble (Appendix Table B1). This was true for all sites individually, apart from site 13 armored where a greater percent pebble overall was observed. However, sediment samples at 13 armored were collected only after beach nourishment, and this value does not express pre-treatment conditions. Regardless of site variability in percent size, across survey years sub-surface sediments consistently comprised greater percent sand than corresponding surface sediments (Figure 50). Patterns of strata effect were less apparent, and dominant MHW substrate size varied between sites. At site 9, sediments collected at the armored location exhibited greater percent sand than the unarmored pair; in contrast to site 13 where greater percent sand was exhibited at the unarmored location.

Following treatment of sites with beach nourishment, percent of surface and sub-surface sand at both armored and unarmored locations increased (Figure 51). Again, no MHW samples were collected at 13 armored prior to nourishment and we could not draw conclusions with regard to pre-treatment conditions. Looking closer at post-treatment years 2017, 2018 and 2019, we observed moderate inter-annual variability in MHW grain size composition across the surface and sub-surface at all sites apart from 13 armored, where changes were minimal. For example, at sites 13 and 9 unarmored percent sand increased greatly the first year post-treatment, i.e. 2017, but slowly lessened each successive year to near pre-treatment conditions (Figure 52 and

53). However, at site 9 armored, initial increase in percent sand was small and increased generously in years 2018 and 2019.

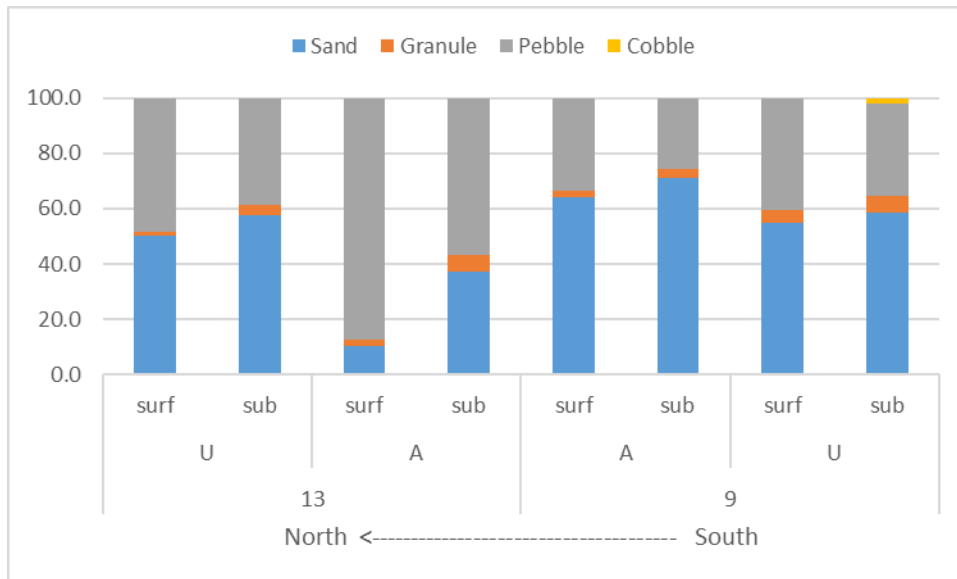


Figure 50. Sediment grain size composition by percent total weight at Nourishment Region sites 13 and 9 in Snohomish County, WA. Values are averaged across survey years, 2015 to 2019. Sediment sizes are binned by sand (< 2mm), granule (2 - 4 mm), pebble (4 - 64 mm) and cobble (> 64 mm). Arrow indicates direction of drift.

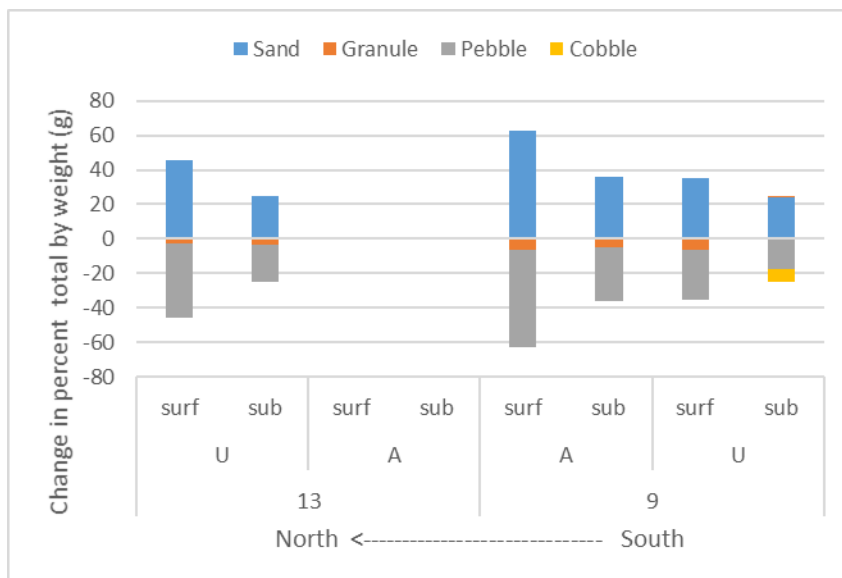


Figure 51. Average change in sediment grain size composition (% by weight) measured before (2015-2016) and after (2017 - 2019) beach nourishment at sites 13 and 9, in Snohomish County, WA. Sediment sizes are binned by sand (< 2mm), granule (2 - 4 mm), pebble (4 - 64 mm) and cobble (> 64 mm). Note that no sediments were collected at site 13A prior to nourishment because MHW was inaccessible due to the waterward extent of armor. Arrow indicates direction of drift.

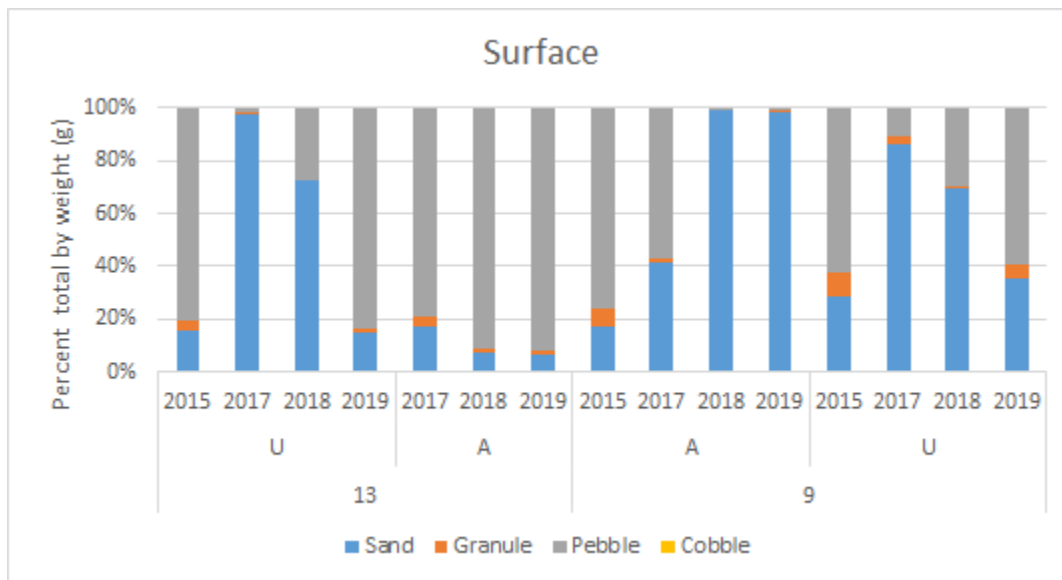


Figure 52. Surface sediment grain size composition by percent total weight. Samples were collected at MHW at Nourishment Region sites 13 and 9 from 2015 to 2019, in Snohomish County, WA. Sediment sizes are binned by sand (< 2mm), granule (2 - 4 mm), pebble (4 - 64 mm) and cobble (> 64 mm).

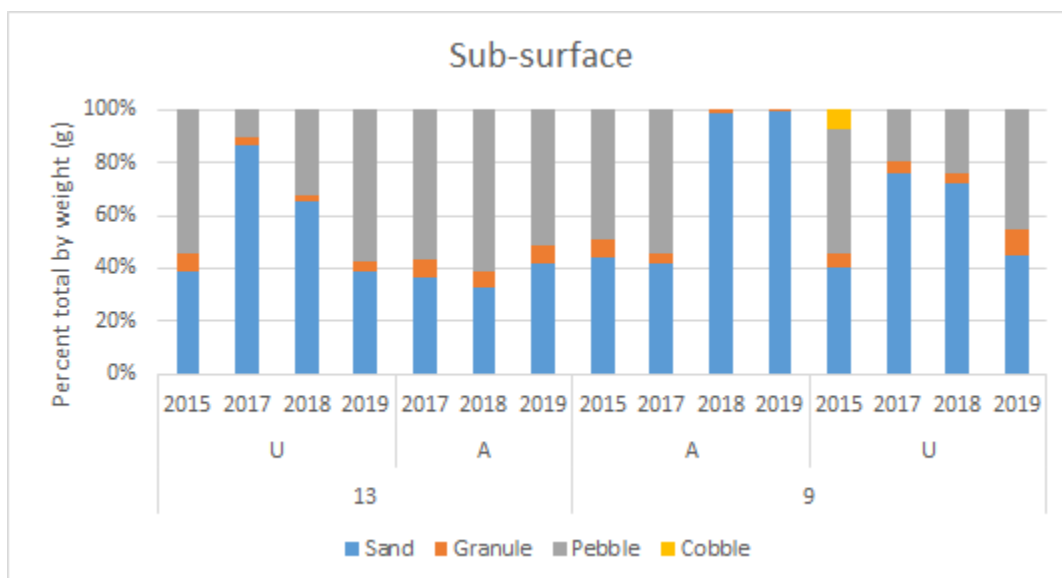


Figure 53. Sub-surface sediment grain size composition by percent total weight. Samples were collected at MHW at Nourishment Region sites 13 and 9 from 2015 to 2019, in Snohomish County, WA. Sediment sizes are binned by sand (< 2mm), granule (2 - 4 mm), pebble (4 - 64 mm) and cobble (> 64 mm).

Sediment samples collected at MHW were also looked at for size suitability for forage fish spawning. The dominant spawning substrate size for surf smelt is 1 - 7 mm, and for Pacific sand lance is 0.2 - 0.4 mm (Penttila, 2007). We found that, averaged across sites and survey years, the greatest percent composition of forage fish sediments was found at unarmored locations;

this was the case for both surf smelt and sand lance substrates. In accord with finer sediments observed across sub-surface samples, we found that these samples contained greater amounts of forage fish sediments than surface samples. For the most part, all samples contained greater percent surf smelt than sand lance substrate, but this could be a simple reflection of surf smelt suitable substrate covering a wider range of sediment grain sizes. Following beach nourishment, percent forage fish substrate decreased on average across sites and post-treatment survey years; however, this varied by site, sample and sediment class, i.e. surf smelt versus sand lance. Site 9 armored and unarmored decreased overall in percent forage fish sediment, with a slight increase measured within the sub-surface sample collected at 9 unarmored. At Site 13 unarmored, surface sediments increased in percent suitable forage fish substrate, while the sub-surface sediments decreased (Figure 54). Across most samples, the magnitude of change either positive or negative was greater for surf smelt substrate, which drove overall calculations of change in forage fish sediments, e.g., smaller increase in percent sand lance substrate negated by greater decrease in surf smelt substrate. Finally, percent sediment grain size by forage fish substrate demonstrated similar interannual variability as that observed by percent sand and pebble (Appendix Figs. B25 and B26), e.g., greater increases in sand lance suitable substrates at site 9 armored in later survey years 2018 and 2019.

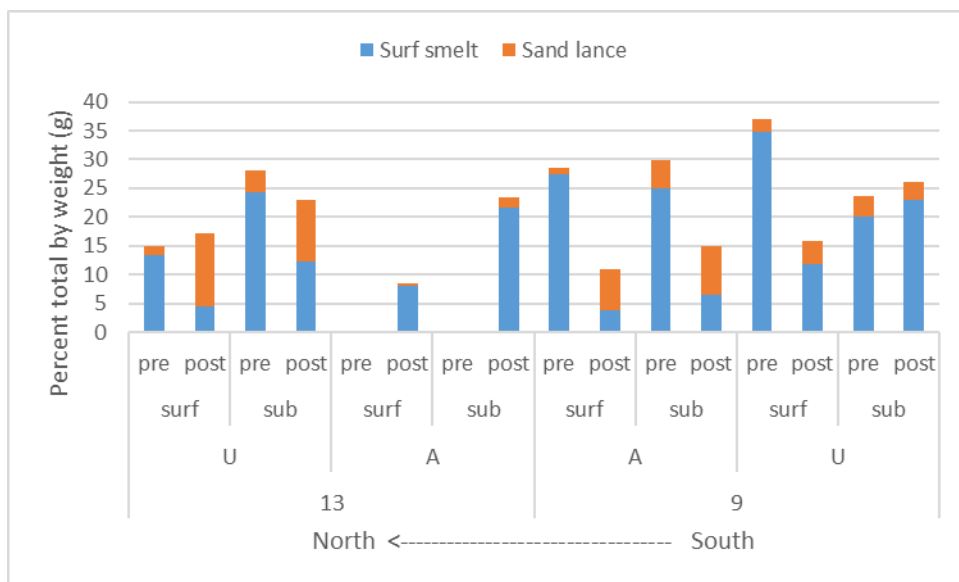


Figure 54. Average sediment grain size composition by percent total weight measured before (pre), i.e. 2015-2016, and after (post), i.e. 2017 - 2019, beach nourishment at North sites 13 and 9, in Snohomish County, WA. Sediment samples were collected at MHW (or highest accessible beach) at surface (surf) and sub-surface (sub). Sediment sizes are binned by forage fish suitable substrates for surf smelt (1 - 7 mm) and Pacific sand lance (0.2 - 0.4 mm). Arrow indicates direction of drift.

Wrackline. In the wrackline, which was generally slightly higher on the beach than MHW, proportion of sediment sizes in the sand category actually decreased over time at the armored Nourishment sites, particularly at Sites 13 and 6 (Table 4, Figure 55, and Appendix Figure A2). There was an initial increase in sand post-nourishment, but this decreased with time at both armored and unarmored sites, returning to baseline levels at the unarmored sites after Year 3.

Thus it seems that sand washed away faster at the armored sites, and that sand was better maintained and/or drifted into unarmored sites.

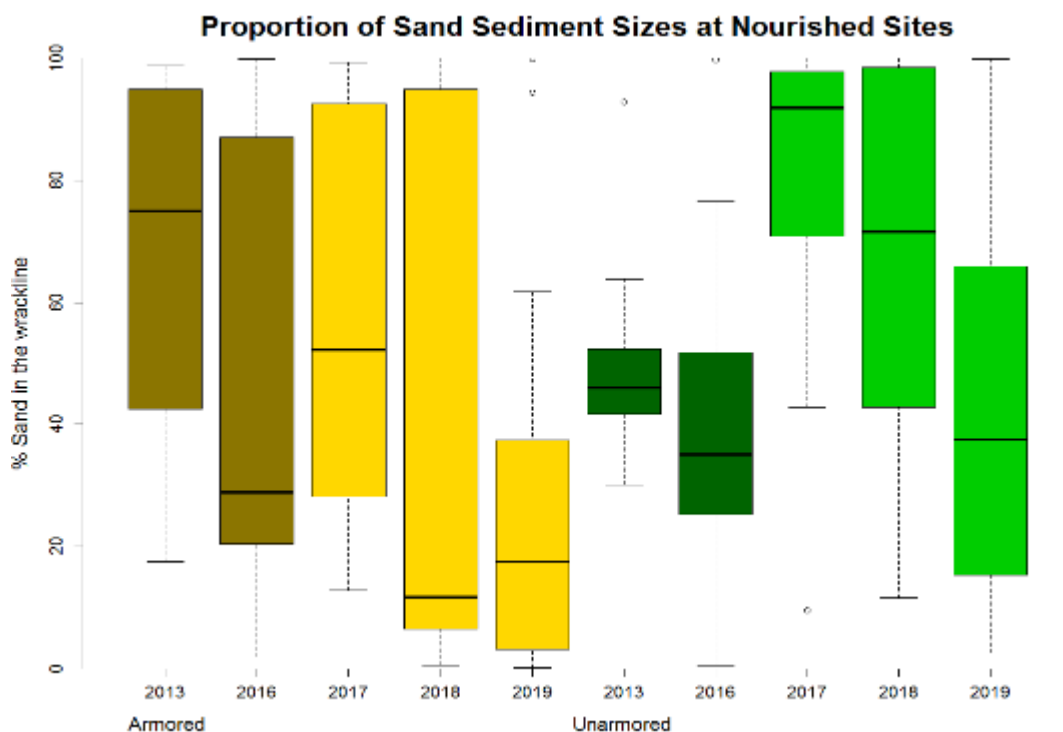


Figure 55. Boxplots of the proportion of sand sediment sizes in the wrack at armored and unarmored Nourishment sites. For all graphs at Nourishment sites, golden colors are at armored sites, green colors are at unarmored sites, including Sites 2, 6, 9, and 13. Darker shadings of colors are before nourishment, and lighter shadings are after nourishment. Bars represent combined data from all 4 sites, graphs of all sites are in the appendices. Upper and lower hinges of the boxplots represent first and third quartiles, the midline is the median, the whiskers are points within 1.5x interquartile range, and dots represent data outside of 1.5x interquartile range.

Mean low water. Sediments at Mean Low Water changed in some parallel ways to those in the wrackline. In general, few impacts of shoreline armoring have been detected down the beach face below the wrackline, even in our very broad study around the Salish Sea (Dethier et al. 2016). However, we did find a 'signal' of beach restoration in the Nourishment Region at Mean Low Water (roughly halfway down the shoreface). Figure 56 illustrates changes in surface sand across the 4 years with complete data (other sediment sizes are illustrated in Appendix Fig. A1). While some beaches showed little change through time (Site 13 Armored, Site 6 Unarmored), most showed a substantial increase in abundance of sand between June 2016 (before nourishment) and June 2017 (11 months after nourishment). At some sites (e.g., Site 9) this sand persisted over the following 2 years, while at others (e.g., Site 13U, 2A) it disappeared, either rapidly (by 2018) or more slowly (by 2019). These data suggest that some of the emplaced sediments moved down the shore to the mid zone, but then generally did not persist through the duration of the monitoring.

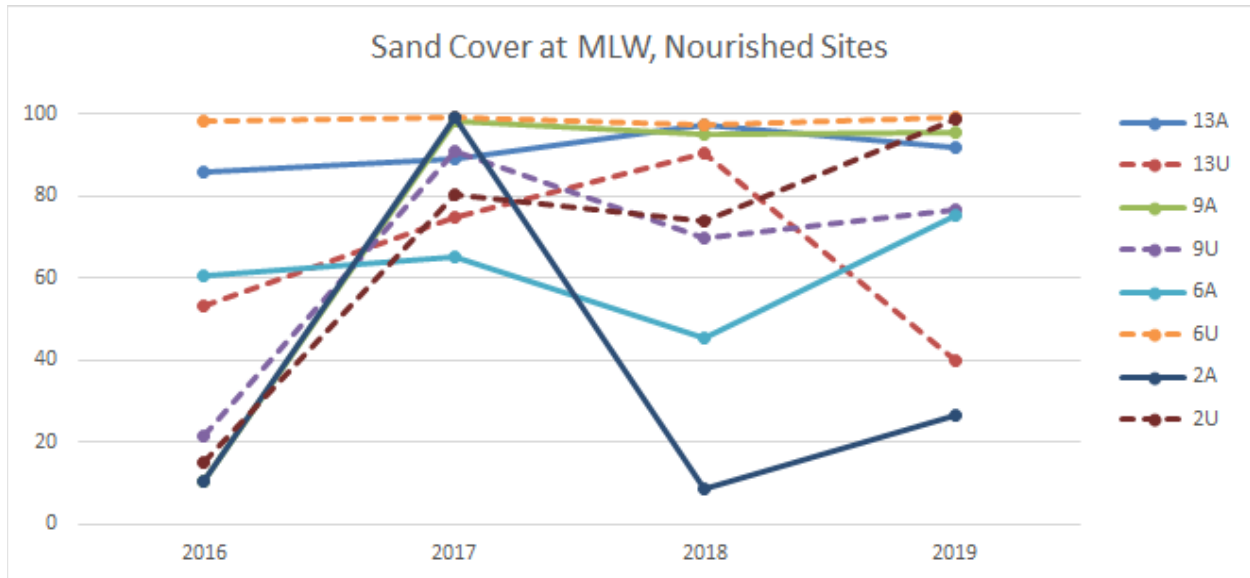


Figure 56. Percent cover of sand at the surface of quadrats at MLW. Each point is the average from 10 samples along the transect. Unarmored sites are shown with dashed lines.

Figure 57 shows similar patterns in a multivariate analysis of data from small quadrats that quantified both surface and subsurface sediments at MLW. In these and subsequent multivariate plots, points closer together indicate greater similarity, in this case of the relative proportions of sand, granules, pebbles, and cobbles. This figure shows, for example, that the sediments at Site 9 before nourishment (2013 and 2016) were quite similar, but after nourishment these points shifted to the left. BACI analyses of these data showed significant effects of Time (Before vs. After) and of Treatment (Armored vs. Unarmored), and an interaction between Site and Time, but no interaction of Treatment and Time - i.e. the sediments changed similarly on both Armored and Unarmored beaches following nourishment. An overall analysis of these Before-After changes for all sites indicate that differences were driven by an increase in sand cover from 56 to 71% on average, and a decrease in pebbles from 27 to 12%. The high variation in sediments at Site 2 visible in the scattered points may be indicative of inadvertent changes in transect location, described above.

Nourished Sites Sediments Small Quads

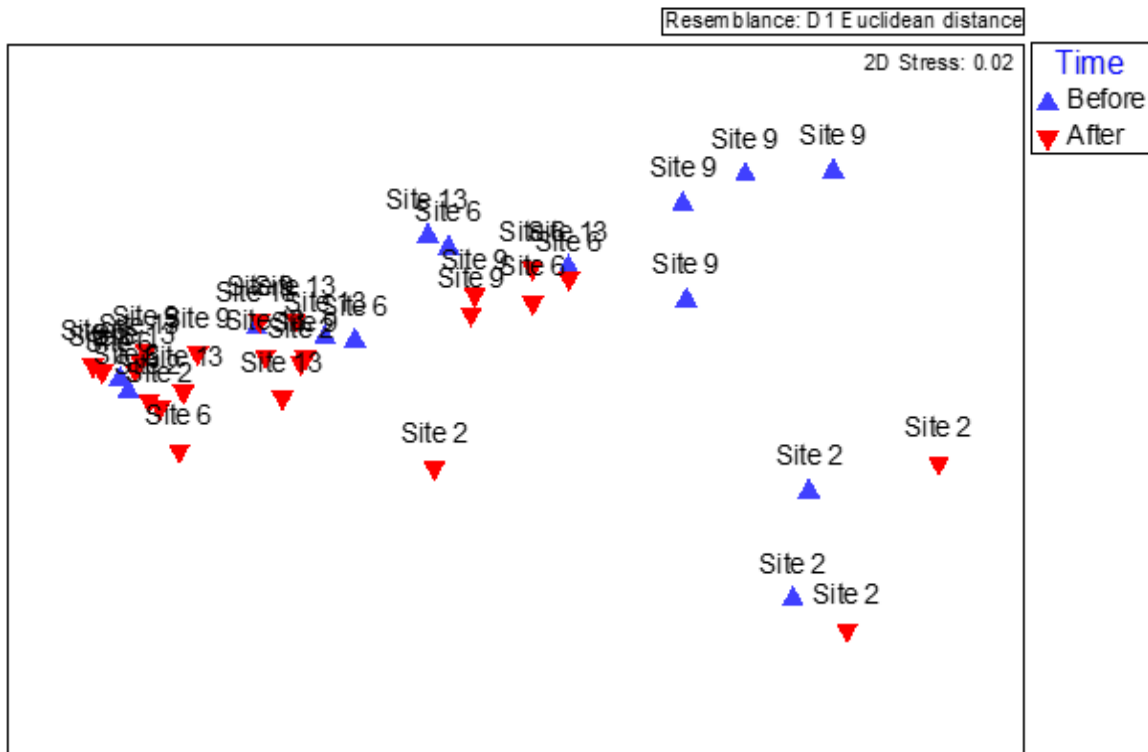


Figure 57. Non-metric multidimensional scaling (NMDS) plots of surface and subsurface (averaged) sediments at the Nourishment sites on each sampling date. Each point represents the sediment composition (relative abundances of 4 different grain sizes) across one transect (3 samples averaged) in one year. Points closer together indicate more similar sediment composition.

6.1.4 Wrackline sampling: logs, wrack, and pitfall traps

Effects of sediment nourishment were seen in the wrack and loglines of the upper beaches of armored sites (Figures 58-62). Total wrack percent cover (as measured with quadrats) and depth of the wrack both showed an increase post-nourishment at armored sites, particularly at Site 13 (although Site 2 did see a decrease in percent wrack) (Table 4). Wrack percent composition was a mixture of algae, eelgrass, and terrestrial sources, with small amounts of human debris (Appendices). Unarmored sites typically had more terrestrial input. Number of logs also increased, particularly at Site 13 and Site 6. There was no nourishment effect in width of the wrack line.

Table 4. P-values for analysis at Nourishment sites. Bold indicates $p < 0.05$. The interaction term is indicative of a nourishment effect (BACI). Strata = armored versus unarmored; Period = before and after nourishment.

Positive results shaded in blue (interaction, nourishment effect).					
Negative results in orange (Arm-Un differences become more extreme after nourishment).					
	Site	Strata	Period	Interaction	Site interactions and other notes
Total % wrack	7.81E-06	2.20E-16	0.8408	0.007	Site 13 up, Site 2 down
Wrack width	4.65E-08	< 2.2e-16	3.85E-01	0.28	
Wrack depth	0.00141	1.11E-14	0.45	0.004	Site 13
Log number	3.01E-05	2.20E-16	0.24	0.02	Site 13, Site 6
Log width	0.001	2.20E-16	0.31	0.13	
Wrack total inverts	0.03	1.59E-06	0.03	1.36E-04	Site 9, Site 6, Site 2
Pitfalls total inverts	0.03	0.03	0.14	0.20	interaction of strata x elevation significant, high elevation more inverts at UN
Sediments, %sand	0.002	0.27	0.27	0.001	Sites 13 and 6

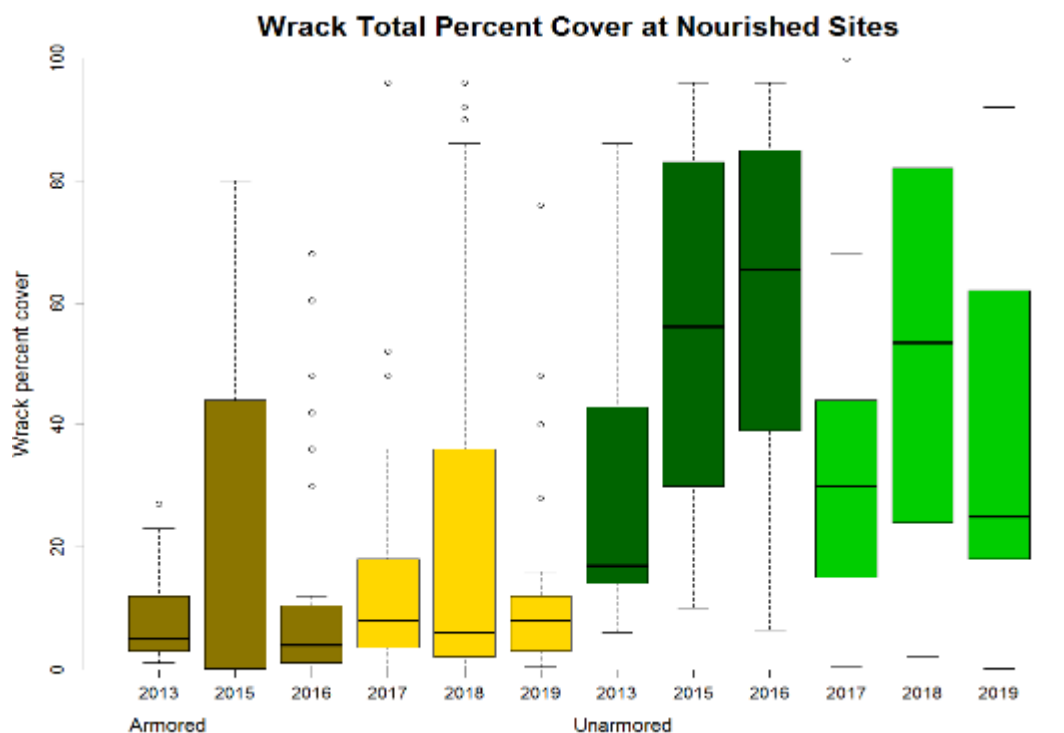


Figure 58. Wrack total percent cover at armored and unarmored Nourishment sites. Darker shadings of colors are before nourishment, and lighter shadings are after nourishment (graph details same as in legend for Figure 55).

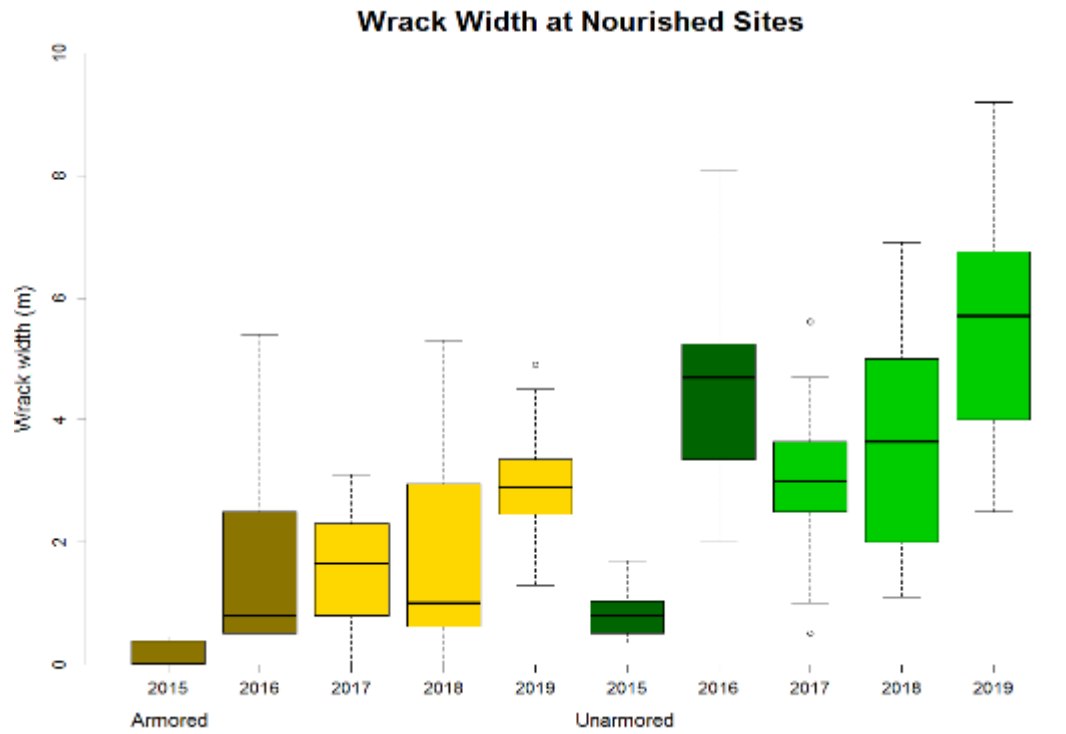


Figure 59. Wrack width (m) at armored and unarmored Nourishment sites.

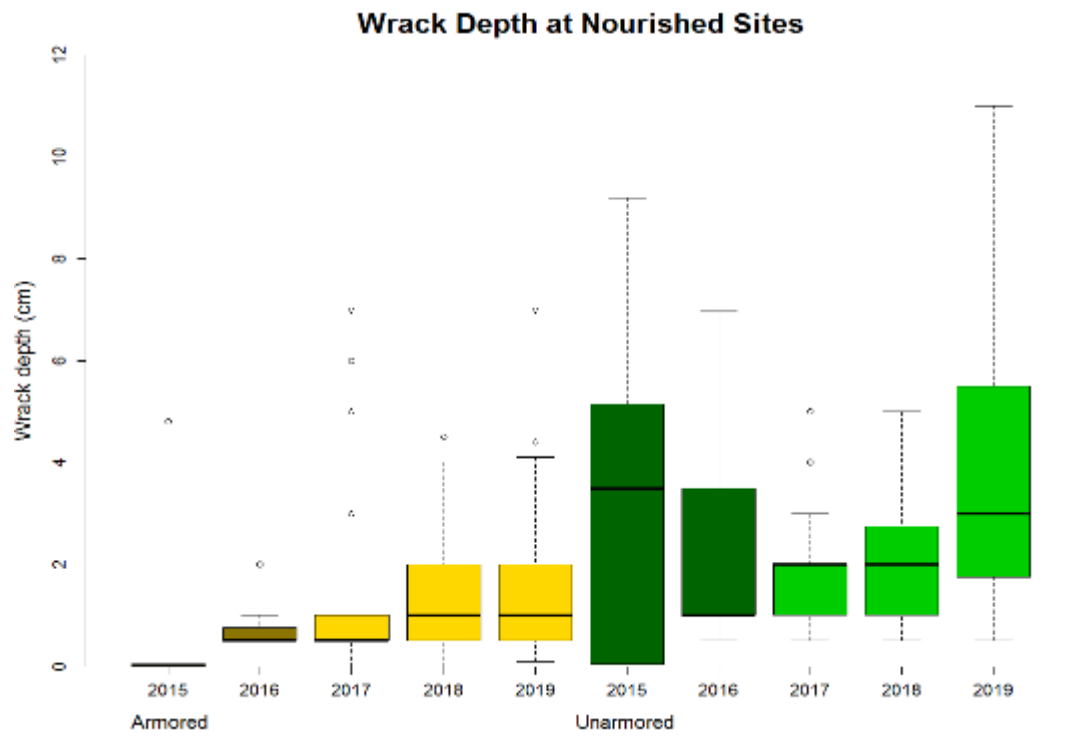


Figure 60. Wrack depth (cm) at armored and unarmored Nourishment sites.

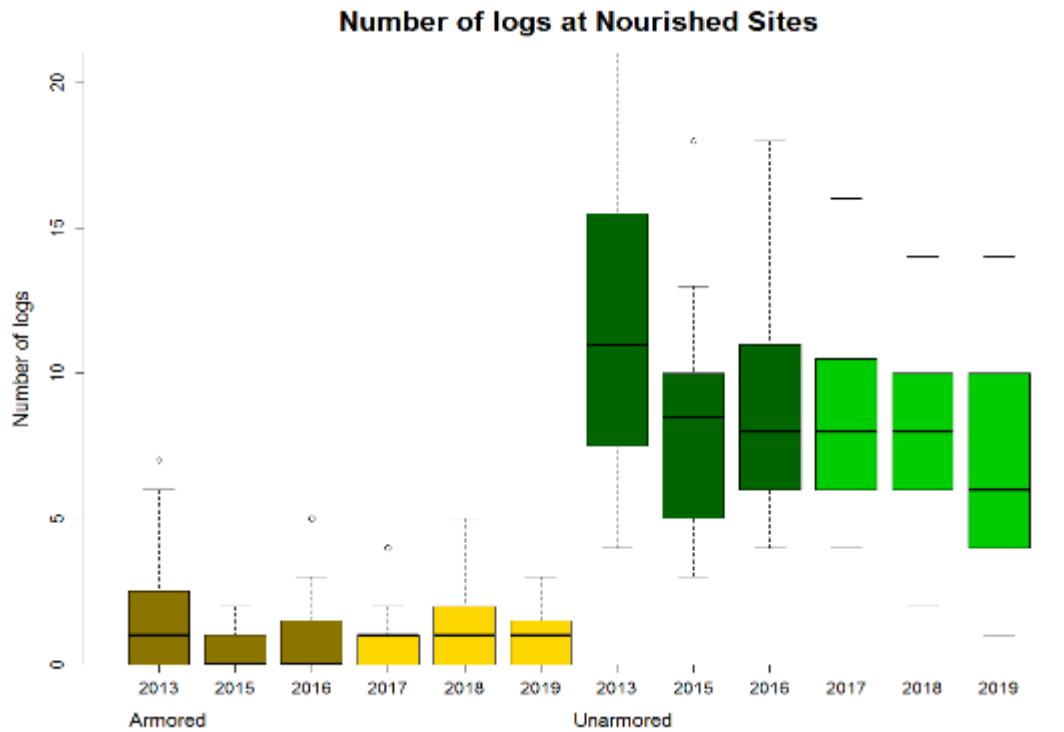


Figure 61. Number of logs at armored and unarmored Nourishment sites. (Site 13 is the main site driving increase at armored; Appendix A).

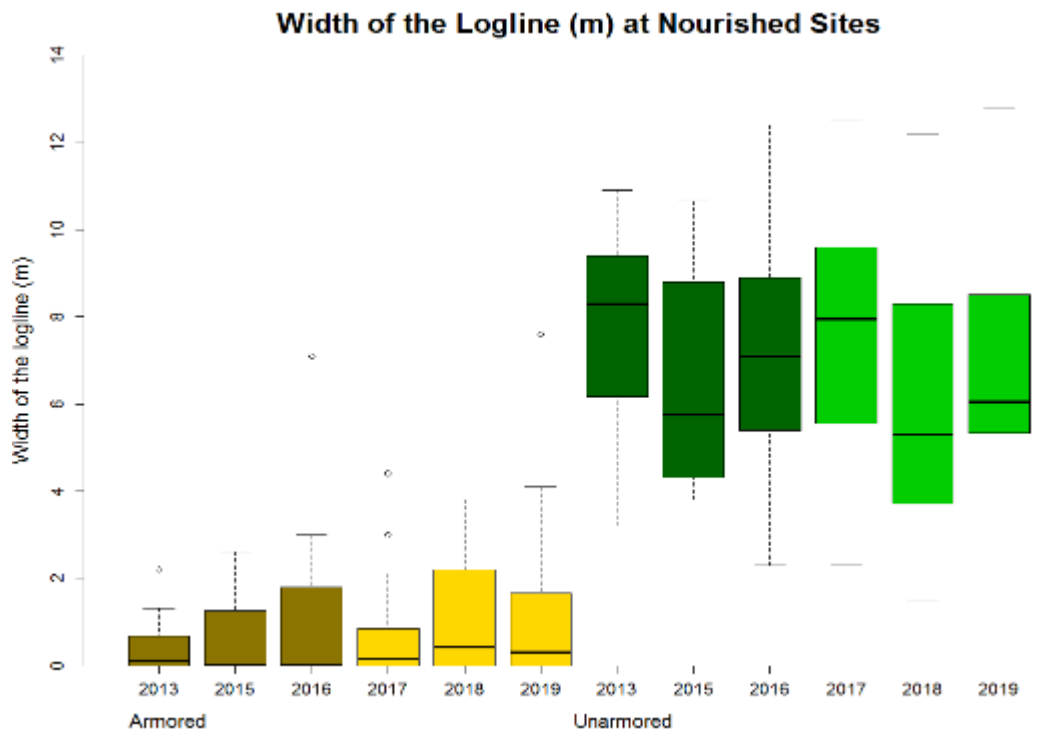


Figure 62. Width of the logline (m) at armored and unarmored Nourishment sites.

The positive effects of nourishment seen in most wrack parameters were not seen in the wrack invertebrates. Invertebrates sampled with cores showed a decrease in numbers at armored sites, particularly at Sites 9, 6, and 2 (Figure 63, Table 4). Mobile invertebrates sampled with pitfall traps showed no effect (Figure 64). It is possible there is a negative placement effect immediately after adding sediment, except for with collembolans, which were abundant after initial nourishment in 2017 (these are fast colonizers that hop along surfaces; appendices). Beachhopper (talitrid) amphipods became more abundant with time post nourishment (they inhabit sediment and under wrack; appendices). In the pitfall traps, there was also an interaction effect of strata x elevation, in that high elevations at unarmored sites had more invertebrates, an elevation that was truncated with riprap at armored sites.

Overall, Figures 63-64 also clearly illustrate the persistent significant differences between armored and unarmored strata, typical of generally lower values of numerous biotic parameters at armored sites found in previous studies (Dethier et al. 2016). These differences did not vanish with nourishment, even though there were some improvements as stated above compared to pre-nourishment.

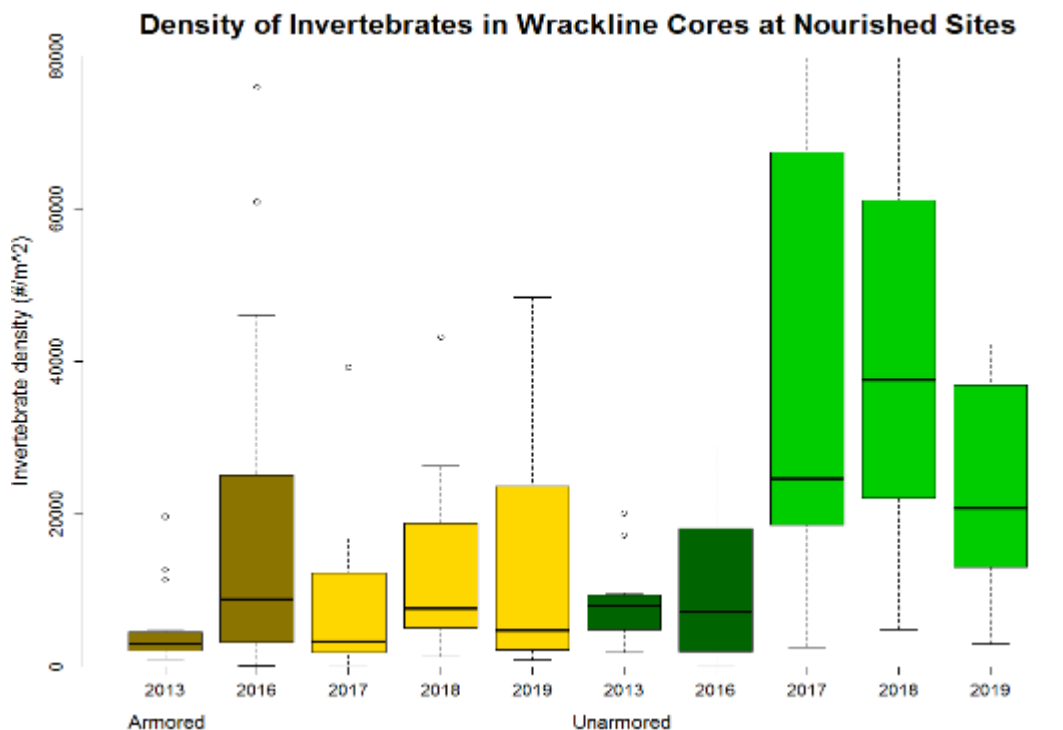


Figure 63. Density of invertebrates in wrack core samples at armored and unarmored Nourishment sites.

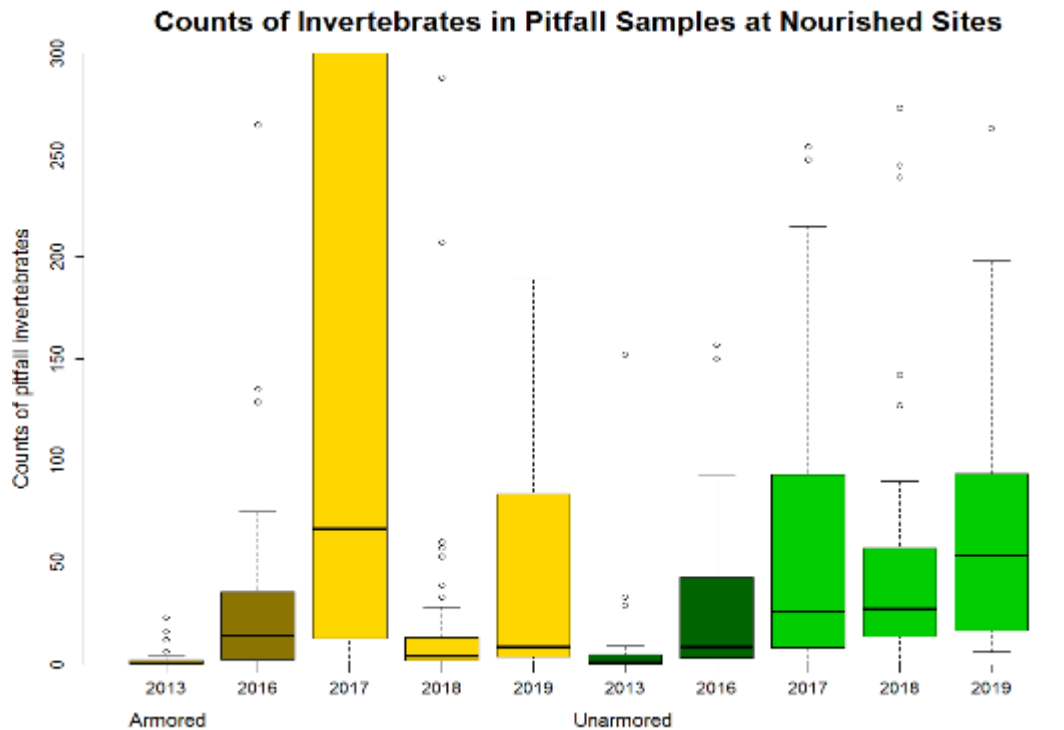


Figure 64. Counts of invertebrates in pitfall samples at armored and unarmored Nourishment sites. The large yellow bar in 2017 reflects an influx of collembolans (springtails, small arthropods that hop along surfaces).

Monthly sampling of the wrack line, post-nourishment from June 2017 - October 2019 by WSU Snohomish County Extension Beach Watchers volunteers (Figures 65-67) specific to Site 13, showed that our extensive June sampling was fairly representative of patterns across the year. Month was not a significant factor for total percent wrack or wrack depth, but was significant for width of the wrack line, with broader wracklines later in the summer and early fall when there was a large spread of broken down wrack on the beach face (Table 5). Strata (armored vs. unarmored) was significant with higher values at unarmored for total percent wrack and wrack width, but not for wrack depth, which largely corresponds to the results from our yearly June sampling (represented in Appendix A figures for Site 13).

Table 5. P-values for strata and month analysis of the beach wrack at Site 13 from June 2017 to October 2019. Bold indicates $p < 0.05$.

	Strata	Month
Total % wrack	9.43E-08	0.10
Wrack width	1.20E-06	4.01E-09
Wrack depth	0.09	0.79

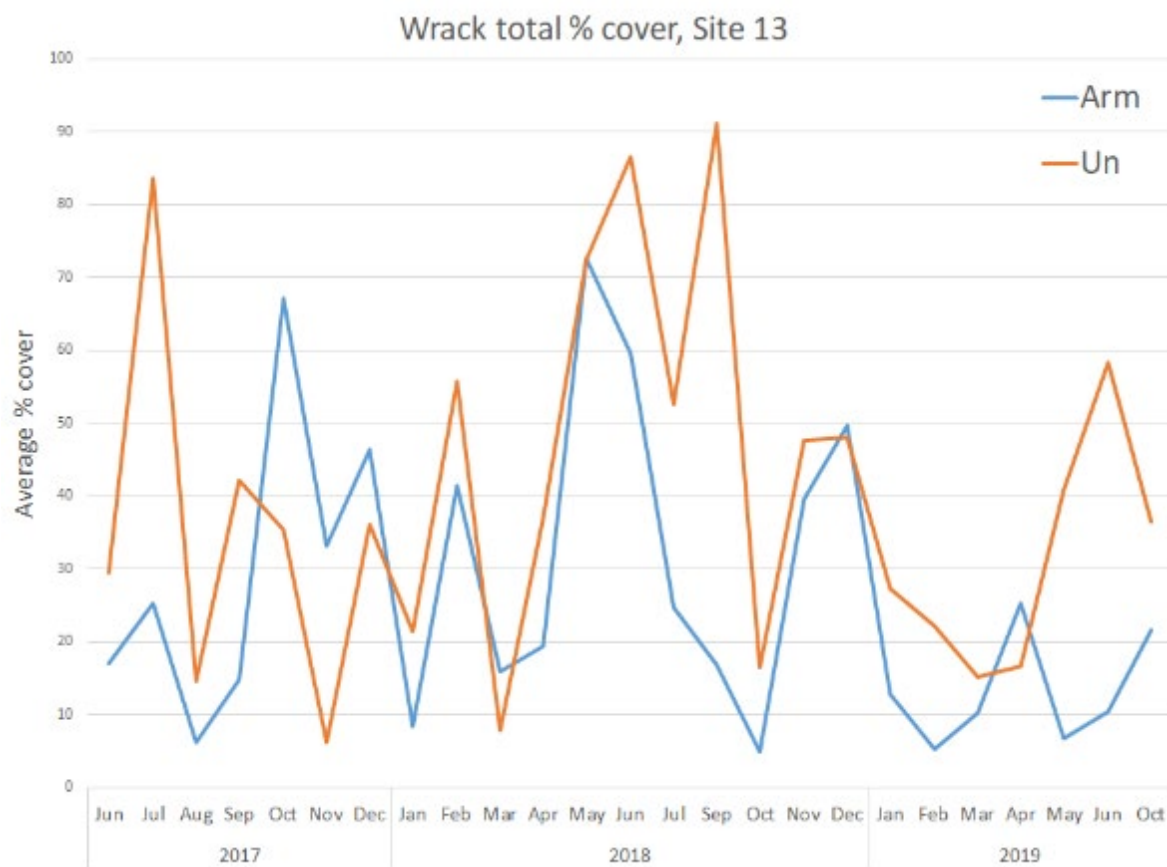


Figure 65. Wrack total percent cover, post-nourishment monthly sampling at Nourishment site 13 armored and unarmored.

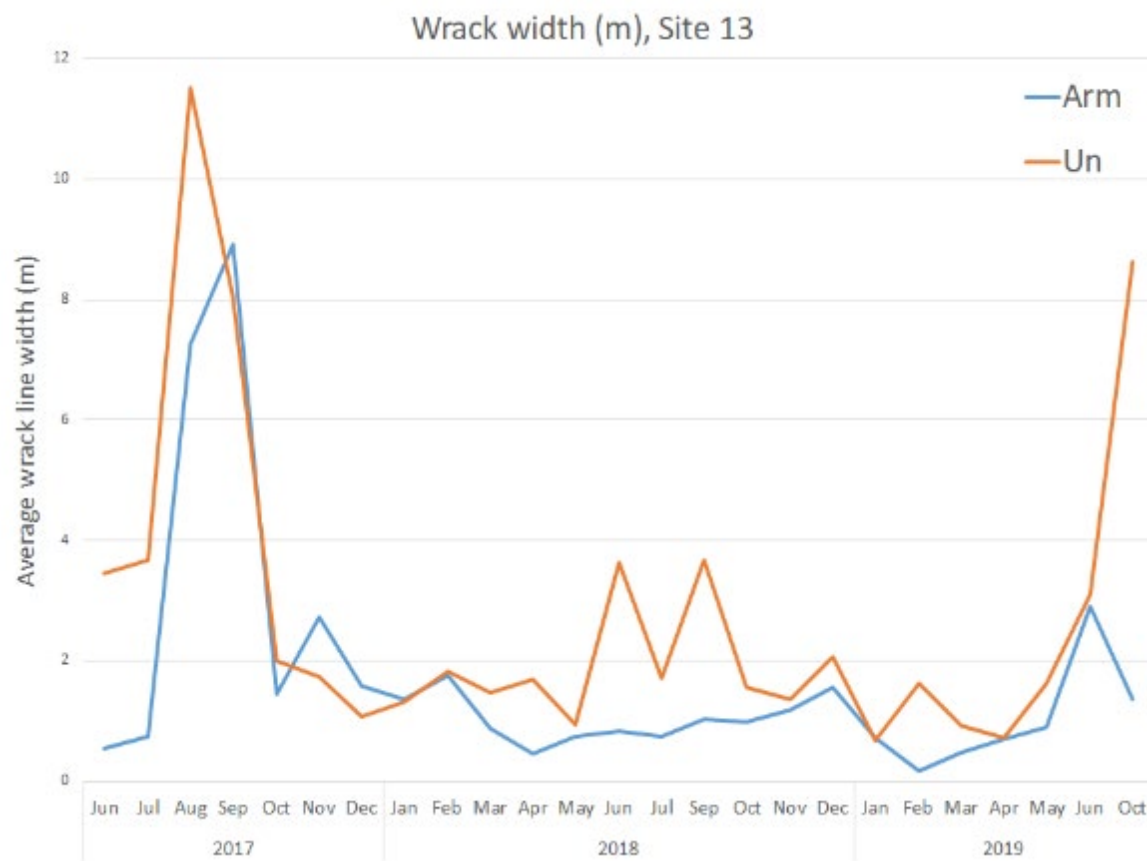


Figure 66. Wrack width, post-nourishment monthly sampling at Nourishment site 13 armored and unarmored.

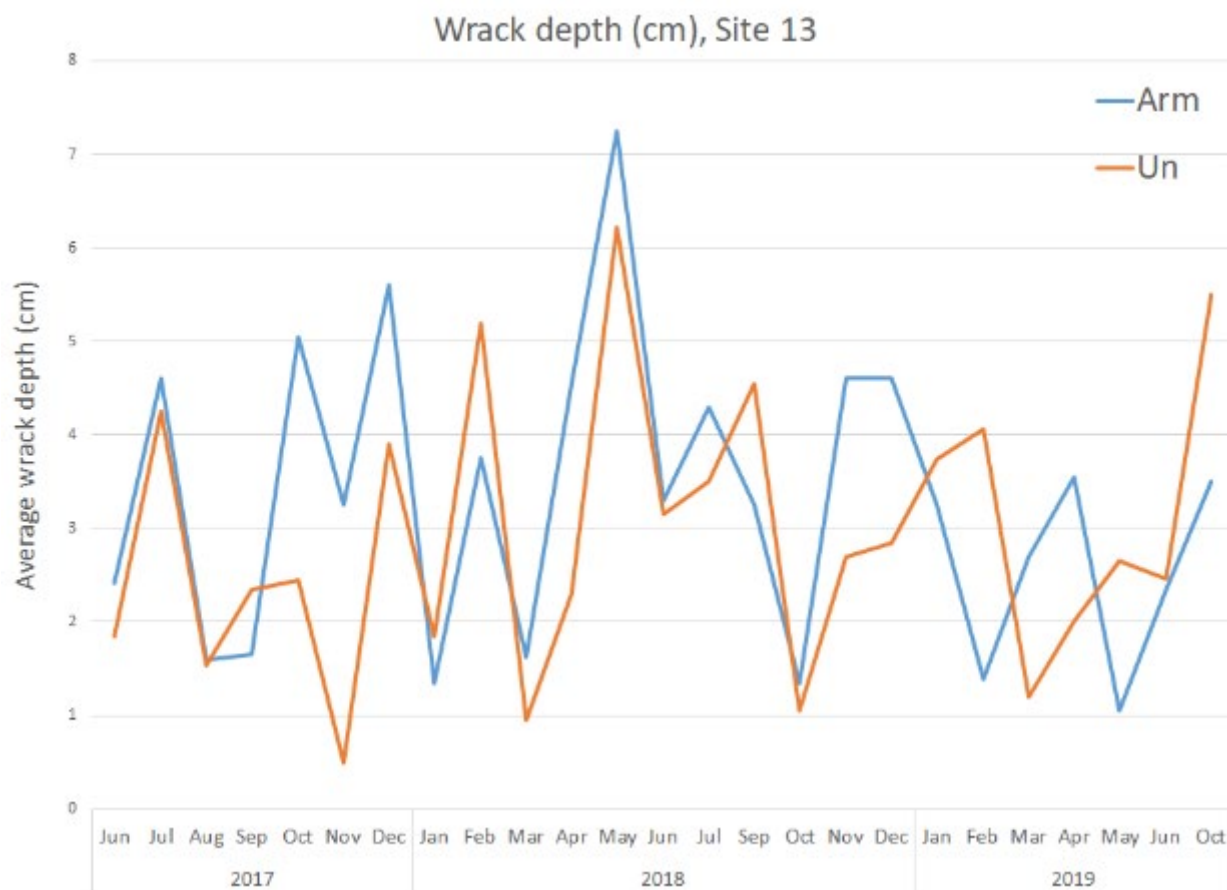


Figure 67. Wrack depth, post-nourishment monthly sampling at Nourishment site 13 armored and unarmored.

6.1.5 MLW sampling: surface biota and infauna

Accompanying the documented sediment shifts at MLW following nourishment were some clear changes in the biota at the Nourishment sites. Overall, biotic communities at this mid-shore elevation are not very diverse. When relatively stable cobble or large pebbles are present, surface flora and fauna consist of green ulvoid algae and barnacles, with some shore crabs and littorinid snails. When no stable rocks are present, the surface biota is very depauperate. Infauna are limited relative to communities lower on the shore, consisting of a few predatory and deposit-feeding polychaete species, gammarid amphipods, and sometimes ghost shrimp.

Figure 68 illustrates overall patterns of biotic communities at these sites both Before (2016) or After (2017-2019) nourishment. Each point represents the surface and infaunal community averaged along the transect on one sample date. Armored and unarmored beaches per site are indicated with an A or U. There were no clear directional shifts through time (i.e. the colored symbols do not shift position in concert), which likely relates to the sediment composition initially shifting to more sand but then shifting back again. However, in general the biota on the beaches Before nourishment were fairly similar (blue points are clumped; overall multivariate similarity of

47%), whereas After nourishment the points are more scattered (similarity of only 31%), indicating greater variation in communities. Changes that drove this shift were decreases post-nourishment in a variety of species that live on or under surface cobbles, such as ulvoid algae, barnacles, shore crabs, and periwinkles. Species that increased were mostly ones that rely on sediment and thus could thrive in the increased sand: juvenile and adult Varnish clams, juvenile softshell clams, and ghost shrimp. Multivariate BACI analyses showed no significant community-level shifts Before vs. After nourishment, although power to detect change is low with relatively few ‘replicates’, e.g., only one “Before” year.

Figure 68. Non-metric multidimensional scaling (NMDS) plots of surface and infaunal biotic communities at the Nourishment sites on each sampling date. Each point represents the community composition (species and relative abundances) across one transect (10 samples averaged) in one year. Armored and unarmored beaches per site are indicated with an A or U. Points closer together indicate more similar biotic communities.

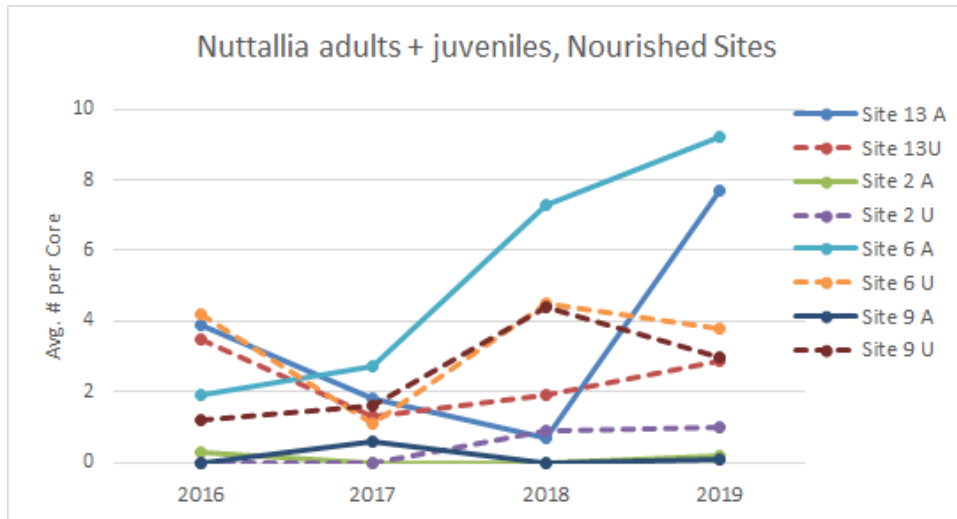


Figure 69. Numbers of clams in 10cm-diameter cores (average among 10 cores per site) before (2016) and after (2017-2019) nourishment. Unarmored beaches are shown with dashed lines.

In general, species richness decreased from 2016 to 2017 at these beaches (Fig. 70); this is what would be expected after a disturbance such as sand addition. At some sites richness then rebounded, e.g., at Site 2A where the sand moved away rapidly.

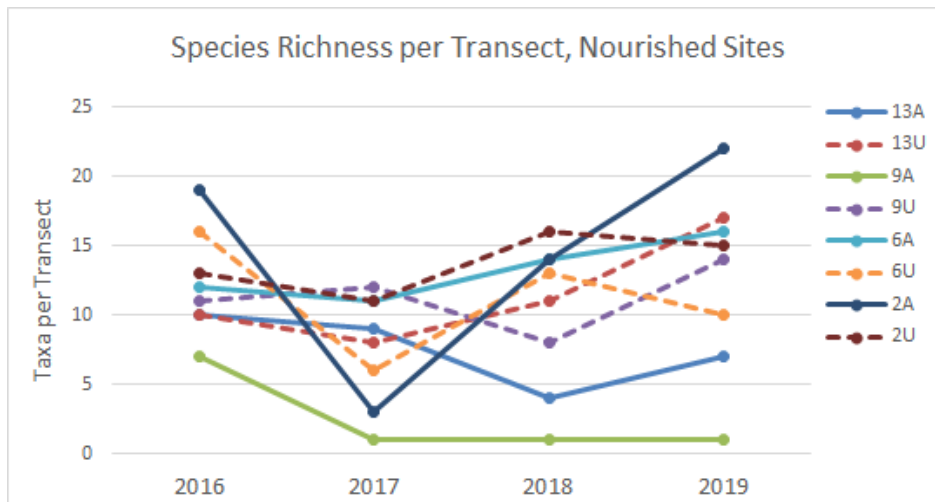


Figure 70. Species richness (total number of taxa per transect) at each site before (2016) and after (2017-2019) beach nourishment. Unarmored beaches are shown with dashed lines.

As we have found at other sites around the Salish Sea, there is often a negative relationship between amount of sand and species richness at MLW; this pattern was broadly true at the Nourishment sites (Fig. 71). In general, the highest diversity on regional mixed-sediment beaches is found where there are surface cobbles because of the stable surfaces they provide. Thus as long as these beaches stay sandy, diversity at this elevation may remain reduced.

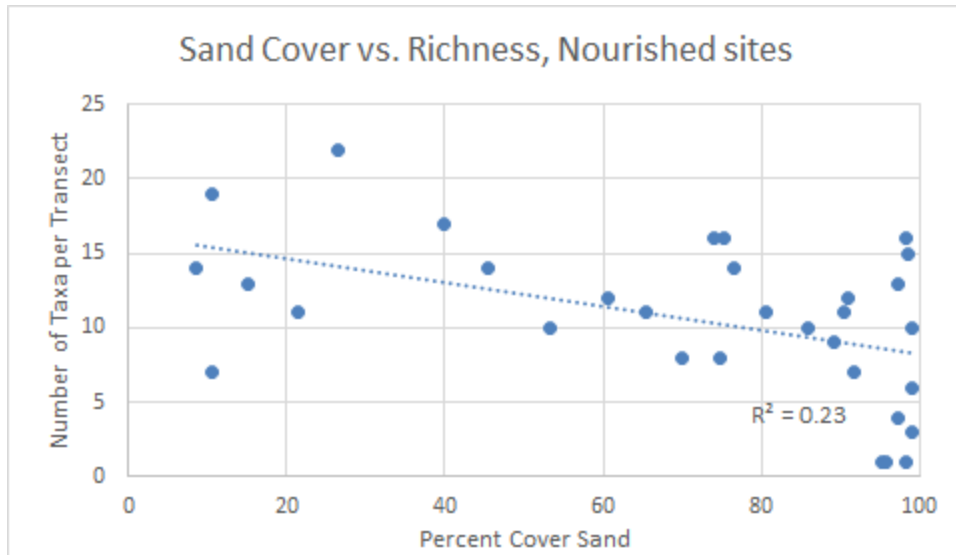


Figure 71. Species richness (total number of taxa per transect) per transect versus amount of surface sand along that transect. Each site and year is one point.

6.1.6 Forage fish sampling

Site effect. The favorability of substrates for forage fish spawning varied highly among both sites and years. We compared results by site type (nourished and downdrift), time (pre- and post-treatment), as well as individual site pairs by month. As an example, Figure 72 shows that sites 5S7 and 5N7 have widely varying substrate size favorability among months and years prior to nourishment, and actual PSL egg counts similarly are variable by year. Post-nourishment, substrate size suitability was persistently high and less variable by month at Site 5N7 (downdrift of Site 5 sediment placement as in Table 1) through 2019. Substrate size suitability improved initially at Site 5S7 post-nourishment, but declined as drift material moved east, as can be seen in Figure 33. The change in substrate size suitability and egg count post nourishment at Site 5N7 is highly significant based on a non-parametric analysis of matched pairs (5N7 and 5S7) by date (PSL substrate - Wilcoxon matched pair, $z=3.48$, $p=0.0005$; Appendix Table C1; PSL egg count- Wilcoxon matched pair, $z=2.2$, $p=0.03$, Appendix Table C9). Results below will further describe changes, differences, and explanatory value of substrate size favorability first, then by forage fish egg count among sites and treatments.

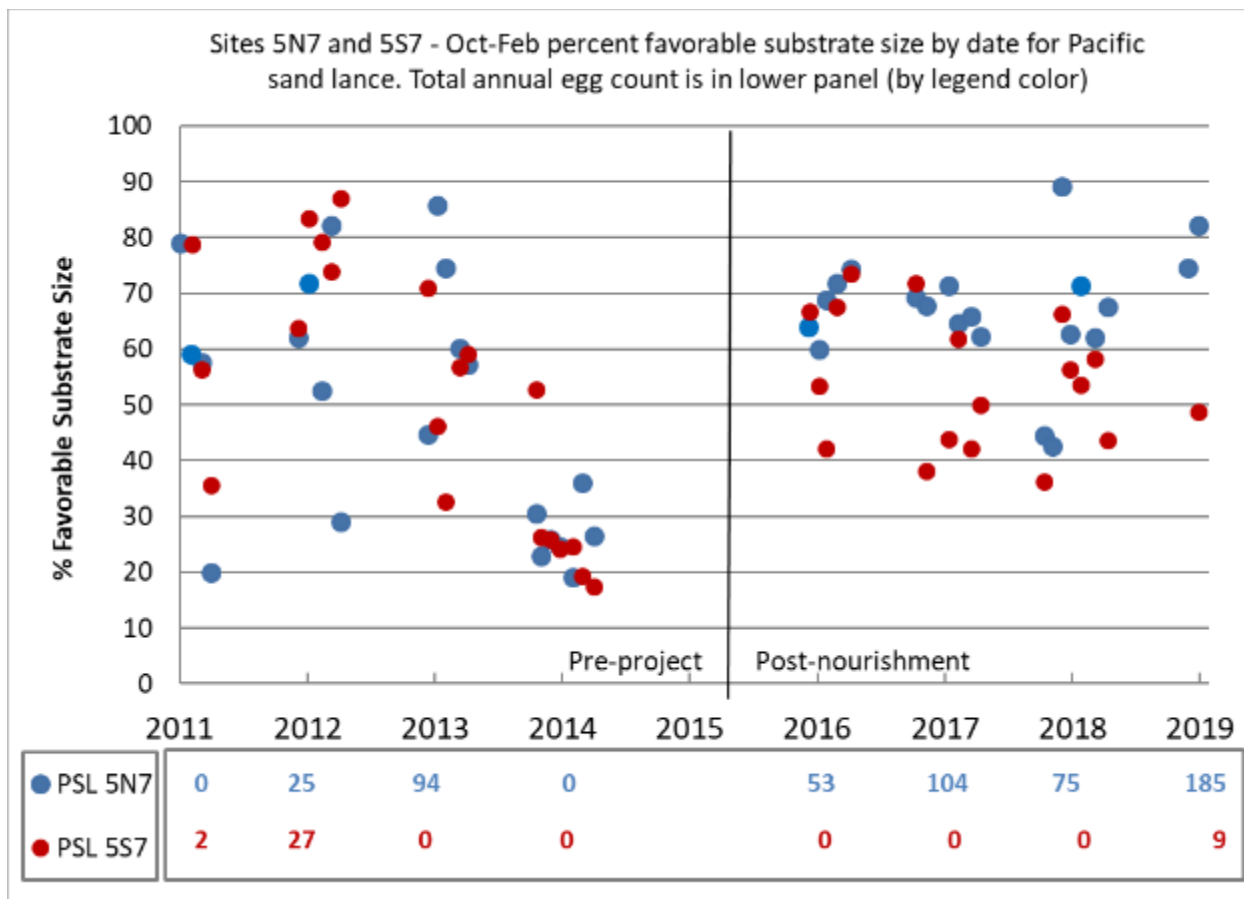


Figure 72. Site 5 PSL favorable substrate size composition pre-project and post-nourishment for two sample locations. Egg count by year is also reported color-coded by site. Nourishment occurred at 5S7. 5N7 was down-drift.

The following graphs highlight the monthly PSL substrate favorability by site for nourishment sites (Figure 73), and drift sites (Figures 74-75). Sites 2S7 and 9S7 increased significantly when comparing pre- and post-nourishment values (Mann-Whitney U test, Appendix Table C2). A change in substrate size at site 5S7 was present, but more subtle. Substrate size by month tended to be less variable post-nourishment. Site 12S7 also significantly changed with nourishment, but the site became coarser in gravel size as a result of being incorporated into the Howarth Park restoration site (HP7).

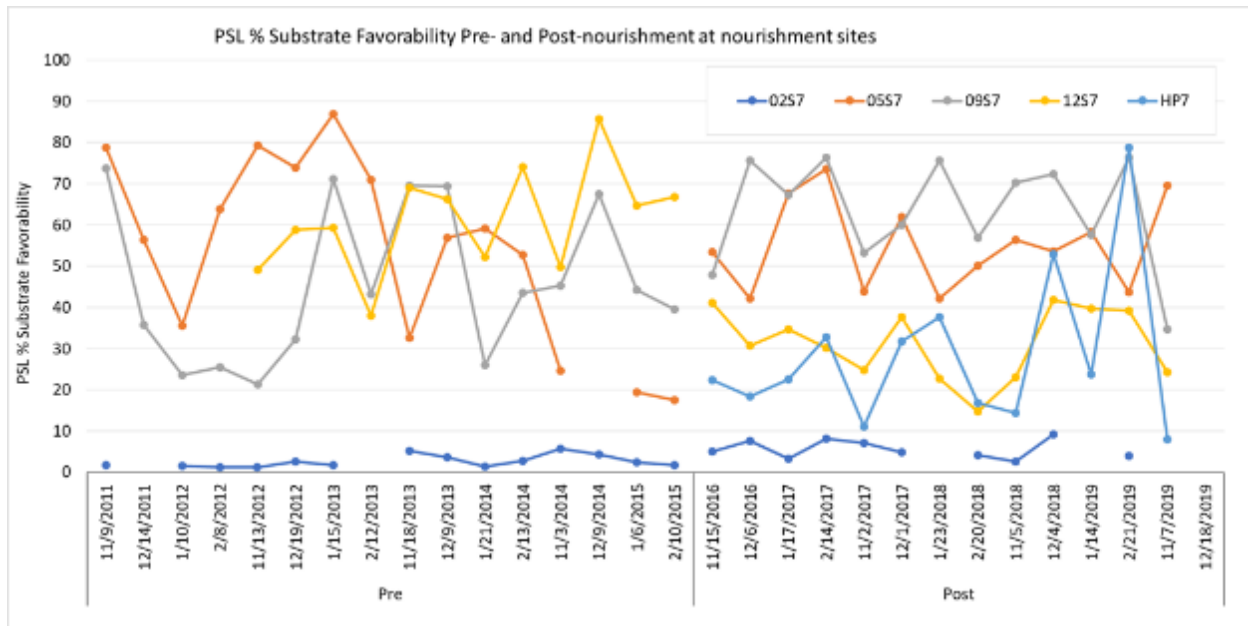


Figure 73. Pre- and post-nourishment substrate favorability by month for Pacific sand lance at directly treated (Nourishment) sites.

Sites that were down-drift of nourishment sites, on the other hand, increased in PSL substrate favorability post-nourishment (Figure 74-75) by individual sites (denoted by Mann-Whitney U test, in Figure 76) and for several sites when evaluating matched drift pairs (Nourish/Drift; Pre/Post; Appendix Table C1). By December 2016, five months post-nourishment, all sites demonstrated a positive response to the beach nourishment. After that, sites either stayed elevated in terms of PSL favorability (2N7, 5N7, 9N7, 12N7, 13N10), or tended toward a prior condition (13N7, 13S7, 13S10, 6S7). Interestingly, Sites 13S7 and 13N7 in the last observed months of 2019 may have received a 2nd pulse of drifting material (originating from Site 10) that had already passed through site 12 in 2018. Site 6S7 seemed to be most unchanged with respect to PSL substrate size favorability, though the pictorial evidence from drift and photos suggests otherwise (Figure 38). However, the placement of substrate sampling made at the time of egg sampling (at the same transect locations) may not have captured the changes that were visually observed across more of the downdrift area and to which forage fish responded.

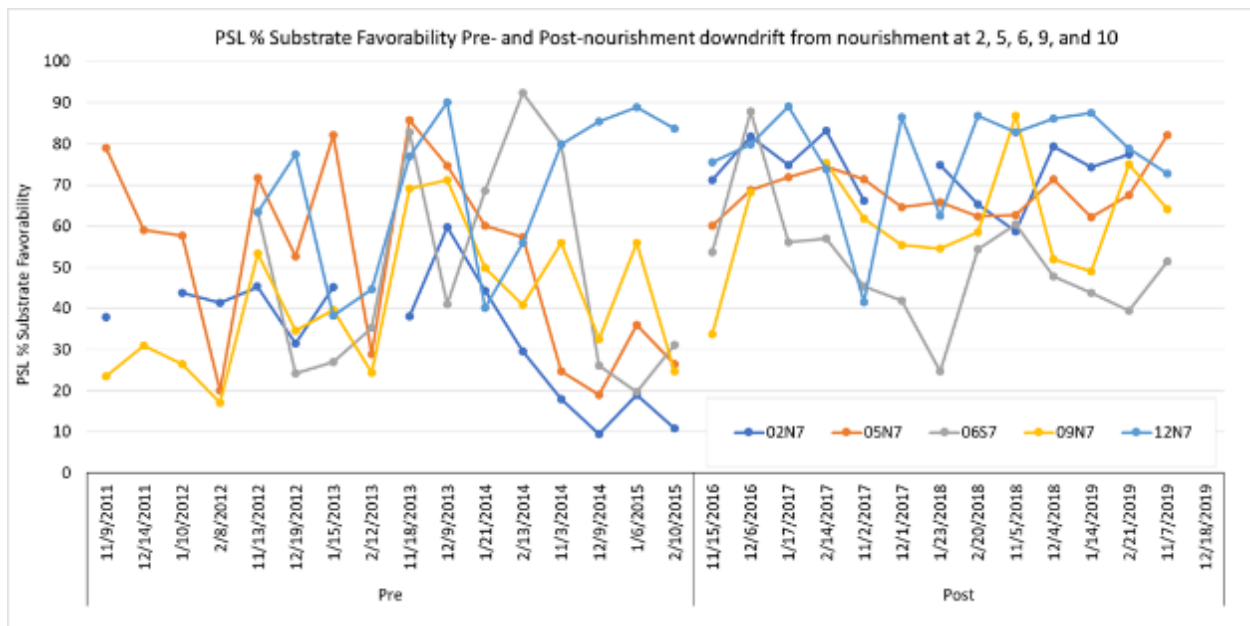


Figure 74. Pre- and post-nourishment substrate favorability by month for Pacific sand lance at sites downdrift from beach nourishment.

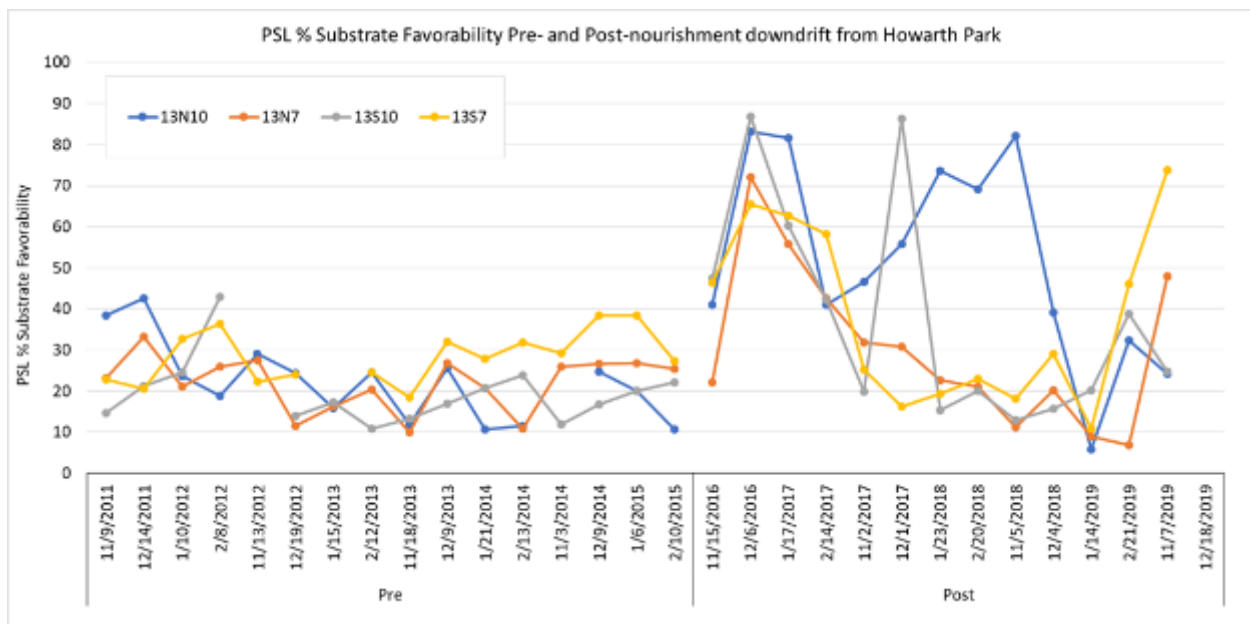


Figure 75. Pre- and post-nourishment substrate favorability by month for Pacific sand lance at sites downdrift from Howarth Park restoration.

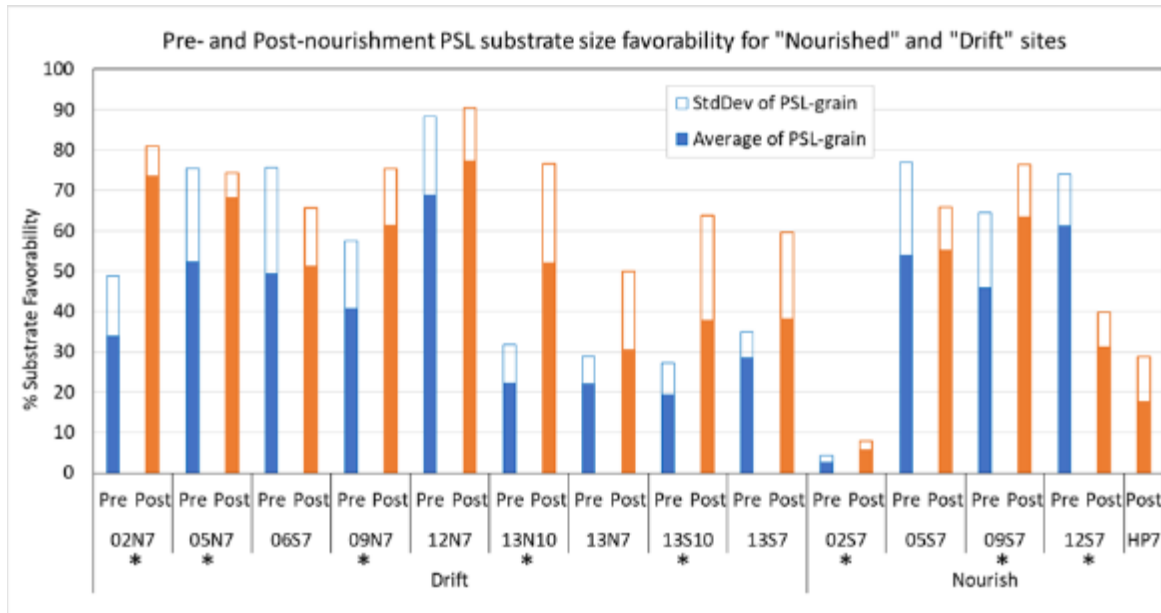


Figure 76. Pre- and post-nourishment PSL substrate size favorability by site for “Nourish” and “Drift” site types. The asterisk below the site name denotes significance at $p=0.1$ (Mann-Whitney U-test). Note site 12S7 is significant because substrate favorability for PSL declined with Howarth Park restoration.

A comparison of matched pre- and post-nourishment values for all sites demonstrates that “Drift” sites on average have higher favorability for PSL post-nourishment (Wilcoxon Matched Pairs test; $Z=2.67$, $p=0.008$; Appendix Table C3). However, matched pre- and post-nourishment percent suitability values for “Nourish” sites (excluding Site 12S7) alone were not significantly different ($Z=1.6$, $p=0.11$; including Site 12S7; $Z=0.37$, $p=0.72$; Appendix Table C3). This is also depicted in the factorial analysis in Figure 77 highlighting the significant interaction effect of treatment type on pre- and post-nourishment PSL substrate (grain) size favorability.

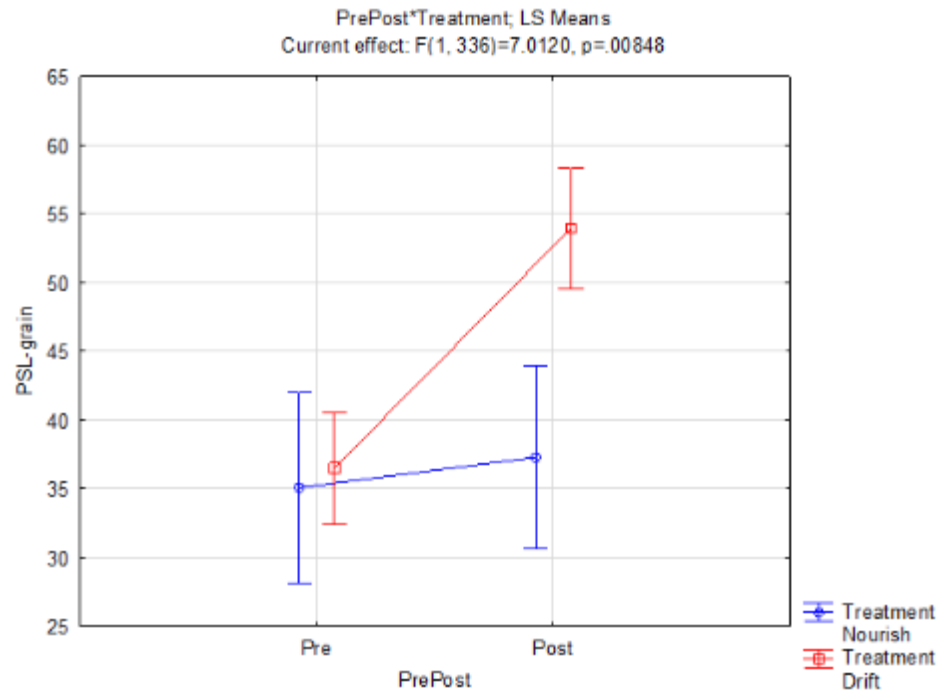


Figure 77. Pre- and post-nourishment seasonal substrate (grain) size favorability for PSL by treatment type showing the interaction term statistic. The full ANOVA is included in Appendix Table C4.

We conclude that sites downdrift of beach nourishment significantly increased in PSL substrate favorability, and, as can be seen in Figure 78, the seasonal variability (as coefficient of variation) differed among sites and the persistence of the changed condition was variable. Drift sites 2-12 were all downdrift of sites nourished with sand (primarily) and the change in favorability and the persistence of the sand tended to reduce the monthly variation in PSL favorability post-nourishment. At Site 13, which was downdrift from Howarth Park restoration, the monthly variance in PSL favorability was higher due to initial increases in finer drift (compared to the initial condition) that declined over time and fluctuated strongly in 2019.

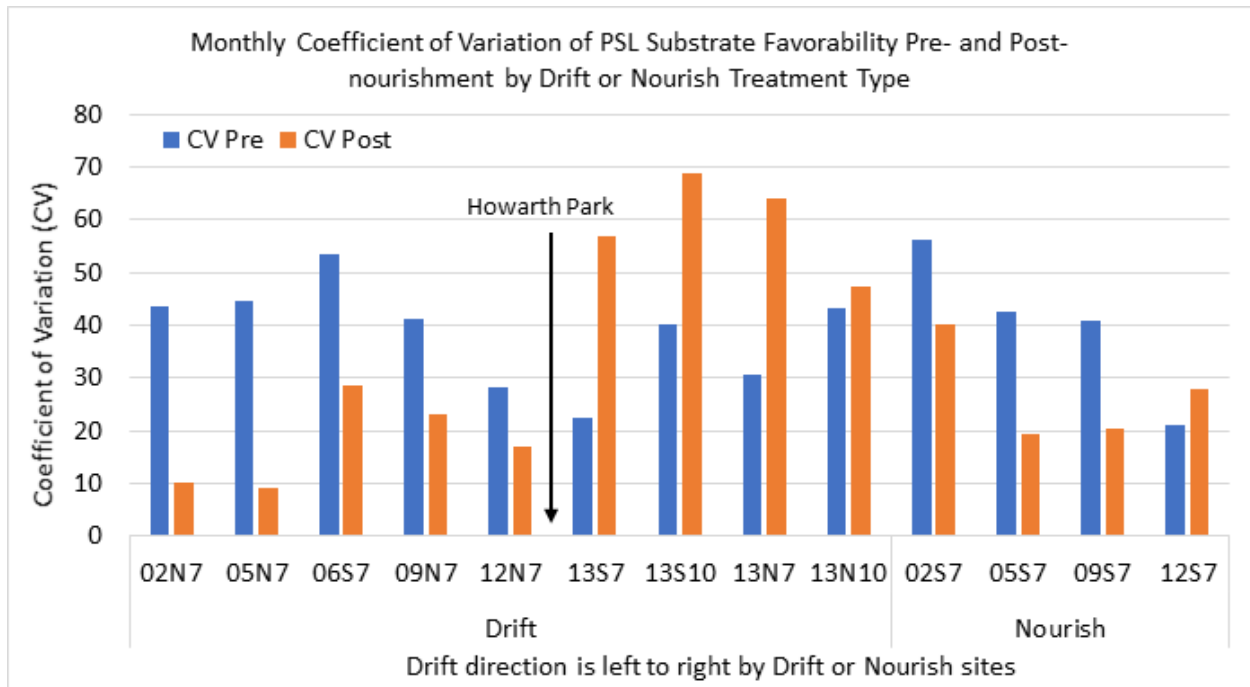


Figure 78. Pre- and post-nourishment monthly coefficient of variation among drift and nourished sites from left to right (drift direction). Location of Howarth Park is shown.

As mentioned, Surf Smelt were rarely found at sites other than site 13, where surf smelt substrate favorability was relatively high compared to all sites and immediately downdrift from Howarth Park (Figure 79). After restoration at Howarth Park, substrate favorability for surf smelt at Site 13 was lower and variable by month for three years (Figure 80). This meant that substrate size became finer with the drift of sand from Howarth Park and notably in the 4th year (2019-2020), declined more from September-November, potentially from sand drifting from Site 10, even farther up-drift. Monthly results for the study period are included in Appendix Figs. C1-C3).

Site 12S7 became more favorable post-restoration at Howarth Park (Figure 80) but declined in the following years. Other sites, including 5S7, 5N7, and 12N7 were highly variable among years in terms of favorability, but generally down-drift sites tended to decline in favorability (sometimes statistically, Figure 79) due to the greater composition of finer sand.

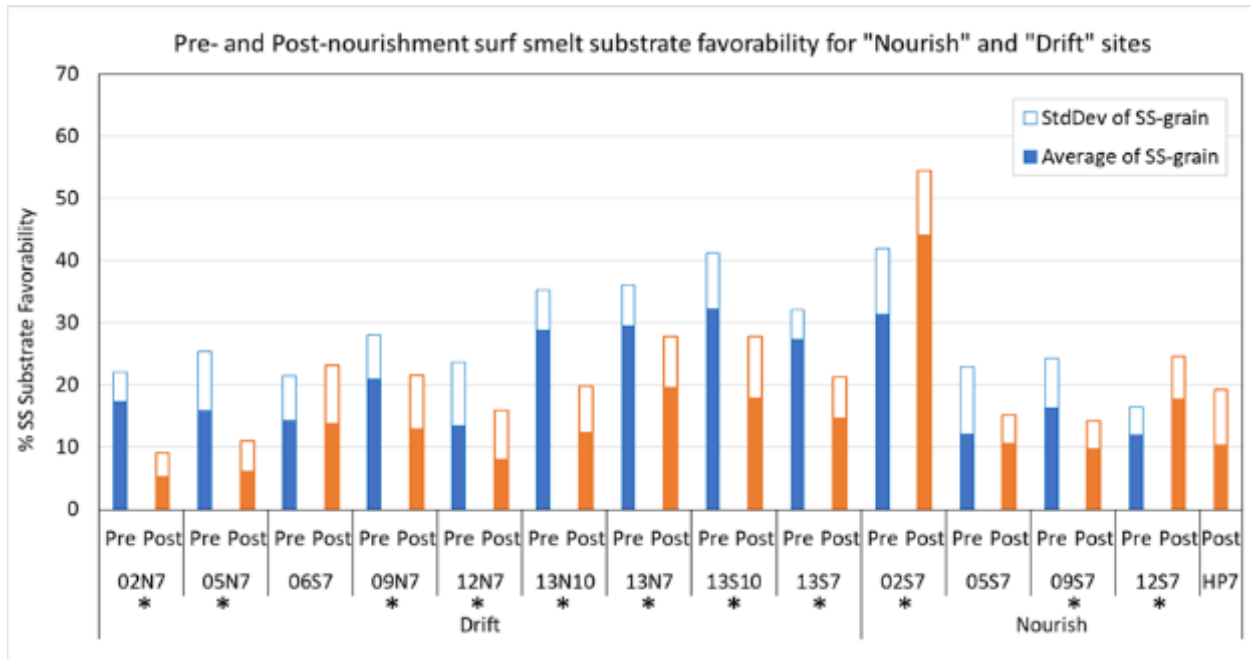


Figure 79. Pre- and post-nourishment monthly average SS substrate size favorability by drift and nourished sites with significant changes highlighted (asterisk; $p=0.1$) based on non-parametric Mann-Whitney U-test (Appendix Table C5).

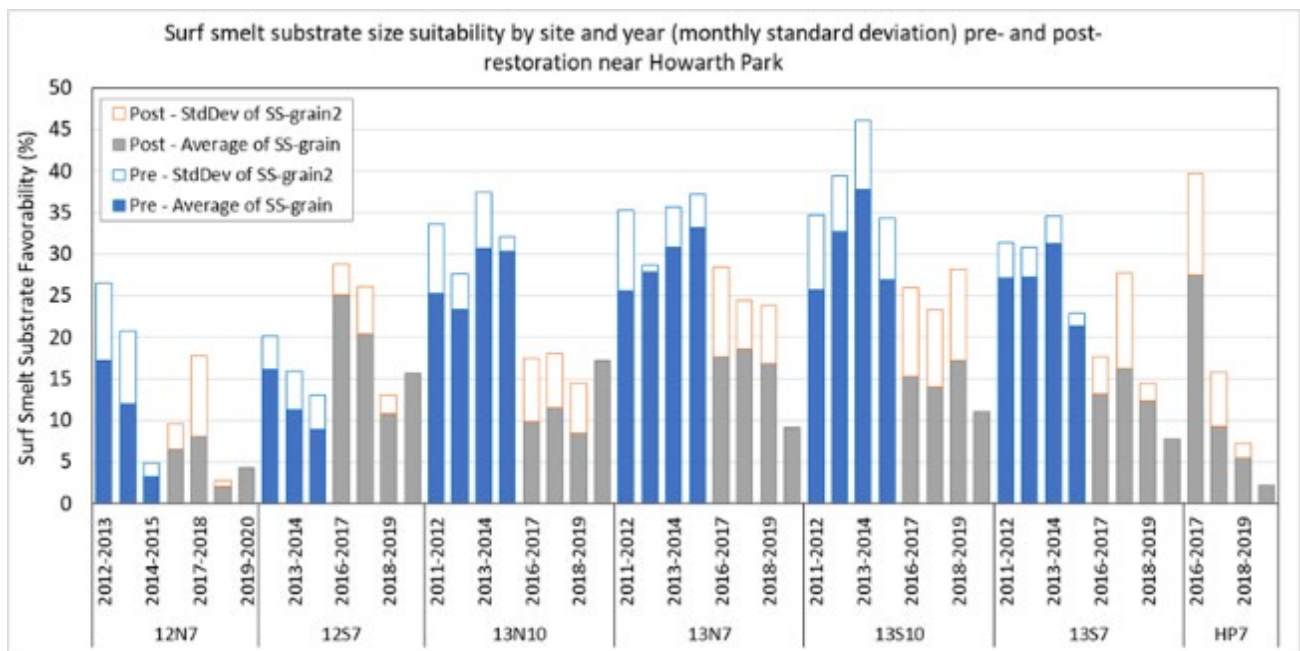


Figure 80. Pre- and post-nourishment annual average SS substrate size favorability for Site 12, 13 and Howarth Park (HP7). Only Site 12S7 increased in SS substrate size favorability.

Otherwise among other beach nourishment sites (Figure 79), Site 2S7 also consistently had favorable substrate size composition according to the sediment sample analyses. However, these beaches were very different. Figure 81 shows how different the appearance of these sites is in terms of boulders, cobbles, beach slope, beach width, and beach toe elevation, even though the substrate size composition of the sampled gravel were similar in terms of calculated substrate size favorability.



Figure 81. Site 2S (left photo) and Site 13N (right photo).

Figure 82 below is illustrative of the surface sediment sizes at 13S7 and 13S10 pre- and post-nourishment and reflects the “pulse” of finer sands that drifted into the site months after project completion. The photos also demonstrate the gradual coarsening of the sites over time, which was more favorable for SS but less favorable for PSL. Similar representation of sediment size changes by site and month are available from Snohomish County [Marine Resources Committee](#).



Figure 82. Change in monthly substrate size through time, including 2 months from before beach nourishment, four months post-nourishment and 2 years post-nourishment.

As with PSL substrate suitability, there was a significant interaction effect between treatment (Nourish/Drift) and time (Pre-/Post-). In the first year post-restoration, nourished sites 12S7 and HP7 demonstrated higher substrate suitability like Site 13 (Figure 80) as they were constructed with relatively larger gravel, in addition to sand. Figure 83 highlights the relatively greater (interaction effect) decline in favorability among drift sites post-nourishment compared to nourished sites.

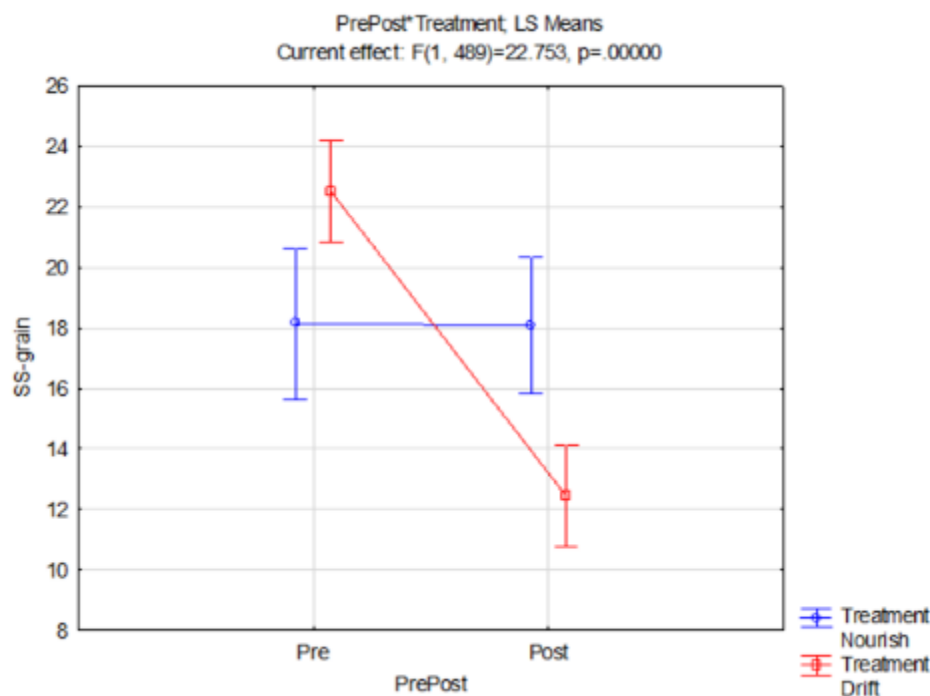


Figure 83. Pre- and Post-nourishment substrate (grain) size favorability (%) by treatment type showing the interaction term statistic. The full ANOVA is included in Appendix Table C8.

Beach nourishment using finer sand-sized material acted to increase the favorability of substrate size for Pacific sand lance at nourishment locations and downdrift from beach nourishment sites but decrease favorability for surf smelt. The favorability for surf smelt was increased temporarily at Howarth Park where site design and construction included substrate sizes favorable for them. Sample sites downdrift from Howarth Park, by-and-large, were influenced by finer drifting material and became less favorable for surf smelt at our sample sites. Curiously, at the sites actually nourished, changes in the substrate sampled for forage fish eggs were less obvious. This was likely due in part to material drifting quickly away from the fixed transect locations where forage fish eggs and gravel were sampled.

Nourishment effect. This study enabled us to test whether changes in substrate size characteristics due to beach nourishment influenced forage fish spawning (egg count). Pacific sand lance and surf smelt egg counts are summarized by monthly total enumerated for the study duration, including during construction monitoring. In all, 654 gravel samples were evaluated for forage fish eggs, though the analyses are limited to the months of expected seasonal spawning.

Among 13 sites, over 6000 PSL eggs were counted, primarily during November-February. Therefore, we limited subsequent analysis to these months. Although 13 sites were sampled prior to beach nourishment (and 14 after), nearly 49% of all eggs were counted at site 12S7 (Figure 84).

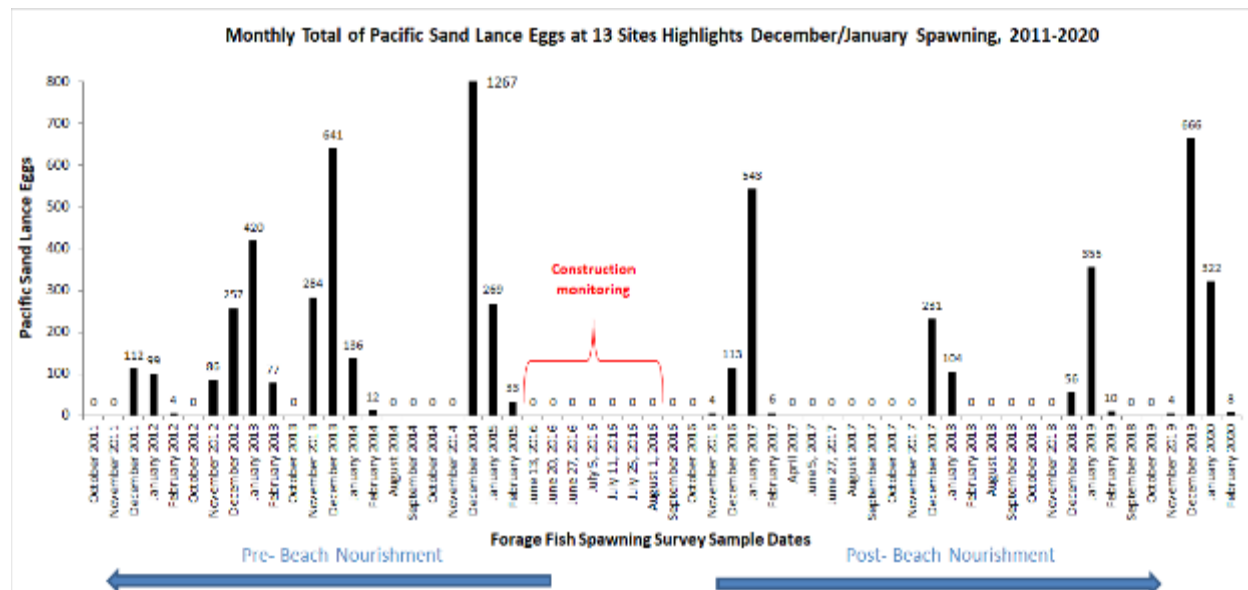


Figure 84. Pacific sand lance egg count by month summed for all sites.

It was hypothesized that directly nourished sites with new beach material and locations downdrift would benefit Pacific sand lance spawning habitat due to the change in substrate size to finer beach substrate. Based on pre-project monitoring, some sites were routinely used for spawning (e.g., site 12S7), while others rarely were used (e.g., 6S7), though it was not known whether this was due to site characteristics or other spawning preferences.

We evaluated the relationship between PSL egg count and our measures of substrate size favorability for spawning months as follows. Among 365 samples collected for forage fish (PSL) egg count and sediment size characterization, 102 contained at least 2 PSL eggs, confirming spawner use. The percent composition of favorable substrate among samples ranged from 5.9% - 90.1% for PSL, and this range was binned into 5% intervals for evaluation of egg presence and count by frequency of occurrence (Figure 85). Figure 85 shows the count of samples with (presence) and without (absence) eggs and indicates that samples with more favorable substrate size do have greater relative occurrence of PSL eggs. For example, where the fraction of suitable substrate size ranged between 20-25% of the gravel sample, 11 samples contained eggs and 35 samples did not. The rate of PSL egg presence is plotted in Figure 86 against the percent composition of favorable substrate.

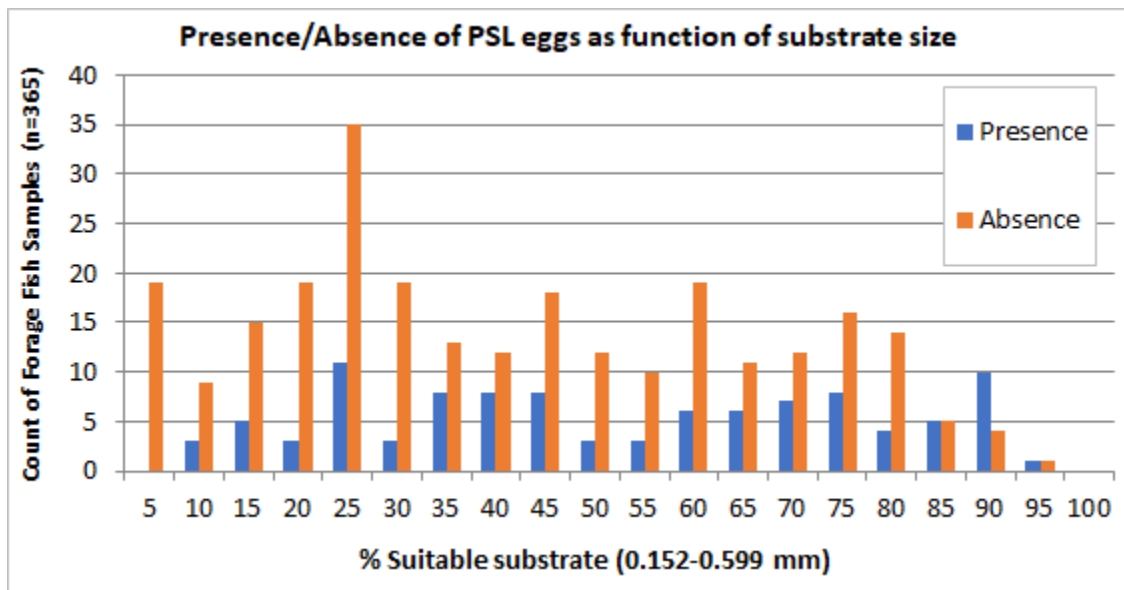


Figure 85. Presence/absence of PSL eggs for samples according to the percent suitable substrate size fraction of the total sample (in 5% increments).

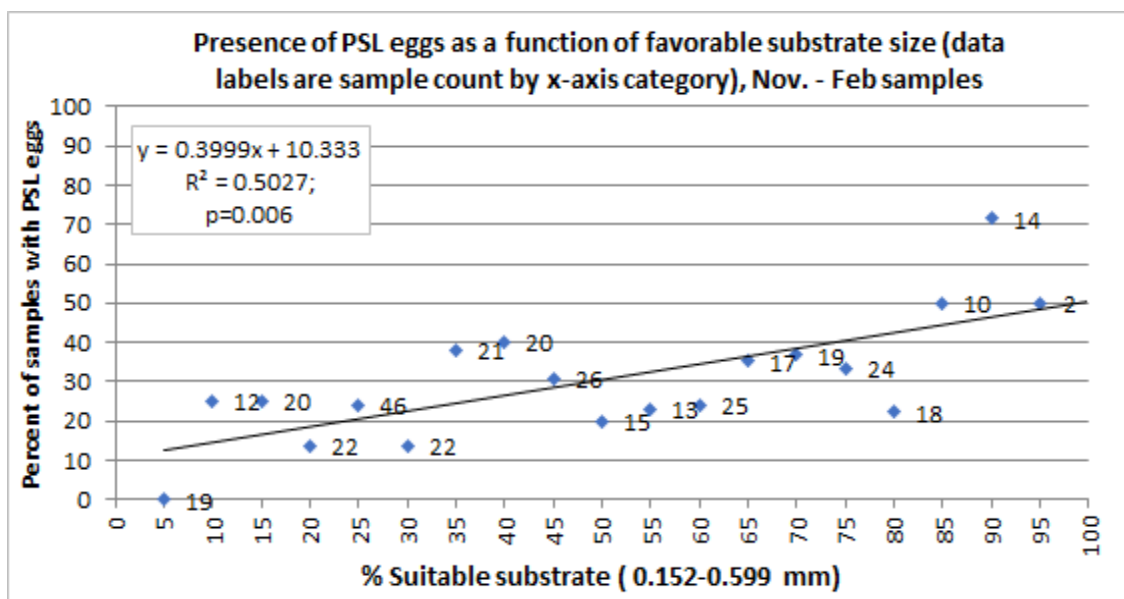


Figure 86. Correlation equation and regression values for percent presence by percent suitable substrate size.

Even without the last 3 categories ($\geq 80\%$) the trend in percent presence with increasing favorableness is significant ($p=0.049$). Thus, the frequency of use of more favorable beaches is higher. We also tested whether more favorable beaches have higher egg count (rather than simply presence/absence of eggs). If we evaluate all samples with egg presence for egg count (log-transformed) relative to the substrate size favorability (log-transformed), there is a

compelling, but weak positive trend (Figure 87). Therefore, do changes in substrate favorability affect PSL (egg count)?

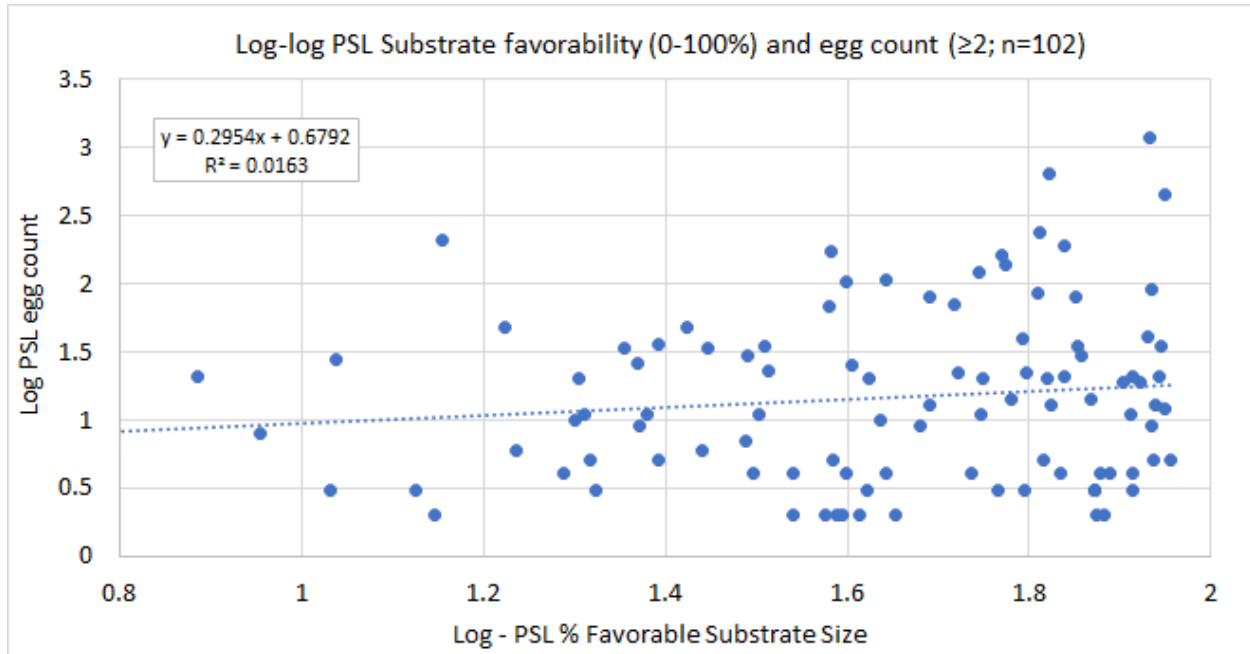


Figure 87. PSL egg count (log ≥2 eggs; n=102) plotted against PSL percent favorable substrate size (log) for 102 samples among 13 sites. Two sites did comprise 30% of samples.

The greatest decreasing change through time in PSL egg count was observed at Site 12S7, which, as mentioned, comprised 49% of sampled eggs across all sites prior to the beach restoration at Howarth Park (Figure 88). At Site 12S7, the substrate size favorability for PSL changed from a pre-project average of 61% to 31% post project (Figure 76), which was low compared to other sites. Separately, site 12N7, immediately adjacent to 12S7 and downdrift from beach nourishment site 10, was not directly part of Howarth Park construction and retained a PSL favorability of 77%. Site 12N7 now sustained the highest PSL egg counts (Figure 89). As the reduction in PSL egg count at Site 12S7 may have been due to the unique alteration of the beach at this site (i.e., placement of coarse gravel) relative to other beach nourishment, we separately considered PSL egg count changes among the remaining sites, including the new HP7 site.

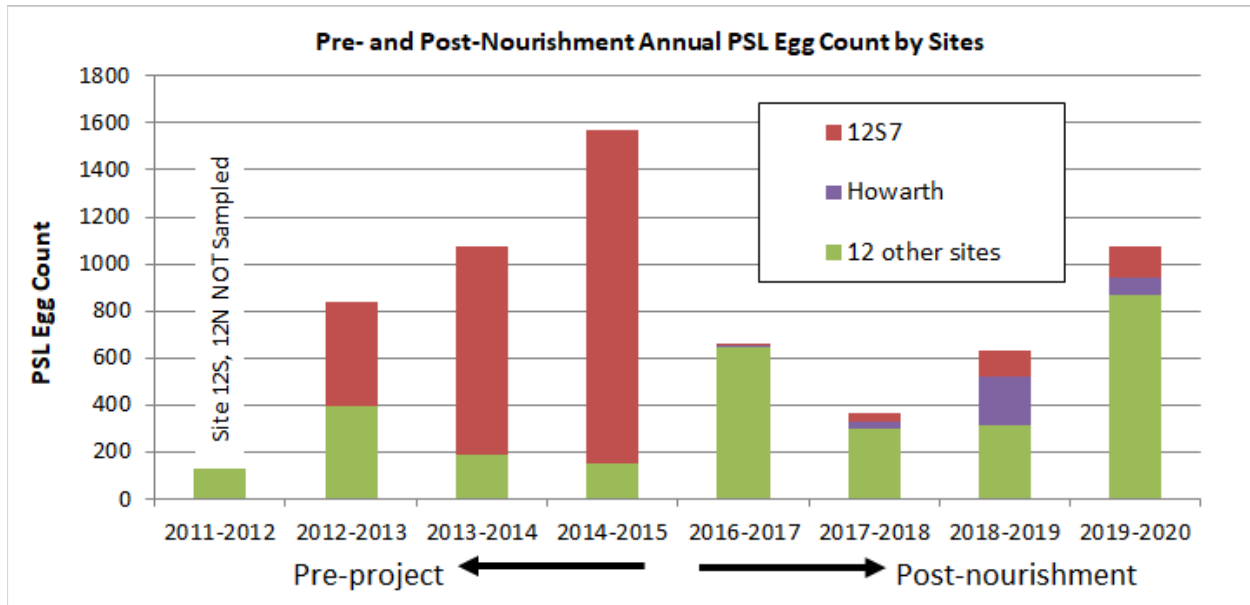


Figure 88. Annual total count of PSL eggs by pre- and post-nourishment years for Site 12S7, Howarth Park (post nourishment) and all other sites.

Post-restoration, our sampling confirmed PSL spawning at Howarth Park which had a relatively higher number of PSL eggs post-project completion compared to most of the other 12 sites (Figure 89), but only in the third and fourth year post-project, when PSL substrate size favorability increased as it did at site 12S7 (see Figure 73, Nourishment Sites).

Other pre- and post-nourishment differences in average annual PSL egg count are shown in Figure 89, highlighting sites with increasing and decreasing egg count. These sample sites are shown with their treatment affiliation, either directly nourished (N) or downdrift (D). Six out of nine drift sites increased in PSL egg count, while the restored Howarth Park site also had PSL eggs. However, all four sites that were directly nourished (including 12S7 as described above) demonstrated no positive response to beach nourishment. Curiously, the substrate samples from directly nourished sites did not appear to reflect higher suitability for PSL. With the addition of finer sand as part of beach nourishment, typically those sites down-drift from nourishment sites changed to become more favorable for Pacific sand lance. Therefore, the downdrift sites may have been more subtly, favorably and predictably (as accretionary shore forms) changed for PSL spawning compared to the sites with 1000's of cubic yards of newly placed material.

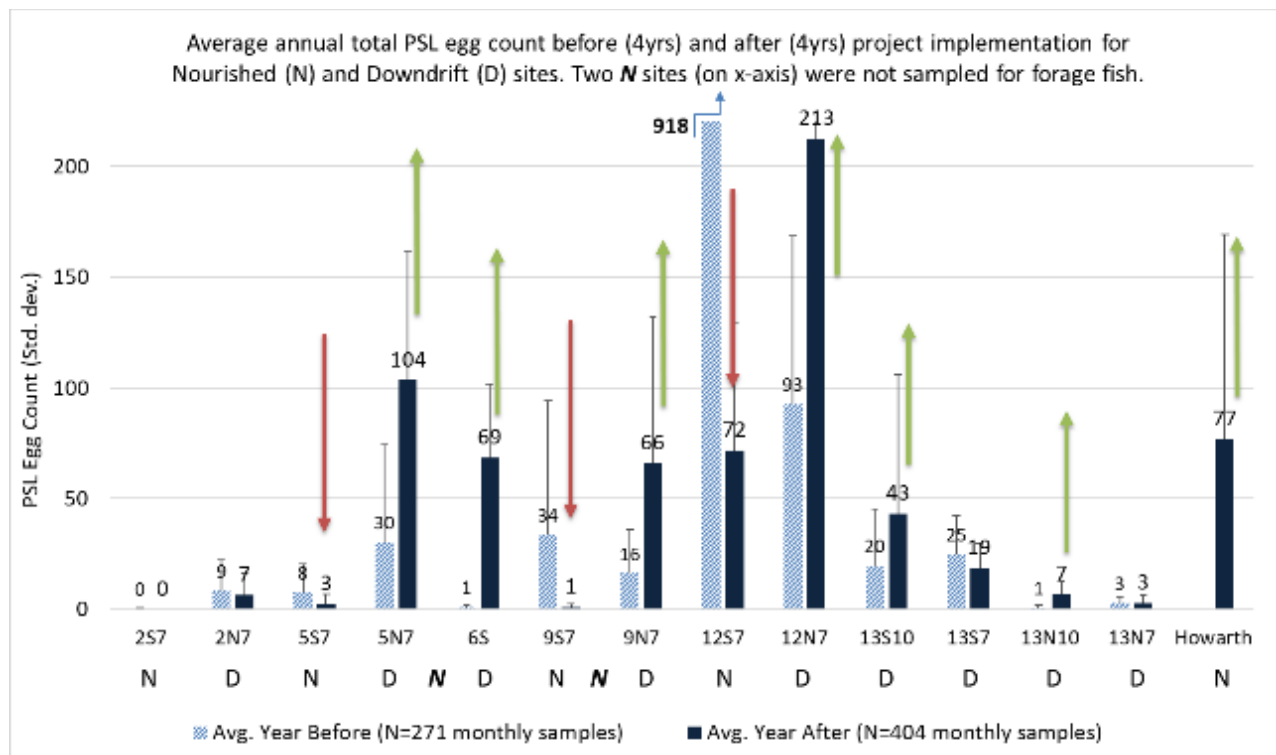


Figure 89. Pre- and post-nourishment average annual PSL egg count by site according to treatment type. Increasing or decreasing arrows are illustrative only.

We tested the effects of beach nourishment type (nourished or downdrift) on egg count pre- and post-nourishment using a simple 2-way ANOVA (excluding the constructed sites 12S7 and HP7 with coarse gravel). Although post-nourishment egg count was higher, and more so among downdrift sites, there was no significant difference in treatment effect or Pre-Post effect, nor as an interaction effect (an increase in PSL egg count post-nourishment specific to the drift sites, Figure 90). This suggests there was not strong conformity among sites which, as reported, differed in beach width, slope, toe elevation, shoreform, initial substrate size, and so on. If, on the other hand, we conform sites by sub-treatment type to exclude Site 13 (due to the unique updrift treatment of Howarth Park) and restrict the ANOVA to only include sites with barge-dumped beach nourishment (2S7, 5S7, 9S7) and downdrift (2N7, 5N7, 6S7, 9N7, 12N7), then results appear to be significant for treatment type (drift>nourish, $p=0.009$) and marginally significant ($p=0.06$, for the interaction of treatment and time, suggestive of a downdrift benefit (see Appendix Table C10 for full ANOVA).

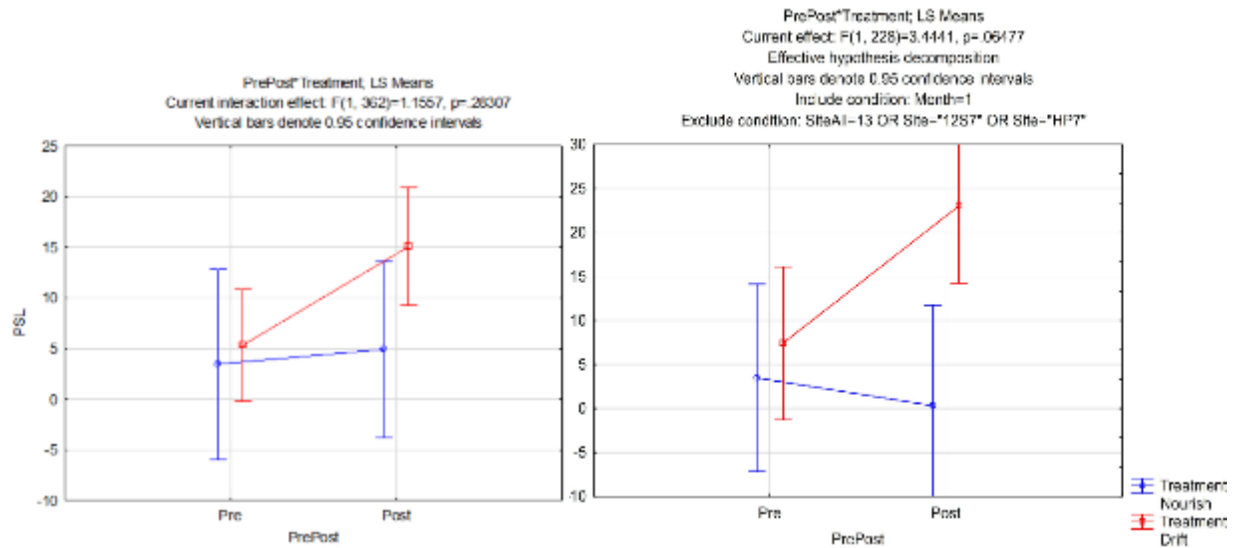


Figure 90. Pre- and post-nourishment PSL egg count (based on monthly values) by treatment type showing the interaction term statistic (left panel, excluding site 12S7; right panel, excluding site 12S7, 13N7, 13N10, 13S7, 13S10, HP7 (y-axis ranges are different)). The full ANOVAs are included in Appendix Tables C10 and C11.

If we consider drift sites alone and test pre- and post-nourishment average monthly egg counts as paired observations, drift sites have greater egg count post-nourishment based on a non-parametric test of paired observations (Figure 91). However, this test reduces the known monthly variability and lacks a control group as part of the test. Site 13 is noted in the figure due to the difference in nourishment treatment (i.e. Howarth Park restoration with coarse gravel, not simple beach nourishment with sands).

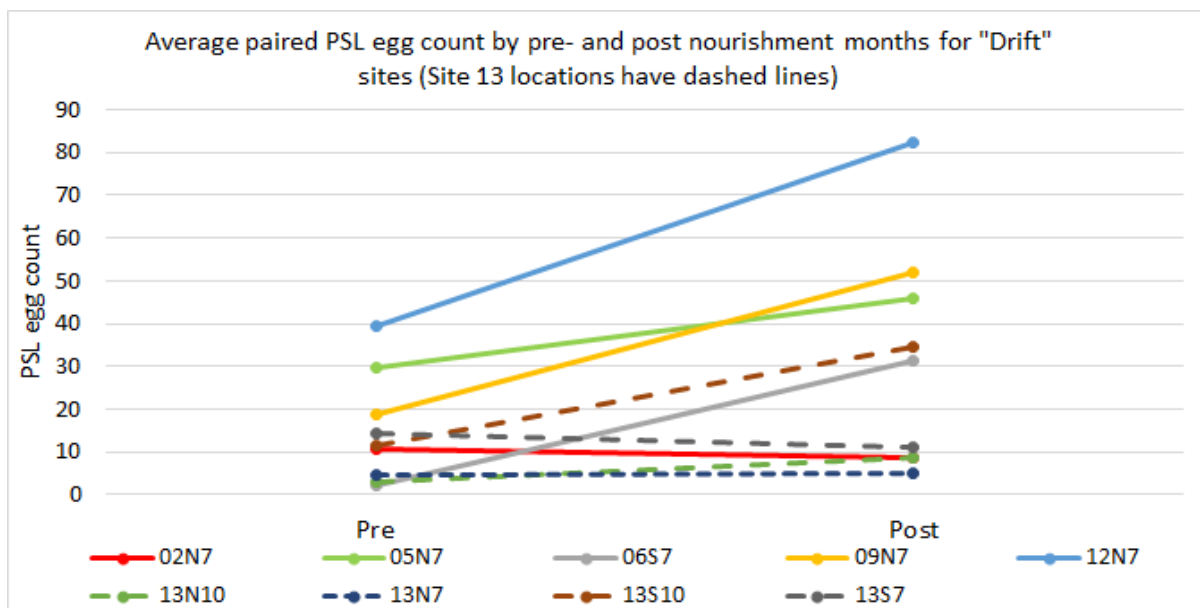


Figure 91. Paired average PSL egg count for pre- and post-nourishment values by drift sites (Wilcoxon matched pairs test; n=9, z=2.07, p=0.04).

As an alternative, we compared paired nourishment and downshift sites (i.e. 5S7/5N7, 9S7/9N7) by sample date and time (pre- and post-nourishment), as there was a notable effect on PSL substrate favorability between these treatments and over time (i.e. Figure 77). Using non-parametric Wilcoxon Matched Pairs tests, Figure 92 illustrates that at certain site pairs, egg count by matched sampling dates was significantly greater post-nourishment at locations downdrift from beach nourishment sites (Matched pairs tests in Appendix Table C9). Downdrift sites 5N7, 6S7, 9N7, and 12N7 all had greater egg count by date when matched to an updrift nourishment site (not a decrease at nourished sites). However, among these sites, only Site 5N7 had significantly more favorable substrate size for PSL than Site 5S7 based on matched pairs. Although, most site pairs improved in PSL substrate size favorability between pre- and post-nourishment dates, so there was no difference by date for matched pairs.

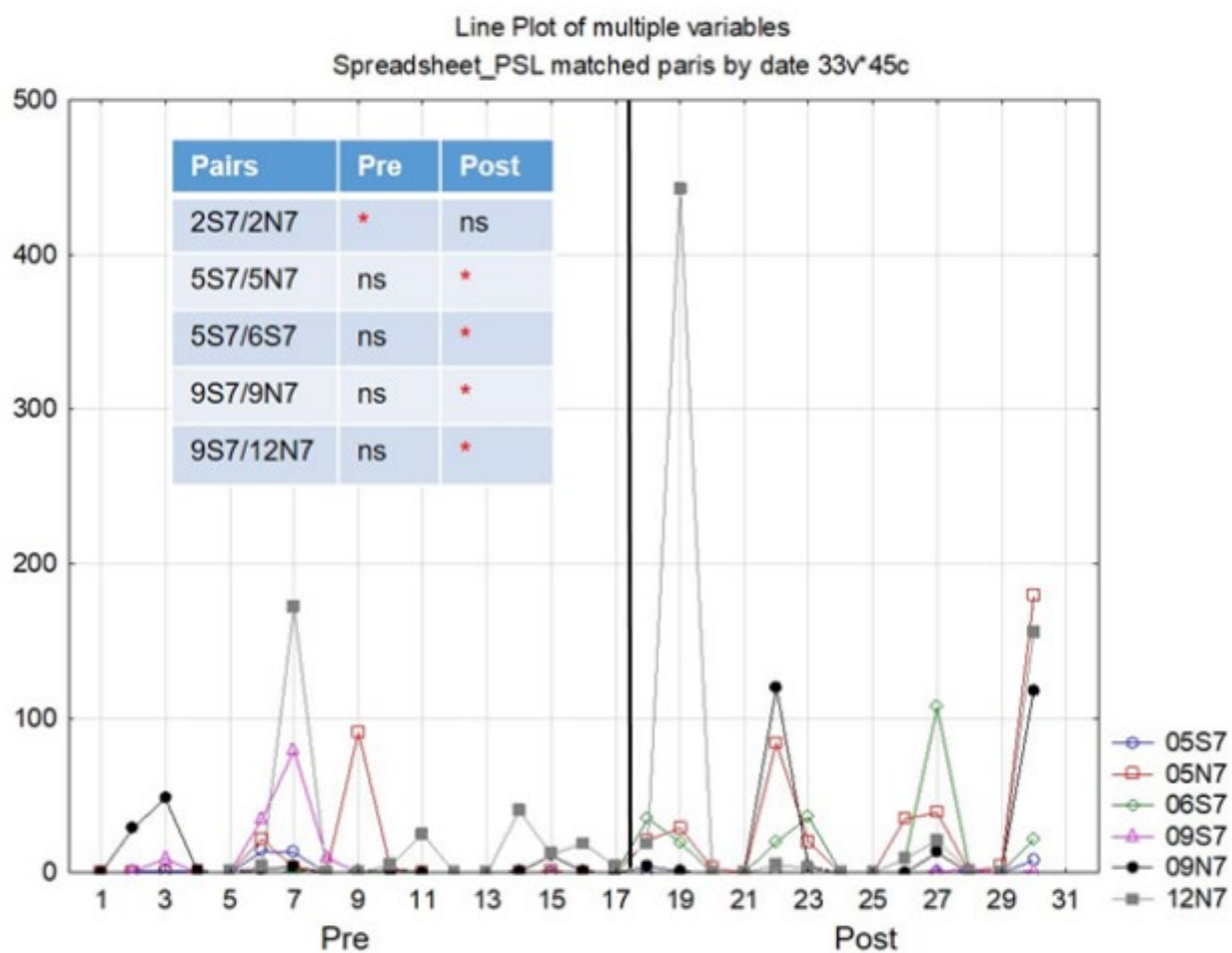


Figure 92. Pre- and post-nourishment egg count by sample date (month # in x-axis) for matched pairs of nourished and downdrift sites (inset table). Asterisk represents significance ($\alpha=0.05$) between pairs by time.

The combined results indicate that PSL spawning (presence and egg count) was affected positively by substrate favorability, at downdrift sites, and sometimes uniquely at individual sites as summarized in Table 6. However, changes in egg count were also evident where

explanations were less quantifiable. For example at Site 6S7, downdrift from beach nourishment at Site 6 (the embayment), pre-project PSL egg Count totaled 2 eggs over 4 years despite average substrate favorability. Post-nourishment PSL egg count totaled 251 eggs among eight different samples, despite little detected change in sampled substrate size favorability. However, as shown in Figure 38, visually this site changed dramatically with finer drifting sand. Also indicative of PSL spawning response, but as an opposite effect, PSL egg count declined the most at site 12S7 which was modified with larger substrate size that negatively changed the substrate favorability of this site.

Surf Smelt were primarily found at sites 12, 13, and at Howarth Park post-nourishment (Figure 93). However, of the nearly 5000 eggs counted, 96% were observed at site 13.

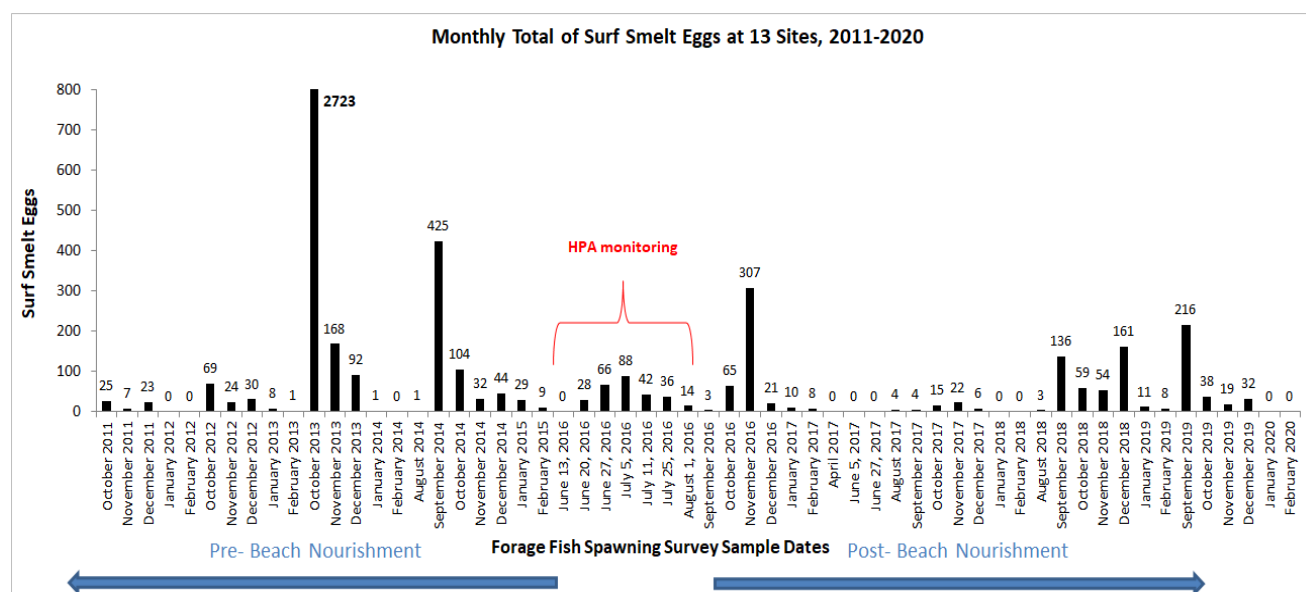


Figure 93. Surf smelt egg count by month summed for all sites.

Hereafter, results are only summarized for sites 12, 13, and Howarth Park. As indicated above, most sampling was implemented in September-February. However, during construction monitoring (HPA Monitoring in Figure 93) in summer 2016, Surf smelt eggs were observed at Site 13, suggesting our sampling may have missed other seasonal surf smelt spawning in other years and at other sites.

Post-beach restoration at Howarth Park, there was initial use by surf smelt in the first sampling year at site HP7 (Figure 94). HP7 initially demonstrated relatively high substrate suitability for surf smelt spawning in the first year (Figure 80), but then favorability declined thereafter, and SS eggs were not observed again. In the first year post-restoration at Howarth Park, the surf smelt eggs sampled at HP7 suggest the substrate size was suitable for spawning, but the proximity to the preferred Site 13 may have also been an important factor, as surf smelt use at Site 13 was depressed compared to pre-project egg abundance. The decrease in the substrate favorability at HP7 may be due to unintended differences in sample transect placement within the sites by date (which was true for one month but would be an unknown source of error). Alternatively, an

increase in finer sands (less favorable for surf smelt) transported from up-drift beach nourishment (at sites 9 and 10) over time could have reduced the favorability for surf smelt over time.

Surf smelt eggs were also detected at Site 12S7 and 12N7 in each of the post-nourishment years, albeit at low abundance. As Site 12S7 became incorporated into the Howarth Park restoration site, this site had more coarsely sized gravel (and sand) that was placed as part of the beach design. The highest combined (12S7 and Howarth) surf smelt egg abundance was observed immediately post construction when substrate size favorability was highest at Howarth Park and Site 12S7, suggesting a potential “dose-response” effect of nourishment and forage fish use. In years after 2016, the “dose” effect was less favorable in terms of the persistence of favorable substrate size for surf smelt and fish use was apparently less (Figure 94).

At site 13, surf smelt egg count declined post-restoration from a high egg count in 2013-2014 (Figure 94), but not significantly due to strong variability among years.

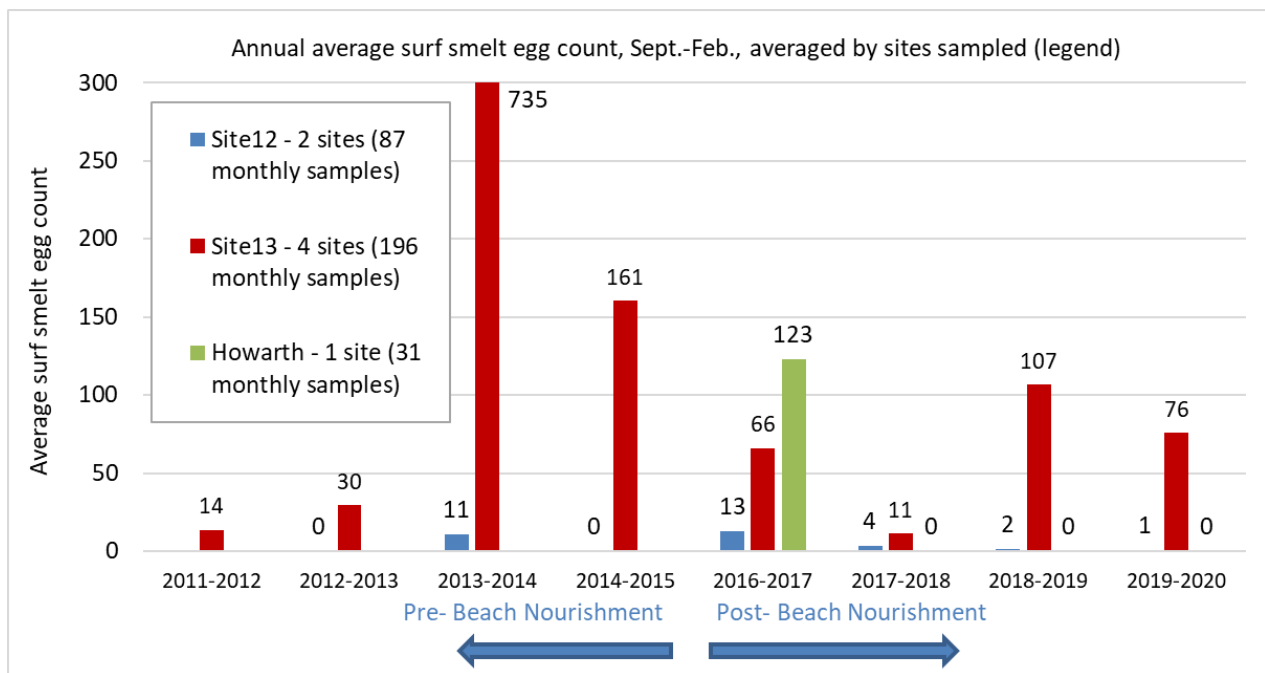


Figure 94. Average surf smelt egg count by year among sites with different sampling effort for three sites. Data labels are average (Site 12, 13) or total (Howarth) egg count. Site 13 included 2 sites at 10 ft tidal elevation.

Annually, the average monthly egg count was statistically different among years, even with 2013-2014 excluded (Figure 95). No difference was evident between the pre- and post- year groups based on a non-parametric test of pre-post differences in egg count, even when the large variation from year 2013-2014 was excluded (Mann-Whitney U-test on pre- and post-values; $z=-1.36$, $p=0.173$).

These annual differences in egg counts could not be attributed to the change in substrate size favorability, which declined after Howarth Park construction, and more so, in the final year potentially due to a 2nd pulse of beach nourishment (from sites updrift). It is more probable for surf smelt than PSL that the high affinity and fidelity to Site 13, among all sites, was strong regardless of the changed site condition. This suggests that surf smelt sensitivity to substrate size changes might be less important than other factors. The short-lived documentation of surf smelt at Howarth Park post-construction may have been a response to new favorable conditions or reflected minor temporary displacement from Site 13 due to reduced favorability there.

Because substrate size at Howarth Park became more unfavorable for surf smelt in later years and eggs were not detected again, there likely was some positive effect of initial beach nourishment on surf smelt, at least in terms of suitability. But much uncertainty remains. Some uncertainty overall was imposed by the lack of sample control sites within the drift cell, but outside of direct beach-nourishment or drift effects. Two other sites outside of this drift cell, sampled in 2016-2019, were intended for comparative analysis, but were never observed to contain forage fish eggs. A summary of results for PSL and SS substrate favorability and forage fish responses is included in Table 6.

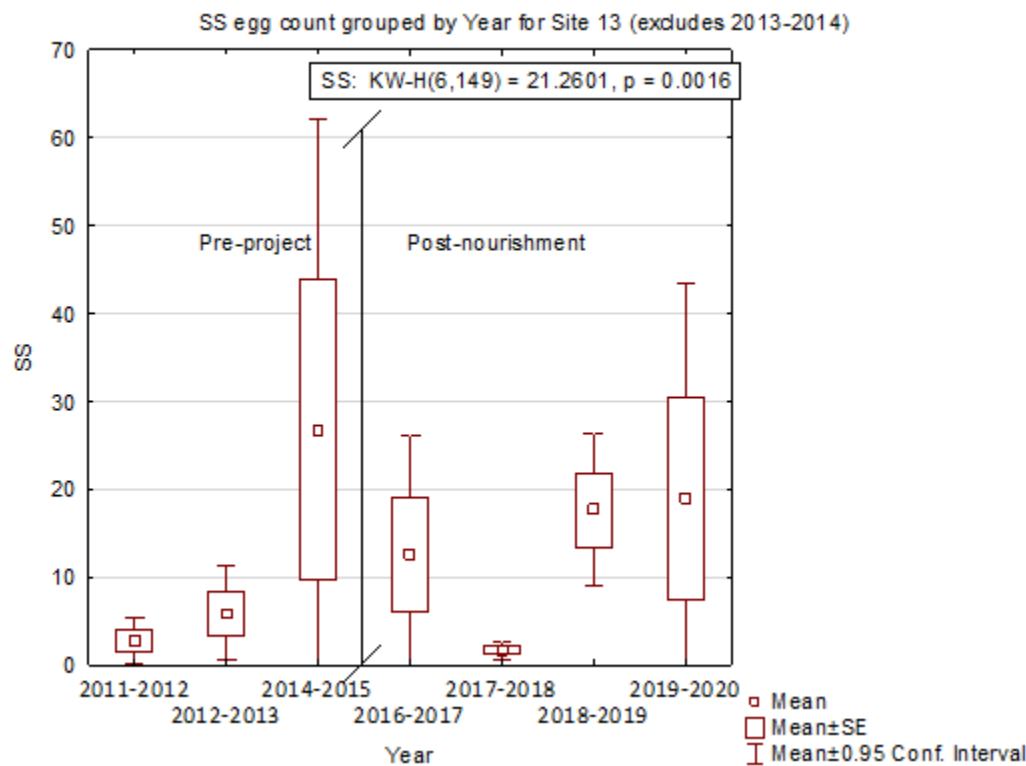


Figure 95. Site 13 annual surf smelt egg count (excluding 2013-2014 outlier year), showing non-parametric comparison of highly variable years.

Table 6. Beach nourishment drift characteristics by site and changes (post- minus pre-project) in substrate size favorability for PSL and SS. Changes in egg count reflect multiple lines of evidence including changes in pre- vs. post-nourishment egg counts parametric and non-parametric, matched pairs tests by monthly observation and analyses of variances by treatment types, as described above in and in Appendix C.

Drift Cell Drift Direction	UW Site ID	SnoCo Site ID	Nourished or Drift	Relative drift rate (from section 6.1.2)	Drift persistence (2016- 2019)	Change in PSL % favorability	Change in PSL egg Count	Change in SS % favorability	Change in SS egg count
	2Un		None			ND	ND	ND	ND
	2Ar	2S7	Nourish	Fastest	None	+2.9	↔	+12.7	↔
		2N7	Drift		Low	+39.5	↔	-12.1	NO
		5S7	Nourish	Med	Low	+1.2	↔	-1.5	NO
		5N7	Drift		Mod	+15.9	↑↑↑	-9.8	↔
	6Ar		Nourish	Low	Mod	ND	ND	ND	ND
	6Un	6S7	Drift		High	+1.8	↑↑↑	-0.4	↔
		9S7	Nourish	Low	Mod	+17.6	↓	-6.6	↔
		9N7	Drift		High	+20.6	↑↑↑	-8	↔
	9Un	10	Nourish	Med	Low	ND	ND	ND	ND
	9Ar		Drift		Mod	ND	ND	ND	ND
		12N7	Drift		High	+8.5	↑↑	-5.5	↔
		12S7	Nourish	Med	Mod	-30	↓↓↓	+5.8	↔
	13Ar	HP7	Nourish	Fast	Mod	NA	↑ *	NA	↑ *
	13Un	13S7, 10	Drift		Low	+13.9	↑	-13.2	↑↑↑↔
		13N7, 10	Drift		Low	+19	↑	-13.7	↔↓↓↓

ND = No data collected; NO - No eggs were observed; so no stats

↔ = No change ↑↓ = pos/neg change, not statistically

↑↑↑↓↓↓ = pos/neg, $p < 0.05$

↑↑↑↓↓↓ = pos/neg, $p < 0.1$

* eggs present, but not compared to pre-project

6.2 Southern region

6.2.1 Beach profiles.

Across the Southern Region, the effect of shoreline armor on beach profile was parallel to that of sites in the Nourishment Region, but with a clearer distinction between strata (armored vs. unarmored). Because the Southern sites were not subject to recent beach nourishment, these clear distinctions remained over time, even with slight inter-annual variations in profile character.

Overall, the beach toe elevation, and similarly relative encroachment, at armored locations were substantially lower than at unarmored locations (Table 7). This pattern was consistent within all Southern site pairs, but weakest at site Meadowdale (MD) where toe elevation at the armored location was highest of all armored locations (Figure 96).

Table 7. Average, minimum and maximum values of beach profile parameters measured across Southern Region sites, in Snohomish County, WA. Values are averaged across all years sampled and summarized by strata (armored or unarmored).

		Armored	Unarmored	Site total
Toe (m +MLLW)	Average	2.44	4.11	3.29
	Minimum	1.66	3.86	1.66
	Maximum	3.94	4.27	4.27
RE (m +MLLW)	Average	0.89	-0.78	0.03
	Minimum	-0.62	-0.95	-0.95
	Maximum	1.67	-0.52	1.67
Width (m)	Average	14.27	53.57	34.40
	Minimum	7.47	32.80	7.47
	Maximum	26.09	81.20	81.20
Slope (m)	Average	0.11	0.07	0.09
	Minimum	0.10	0.04	0.04
	Maximum	0.12	0.10	0.12

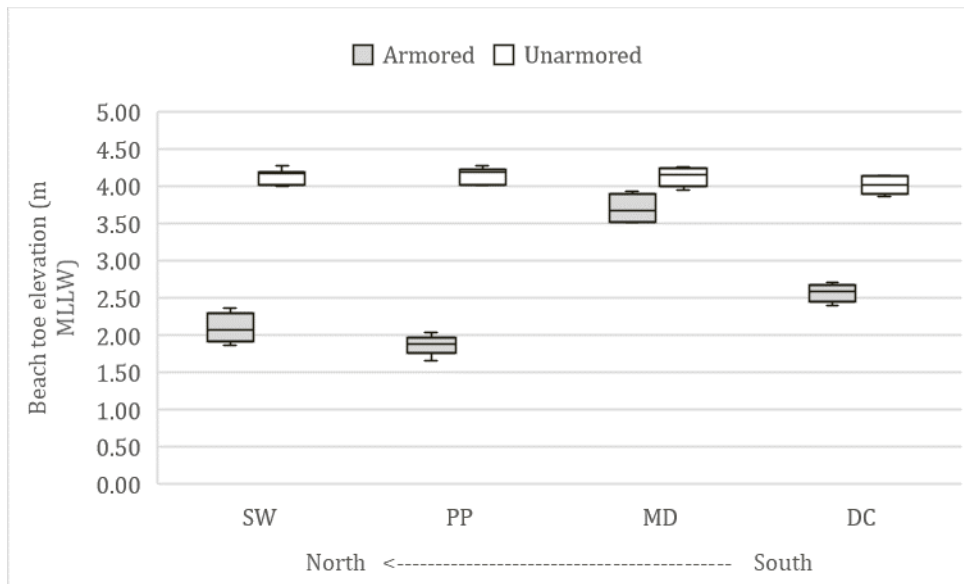


Figure 96. Range of beach toe elevations (m +MLLW) measured at each Southern site Shipwreck (SW), Picnic Point (PP), Meadowdale (MD) and Deer Creek (DC) in Snohomish County, WA. Values are averaged across all survey years 2016 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair. Arrow indicates direction of drift.

Contrary to beach profiles in the Nourishment Region, the signal of armor effect on both beach width and slope across the Southern Region was clear and consistent. At each site, averaged across survey years, armored locations exhibited narrower beach widths and greater beach slopes, compared to unarmored locations (Table 7) (Figures 97-98).

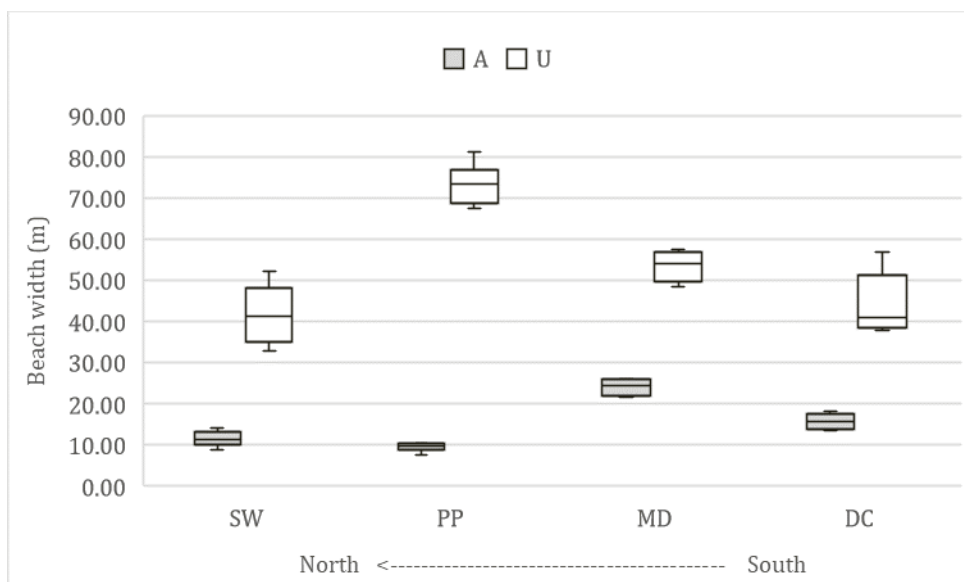


Figure 97. Range of beach widths (m) measured at each southern site Shipwreck (SW), Picnic Point (PP), Meadowdale (MD) and Deer Creek (DC) in Snohomish County, WA. Values are averaged across all survey years 2016 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair. Arrow indicates direction of drift.

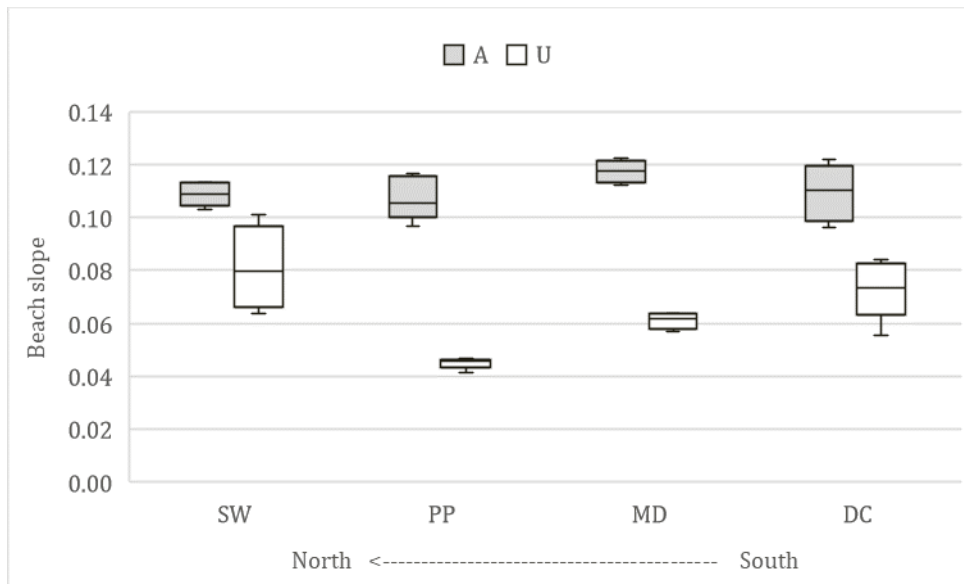


Figure 98. Range of beach slopes (m) measured at each South site Shipwreck (SW), Picnic Point (PP), Meadowdale (MD) and Deer Creek (DC) in Snohomish County, WA. Values are averaged across all survey years 2016 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair. Arrow indicates direction of drift.

Even without active nourishment of the Southern Region, sites still exhibited change in beach profile over our study timeframe, with variation in direction and magnitude observed by site, strata and year. Change in beach toe elevation at Southern sites occurred in the opposite but at smaller scales than Nourishment sites, with slight overall increases at most sites (Appendix Fig. B27). Only Picnic Point and Deer Creek armored exhibited slight decreases in toe elevation. While beach width decreased for the majority of Nourishment sites, we observed equal occurrences of increase and decrease within the Southern Region. However, increases in beach width at sites Shipwreck, Meadowdale armored and Deer Creek unarmored were to a greater degree than decreases at site Picnic Point, Meadowdale unarmored and Deer Creek armored (Appendix Fig. B28). Similar to beach profiles across the Nourishment Region, measures of change in beach slope were less apparent, with most changes in either direction to the scale of millimeters (Appendix Fig. B29).

6.2.2 Sediment grain sizes.

Wrackline and MLW sediment samples from the Southern Region followed similar trends to those in the Nourishment Region, with natural variation in space and time. However, changes through time were not in the same direction as the changes observed at nourishment locations (Table 8, Figure 99). Overall, armored sites were sandier than unarmored sites in the wrackline across all years of sampling, contrasting the signature seen with the Nourishment sites.

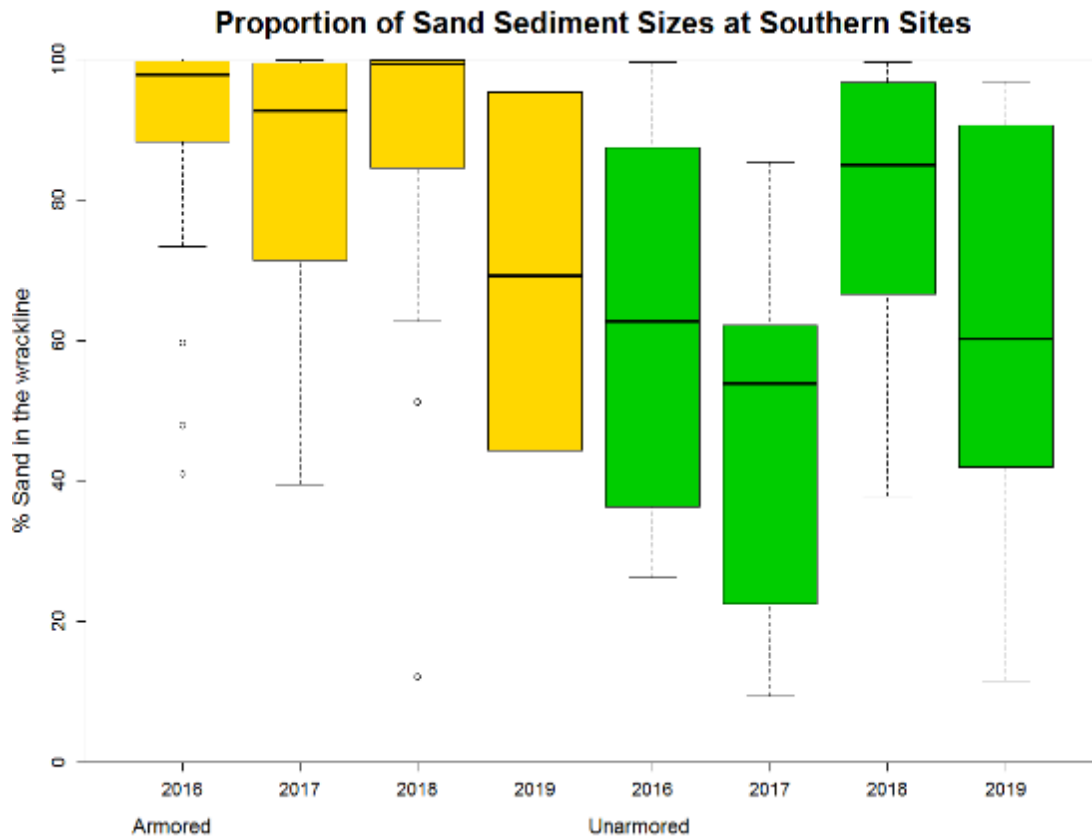


Figure 99. Proportion of sand sediment sizes in the wrack at southern armored and unarmored sites. For all graphs at southern sites, golden colors are at armored sites, green colors are at unarmored sites.

At MLW, changes in surface sediments at the Southern sites are illustrated in Figure 100. While at the Nourishment sites we saw abrupt increases in sand from 2016 to 2017, this change did not occur at the southern sites except for a relatively small increase at the unarmored Meadowdale transect. Most of the southern sites just experienced interannual variation in sand abundance, or a general trend of increasing sand over time. This strongly suggests that the post-nourishment increases and then clear decreases in sand at the Nourishment sites were a result of that intervention rather than a natural pattern. In general, unarmored sites had far more sand than armored sites. BACI analyses of the surface+subsurface sediment data (from the small quadrat samples: not illustrated) showed that sediments differed among Treatments (Armored vs. Unarmored) and Year, but there were no interactions that would have suggested that changes through time occurred differently with treatment.

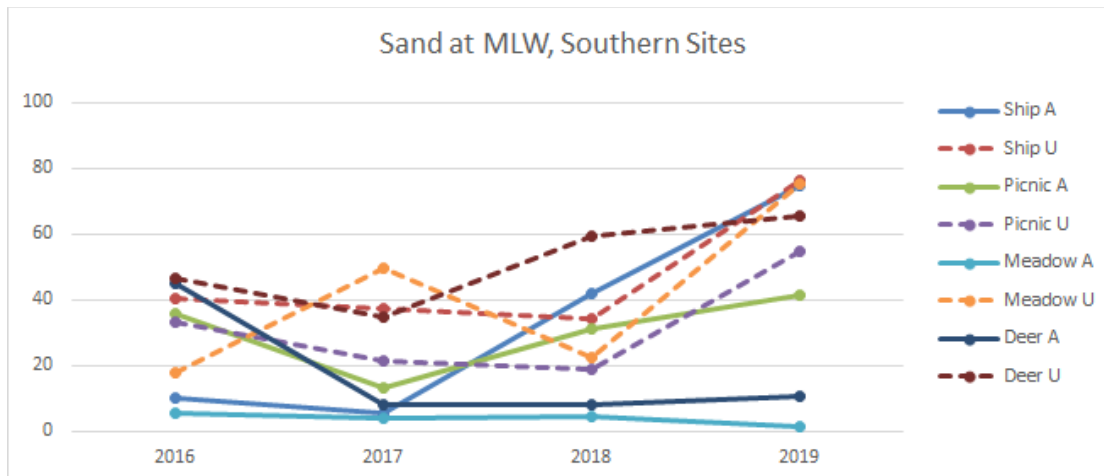


Figure 100. Percent cover of sand at the surface of quadrats at MLW. Each point is the average from 10 samples along the transect. Unarmored sites are shown with dashed lines.

6.2.3 Wrackline sampling: logs, wrack, pitfall traps.

Analysis of the wrack and log line data at the southern sites did not show the interaction with nourishment that was seen in the northern sites, indicative that those results were a result of nourishment, and not natural variation. (Figs. 101-105, Table 8).

Table 8. P-values for analysis at southern sites. Bold indicates $p < 0.05$.

	Site	Strata	Period	Interaction	Site interactions and other notes
Total % wrack	0.003	2.00E-16	0.995	0.97	
Wrack width	1.95E-15	4.64E-12	8.93E-01	0.22	
Wrack depth	0.007	7.50E-13	0.48	0.63	
Log number	5.40E-05	2.20E-16	0.12	0.14	
Log width	3.29E-07	2.20E-16	0.79	0.59	
Wrack total inverts	1.69E-11	0.01	0.59	0.049	Picnic Point, more at UN
Pitfalls total inverts	0.04	0.0002	0.67	0.002	Shipwreck, more at UN
Sediments, %sand	0.002	5.08E-08	0.74	0.24	

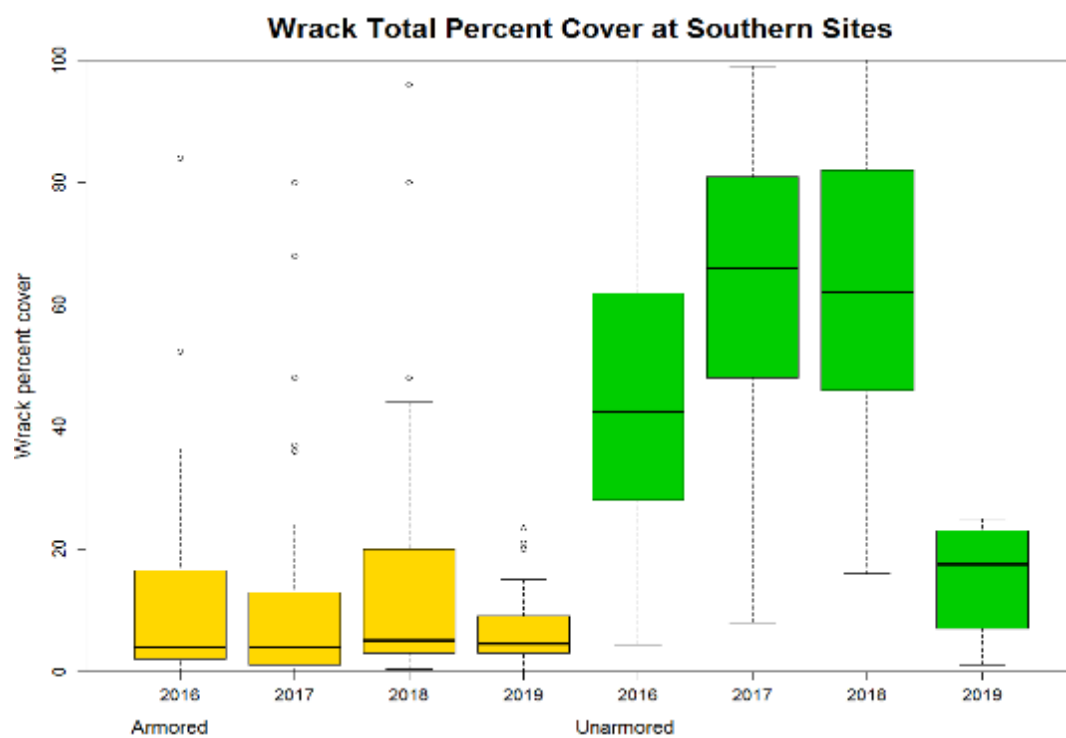


Figure 101. Wrack total percent cover at Southern armored and unarmored sites.

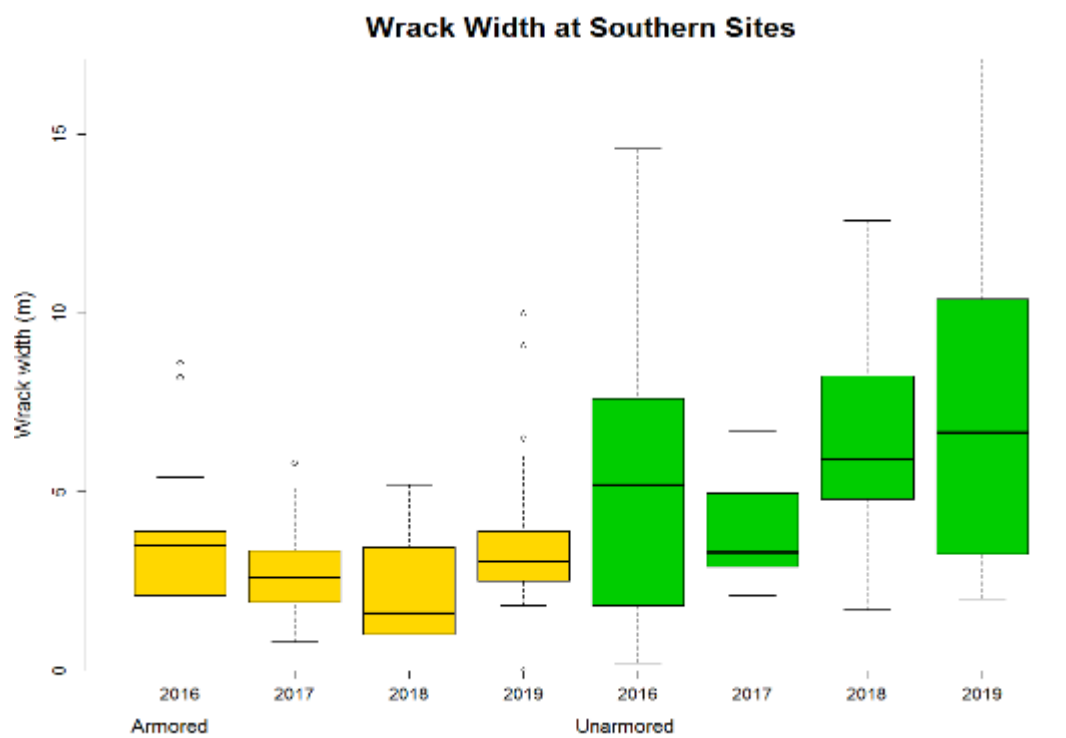


Figure 102. Wrack width (m) at Southern armored and unarmored sites.

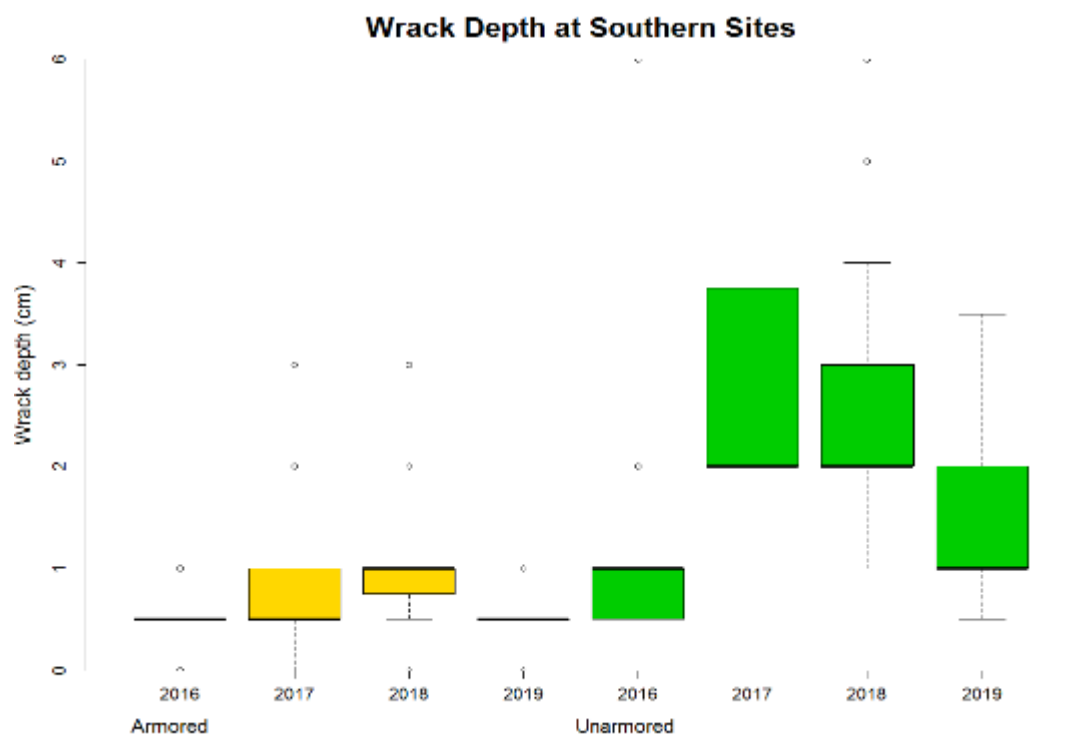


Figure 103. Wrack depth (cm) at Southern armored and unarmored sites.

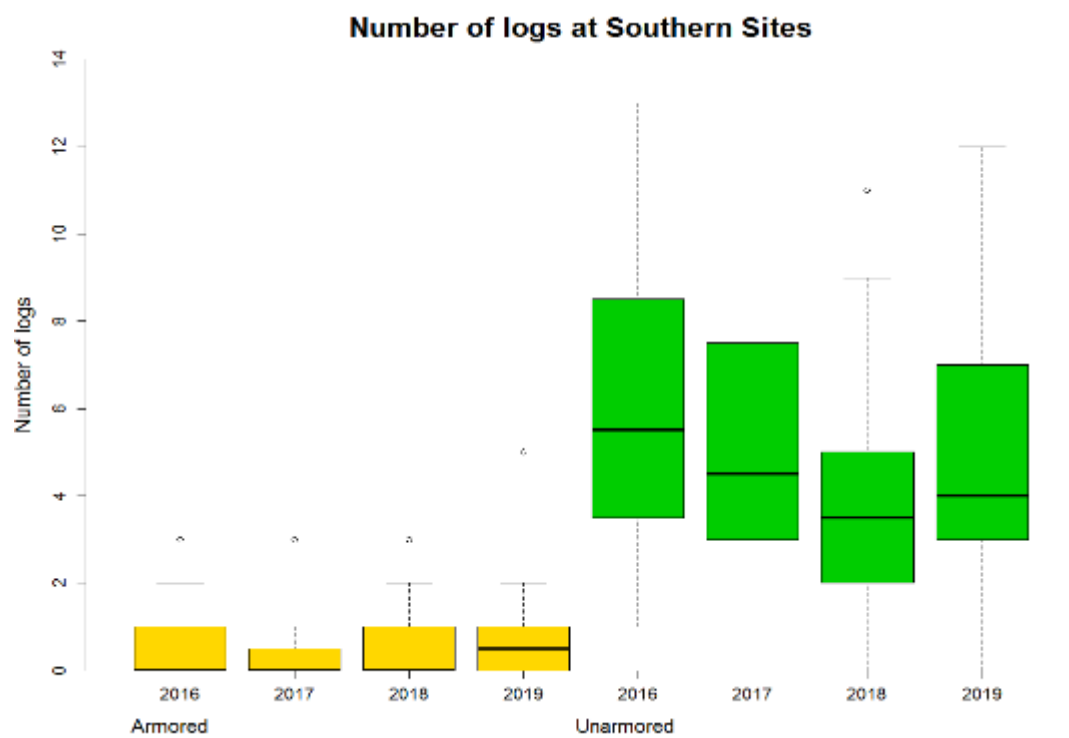


Figure 104. Number of logs at Southern armored and unarmored sites.

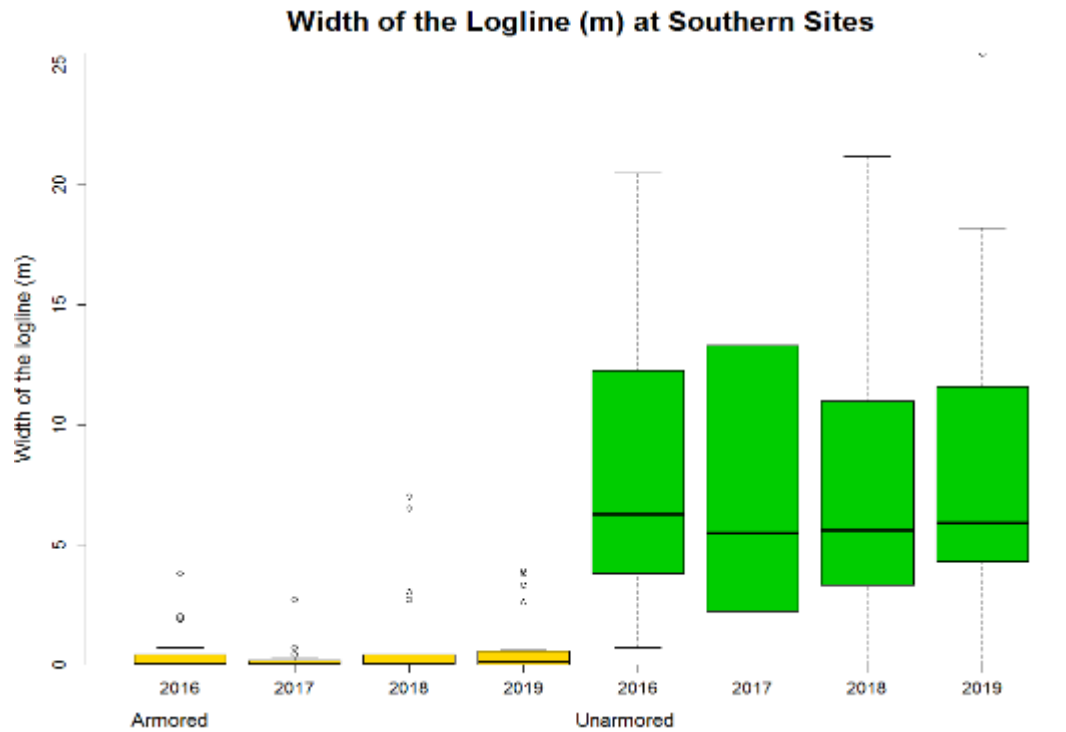


Figure 105. Width of the logline (m) at Southern armored and unarmored sites.

Both sample types of invertebrates (cores and pitfall traps) showed a more extreme difference between unarmored and armored sites, similar to the cores at Nourishment sites, indicating that the decrease in abundance of core invertebrates at Nourishment sites could have been due to natural variation (Figures 106-107, Table 8). There were often striking strata differences between armored and unarmored for all sample types, similar to that found in previous efforts (Dethier et al. 2016).

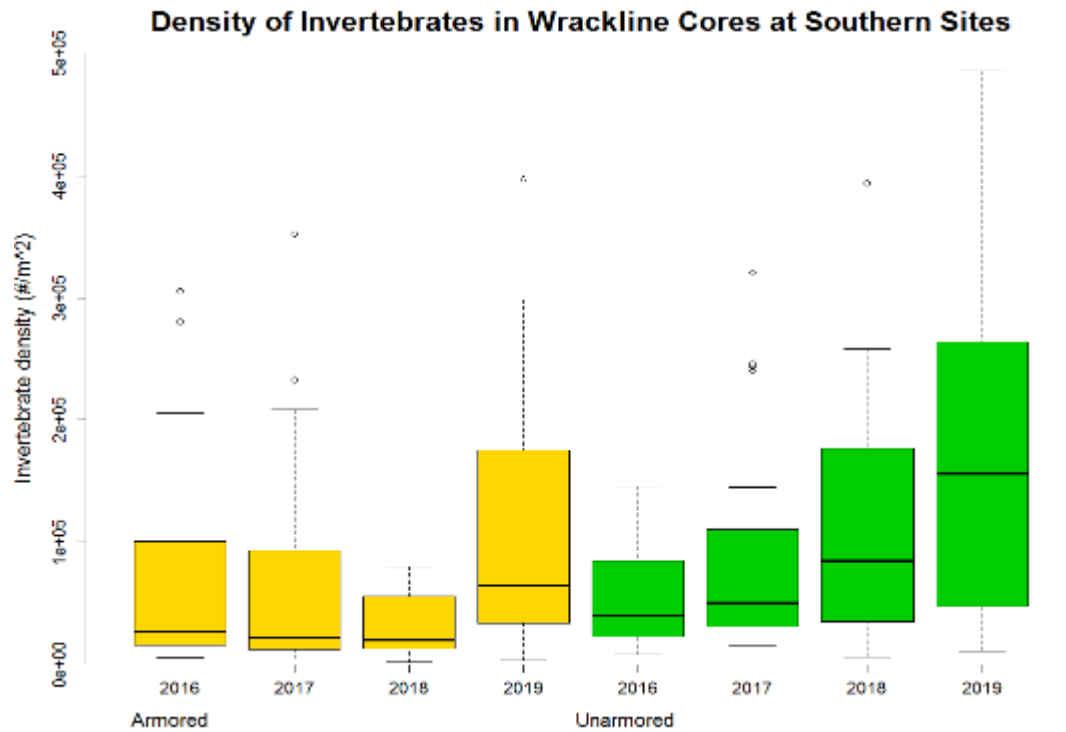


Figure 106. Density of invertebrates in wrack core samples at Southern armored and unarmored sites.

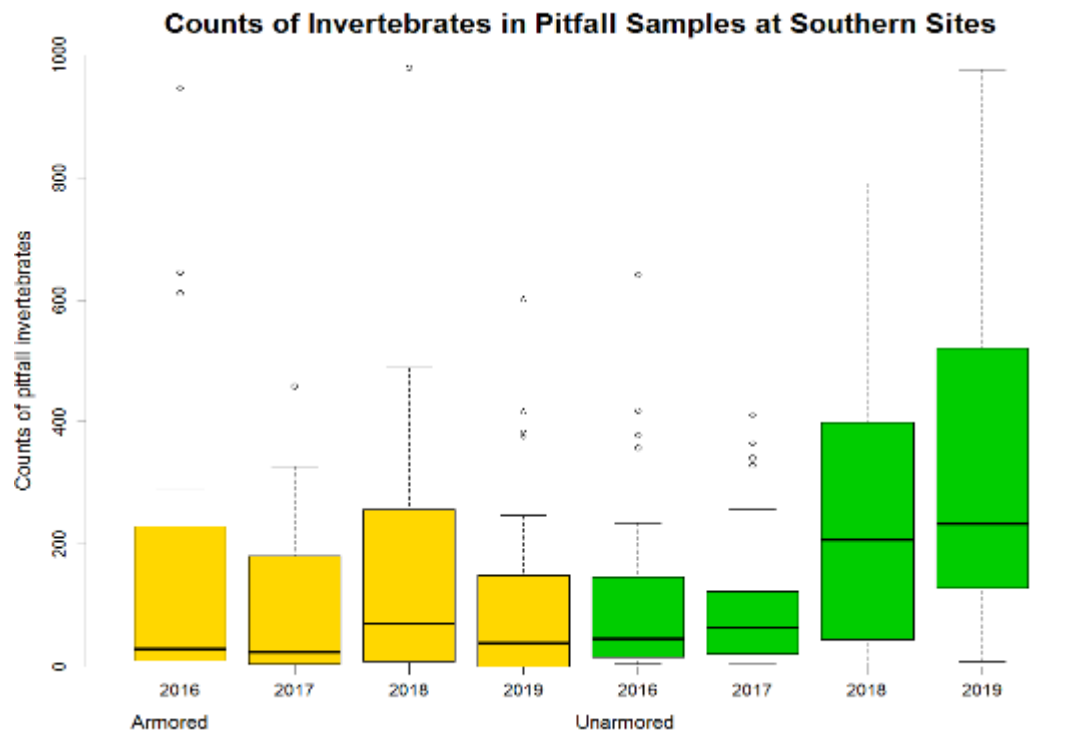


Figure 107. Counts of invertebrates in pitfall samples at Southern armored and unarmored sites.

6.2.4 MLW sampling: surface biota and infauna

In contrast to the sites in the Nourishment region, the biota at MLW in the Southern sites showed no consistent community shifts with time. Unlike at the Nourishment sites, similarity of communities in 2016 (39%) was very close to post-2016 (32%), and there were no clear differences in biota in Before vs. After comparisons. BACI analyses found significant differences only in the biota among Treatments (Armored vs Unarmored), not among years, although the low replication meant that this test had low power to detect change. Figure 108 shows that the key differences among sites and years were those among the Armored and Unarmored beaches. An exception was seen at Deer Creek, where the Unarmored transects were different from those at most other sites. This transect was on the toe of the Woodway slide material (Figure 4) and had different sediments (especially substantial quantities of clay/hardpan) that drove the biotic differences. In general, Armored beaches had substantially less sand (23% averaged among sites and years, vs. 45% at Unarmored beaches). The main biotic differences are that unarmored beaches have more ulvoid algae, barnacles, shore crabs, and predatory infaunal polychaetes; these taxa all tend to be associated with the larger pebbles and small cobbles that provide stability on the unarmored beach faces.

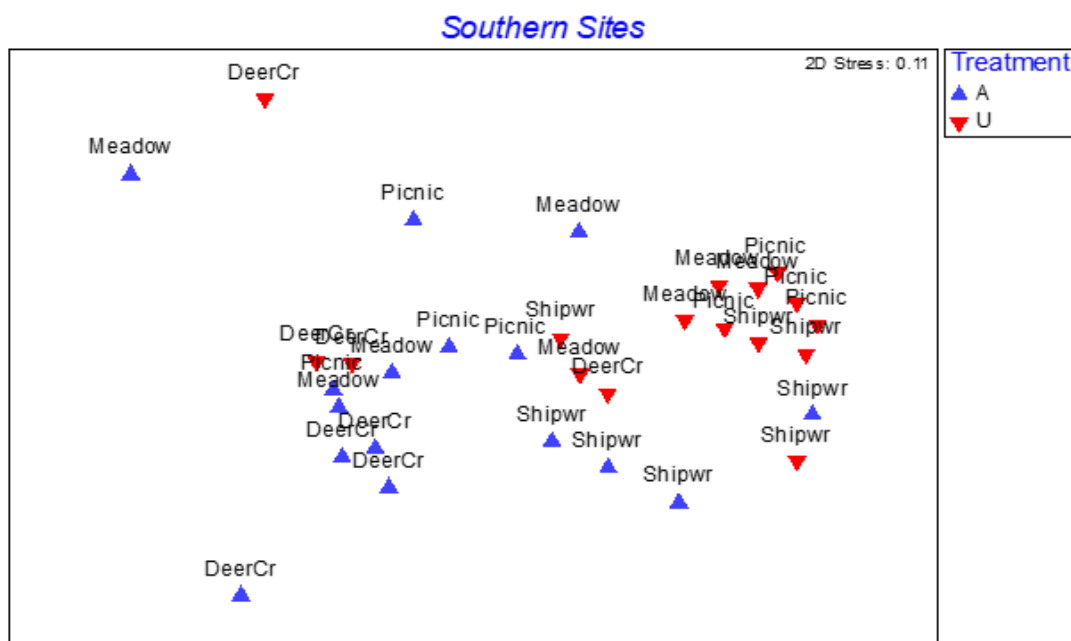


Figure 108. Non-metric multidimensional scaling (NMDS) plots of surface and infaunal biotic communities at the southern sites on each sampling date. Each point represents the community composition (species and relative abundances) across one transect (10 samples averaged) in one year. Points closer together indicate more similar biotic communities.

Interestingly, species richness at the southern transects showed a trend of increasing through time at a number of sites (Figure 109), especially at some of the unarmored beaches, though the taxa per transect was notably less at Deer Creek unarmored with its depauperate clay sediments. Overall, species richness was higher at these Southern sites (average across all

sites and years of 13.4 species per transect) than at the Nourishment sites (10.7 species per transect).

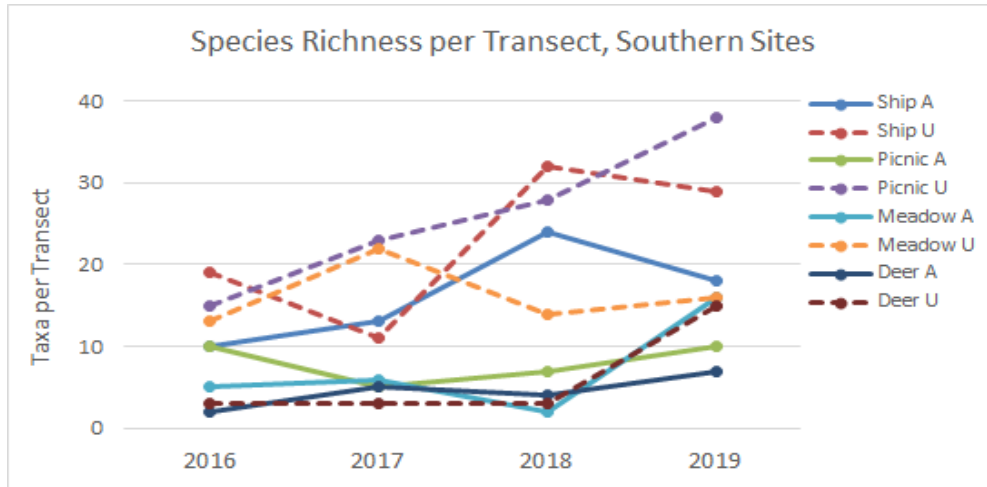


Figure 109. Species richness (total number of taxa per transect) at each southern site before (2016) and after (2017-2019) the timing of beach nourishment at the northern sites. Unarmored beaches are shown with dashed lines.

The negative correlation of species richness with sand abundance seen at the Nourishment sites is actually reversed at the southern sites, where more sand was correlated with higher richness. Further investigation of this pattern showed that this pattern was driven by the armored beaches (Fig. 110); in the unarmored beaches, there was no relationship ($r^2 = 0.002$). Many of the armored beaches at the southern sites were steep and dominated by mobile small pebbles, which is a habitat type supporting very few epibiota or infauna because it is so unstable; beaches that had more sand thus may be indicative of more stable beaches that are able to support more organisms.

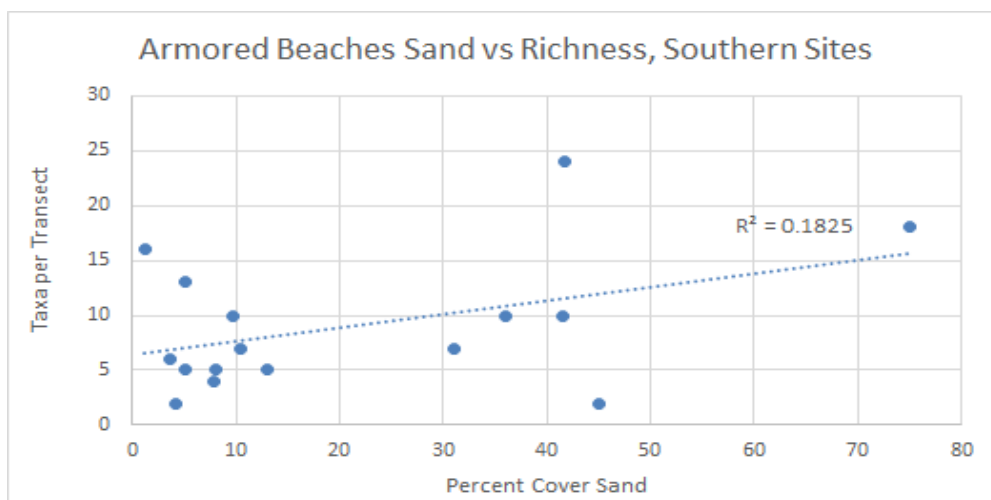


Figure 110. Relationship between percent cover of surface sand and species richness per transect at the southern Armored sites (only).

7 Discussion

The BNSF railroad has been placed for over a century along this stretch of Puget Sound shoreline and presents a unique scenario in which to test restoration actions. Novel restoration actions through the “beneficial use” of sediment nourishment along the railroad grade provided the opportunity to conduct a before-after control-impact study to measure structural and functional responses (physical and biological parameters) to this type of restoration. Moreover, we also included a much older and larger beach modification at the site of the 1997 Woodway slide. This is a rare opportunity to learn from such a large study and inform future recovery and management decisions.

Regional patterns

Overall, the northern (nourishment region) and southern sites differed both physically and biologically; these intrinsic differences complicated our ability to understand nourishment impacts because it was hard to distinguish management impacts from natural spatial variation. In each case, all sites were in front of the railroad grade, and most unarmored sites were on pebble-sand deltas built by small streams. However, analytically our study benefited from the inclusion of the southern sites because we were able to see if the before-nourishment data (2013-2016) differed from the after-nourishment data (2017-2019) in both regions (suggesting broad interannual change) or only in the nourishment region, suggesting a distinct restoration effect.

Broadly, sites across the southern region had lower elevations of beach toe, i.e. elevation of the armoring or berm, and therefore greater relative encroachment of the toe onto the upper shore. Corresponding with this regional difference, southern beaches had narrower widths and steeper slopes compared to the nourishment region. These differences may all relate to higher wave energies at the southern beaches (Finlayson 2006; see Figure 3.2) due to greater exposure to fetch from Puget Sound, while the northern beaches were more protected within Possession Sound (with the exception of uncommon strong northerly storms). Because of these differences in the physical environment, it was not feasible to make broad regional comparisons of upper shore profiles. Instead, differences were more clearly related to site-specific features and whether sites were armored vs. unarmored. While we did not measure oceanographic parameters, it is likely that the waters of the nourishment region are lower salinity because of the influence of the Snohomish River. These riverine waters also leave alluvial deposits of finer sediments at tidal elevations lower on the beach. Both regions had drift cells running consistently south to north.

At Mean Low Water (mid-shore), the beach character differed from site to site but not necessarily by region; some unarmored sites in both regions were on built-up deltas and had substantial coarse sediments stabilizing the beach; others were more protected from waves, and had sediments at MLW that were finer and occupied by ghost shrimp across an extensive beach terrace (Sites 2 and 6 in the north, Shipwreck in the south). All the armored sites were on relatively steep beaches that were dominated by pebbles except for Site 6; here, both unarmored and armored areas were contained within a subtle embayment, and a large

stream culvert running under the railroad grade brought enough sediment onto the shore to build out a delta despite the armoring. Overall, the biota at MLW differed more among regions than among armored vs. unarmored sites, but all differences were subtle and site-specific.

Differences associated with armoring

It is important to acknowledge that as in past studies (Dethier et al. 2016), our data showed substantial overall differences between armored and unarmored beaches that are unrelated to measurements of the effectiveness of nourishment. All wrack, wrack-invertebrate, and log parameters were reduced at armored as compared to unarmored sites along the railroad grade, highlighting the altered condition and functions there and the broad need for restoration actions. The mid-shore sediments and biota also tended to be different between armored and unarmored beaches, although there was other site-to-site variation that related in some cases to wave energy or to underlying geology (hardpan vs. sediment).

Beach profiles were distinctly different between armored and unarmored pairs. At armored locations, beach toe elevation was consistently lower, i.e. emplaced further waterward, and beaches were narrower. However, in the nourishment region, beach width varied considerably from site-to-site. Some of the observed armored-unarmored differences, especially on the mid-shore and in metrics such as beach width, likely relate to the unarmored sites mostly being placed on (or on the fringes of) deltas created by small streams that issue from culverts under the railroad grade. Since these deltas provide more ‘natural’ habitat than the beaches in front of the railroad armor, and because they provide sediment that moves along the drift cell, they may have substantial ecological importance to beaches in this region in addition to their use by salmonid fishes (Beamer et al. 2005). Giving these small stream mouths the opportunity to connect more naturally into Puget Sound, so that they can provide not just sediment but improved fish passage, is an important future restoration focus, with a systematic identification and rating of all streams and embayments recently completed ([factsheet available here](#)).

Sediment grain sizes high on the shore did not follow the pattern sometimes seen in armored-unarmored comparisons, i.e. the high shore was not necessarily sandier on unarmored beaches. In the southern region, at the wrack-line, armored sites were actually sandier as compared to unarmored sites. This was not the case in MLW samples. In the nourishment region, sediment samples collected at MHW also did not show a strong effect of armor; instead, the dominant substrate class (i.e. sand vs. pebble) varied more among sites and survey years. This was also true of substrate size evaluated at forage fish sample sites, where additional variation was seen among sample months (Oct-Feb), particularly prior to beach nourishment. Thus, all our data suggest that grain size data are spatially and temporally highly variable and hard to attribute to any one cause.

Changes associated with nourishment

For metrics derived from beach profiles, we found it difficult to separate strong site-to-site variability from effects related to nourishment at both armored and unarmored locations. This lack of consistent effect likely relates in part to sediment moving downdrift from where it was

emplaced, rapidly obscuring the differences between sites. Changes following nourishment in measures of beach toe elevation, width and slope were slight overall and varied in both direction and magnitude between sites and survey years. For the most part, we found that following beach nourishment, armored and unarmored locations became more similar in their beach profiles, but greater change was often observed at armored locations, particularly in beach slope. We also observed a lowering of elevation at beach toe across nearly all sites, except for the unique situation at Site 13 where shoreline armor was removed in conjunction with nourishment. However, this reduction in toe elevation was similarly observed across most sites in the southern region, suggesting it was independent of nourishment treatment.

For some parameters measured in the wrackline, we found nourishment to have an overall positive effect, seen in increases in total percent cover of wrack, depth of wrack, and number of logs (Table 9). Site 13 showed the most positive responses in wrack and log measurements; this was the site that also included armor removal, placement of logs, and planting of vegetation, as opposed to the other project sites that only had sediment nourishment. However, parameters related to invertebrate responses showed no effect of nourishment, or at some sites actually showed a negative effect where numbers of wrackline invertebrates decreased following nourishment, although this signature was also seen in the un-nourished southern region. The percent of sand at the wrackline ultimately showed a negative response, either because the sandier sediment washed away post nourishment, or in the case of Site 13, where coarser sediments were placed compared to other nourishment sites.

Table 9. Summary of statistical evidence of sediment nourishment effectiveness for wrack and log measured parameters, comparing armored versus unarmored and before versus after nourishment. Blue shading or font indicates a positive response, orange negative, and white no effect.

Over all 4 sites	Specific site responses
Total % wrack	Site 13, Site 2
Wrack width	
Wrack depth	Site 13
Log number	Site 13, Site 6
Log width	
Wrack total inverts*	Site 9, Site 6, Site 2
Pitfalls total inverts	
Sediments, %sand	Sites 13 and 6

*not colored as negative, as southern sites saw the same response

For parameters measured lower on the shore, sediments did show an increase in sand at the nourishment sites, but this change sometimes only lasted a year before the sand moved away, presumably to downdrift locations or into deeper water. In general, biotic communities at this mid-shore level are not very diverse, with only 5-20 macroscopic species found per transect, a mix of surface algae and invertebrates, and a few infaunal clams and worms. These communities are more species-rich when the sediment is stabilized by cobbles; beaches where

the sediment is predominantly unstable pebbles or pure sand tend to have fewer plants and animals. Thus, the addition of sand from nourishment efforts created a habitat that was better for clams in the short-term but tended to reduce numbers and diversity of other beach biota.

At both nourishment sites and downdrift from these locations we measured surface sediment size at a beach elevation where forage fish would typically be expected to spawn seasonally. As beach nourishment was primarily of sandy material for the SCBNP, the predominant change was to reduce surface substrate size immediately as-built and within months downdrift of project implementation. This improved the substrate size favorability for Pacific sand lance spawning, but not for surf smelt. The beach nourishment material at sampled locations immediately downdrift generally persisted longer than at the actual nourishment sites, where we estimated the loss of sand ranged from 66-105 cubic yards per month. The persistence of drift appeared to be influenced by beach accretionary shoreforms like small creek deltas. Downdrift from Howarth Park, where no accretionary shoreform was present, drift of sand was less persistent, noted as substrate size reversion toward pre-project conditions over the study period.

The change in substrate size favoring the more widely spawning PSL appeared to actually support more spawning (based on egg count) at several downdrift locations. No directly nourished sites supported more PSL or surf smelt egg count. Conversely, the restoration of the Howarth Park site (that included coarse gravel at Site 12S7) likely contributed to the reduced PSL spawning, but supported limited surf smelt spawning in year one post-restoration. These varied changes all provide insight to forage fish spawning responses to substrate alteration that are consistent with our interpretation of the role of substrate size.

In the case of surf smelt, observed spawning was spatially restricted to the areas of higher substrate favorability (mainly small gravel) we documented at Site 13 downdrift from Howarth Park. Post-restoration the gravel size became finer with drifting sand, and more variable by month. However, we did not observe a statistically negative response by surf smelt at Site 13. In fact, we may have seen opportunistic spawning at Howarth Park where substrate was favorable, at least in year one post nourishment. Hence, because the nourishment effects were both detectable and variable by location (treatment), by time (Pre- and Post-) and by species, our understanding of potential benefits and risks is modestly improved. Figure 111 summarizes the processes and functions hypothesized to change following beach nourishment, the metrics we monitored, and a simplified summary of our findings.

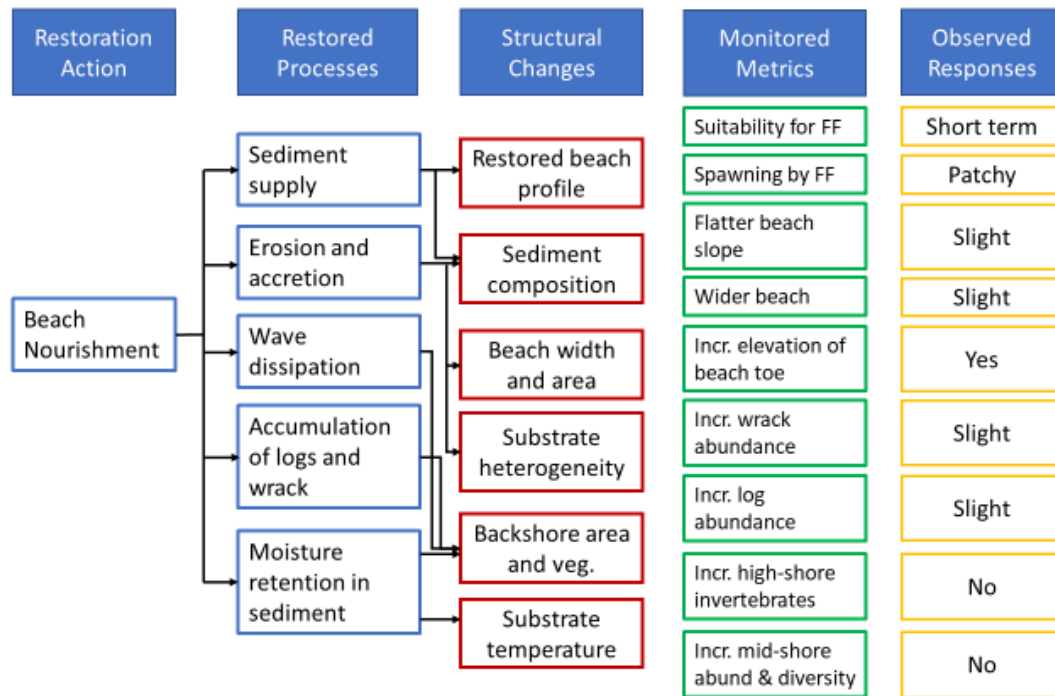


Figure 111. A conceptual model of the impacts of using beach nourishment as a restoration action. Modified from Clancy et al. 2009.

Beach nourishment drift and persistence

Drift rate, or the speed of sand loss from the nourishment footprint, appeared to be affected by a combination of important factors including the relative encroachment of built structures on the beach, exposure to drift forces, and the size of nourishment material used. Placement of beach nourishment material is generally determined by the location of the toe of the encroaching structure. In the case of the railroad, this was somewhere between the bluff face and the beach terrace (Figure 1). As the remaining beach width is necessarily correlated with relative encroachment, secondary factors that can modify drift rate are beach terrace extent and beach slope. Shoreform shape (convex versus concave) is also important. Among our sites, the rate of drift (or loss of sand we observed) from the placement location varied as follows;

- 1.) Fastest, where encroachment was greater (lower toe of armoring); beach width was narrower; beach slope was steeper; and wave energy was higher due to a straight or convex shoreform with no adjacent accretionary shoreform (to interrupt longshore transport) or wider beach terrace (to dissipate wave energy).
- 2.) Slowest, where the shoreform included a subtle embayment (concave feature) or abutted a creek delta (accretionary shoreform), even where the armoring toe was low.

Drift at these sites was also likely slowed by a wide beach terrace with very low slope because this could potentially dissipate wave energy.

- 3.) Intermediate in rate where the relative encroachment was low (allowing back beach placement of nourishment), and the beach was wider. In some instances, the drift of material may have been modified (slowed) by an adjacent accretionary shoreform that simply acted to back up the transport of particles around the shoreform.

Accretionary shoreforms maintained the longest persistence of drifting sediment and were affiliated with high favorability of PSL spawning substrate size, PSL egg presence, and egg count. Unfortunately, our data suggest that the numerous factors acting to impair natural beach functions and affect beach nourishment outcomes are highly site specific. This makes it challenging to classify site suitability or create a definitive decision-making framework. However, our data on these interacting factors contribute some explanatory value for decision-making, as a set of considerations to be used alongside other logistical issues. For example, if retention of beach nourishment at the location of placement is a high priority, then the type of sites supporting that objective might include ones with a wider beach, lower slope, broader terrace, concave shape, and higher elevation of armoring. That would be particularly true for the size of beach nourishment material used in this study, originating from stockpiles of clean Snohomish River dredge material. Ironically, these 'high priority' sites are ones that already have relatively high levels of ecological functions.

How well did nourishment fulfil its mission to make the beach more natural?

The degree to which nourishment of beaches in the SCBNP made the beach more "natural" or higher-functioning depends on the parameter being considered. The addition of sand and the general increase in beach width and slight decrease of beach slope that immediately followed nourishment brought those parameters into a range that likely is closer to historical conditions that existed before the drift cells became sediment-starved by the railroad grade. Numbers of logs and amount of wrack reflect these more-natural conditions, and some data on forage fish spawning suggest a general improvement in beach functions. However, since emplacing large amounts of sediment onto a beach face constitutes a major disturbance, it is not surprising that there were negative immediate consequences to invertebrate communities at the wrackline and to a lesser extent in the mid-shore. As the rate of drift and changes in some parameters, like substrate size favorability, were relatively rapid, any negative effects from smaller scale nourishment (i.e. SCBNP) might be shorter lived, compared to much larger nourishment like the Woodway slide.

A recent study from southern California found that at beaches with intense maintenance regimes of sediment filling and grooming (done to create wider beaches for human recreation), invertebrates are negatively impacted especially in the upper intertidal wrack zone (Schooler et al. 2019). Scientific reviews have suggested that even though nourishment is generally considered as an environmentally-friendly option for beach restoration, sizeable negative impacts on several beach ecosystem components can occur, and thoughtful monitoring and interpretation is needed (Peterson and Bishop 2005, Speybroeck et al. 2006, Defeo et al. 2009).

If the sediment had remained in place on the nourished and downdrift beaches we studied, with limited additional human intervention, it is likely that invertebrate communities would eventually have responded positively to the more natural/higher abundances of wrack and structure provided by woody debris.

We do not have data to address the time frames that would be required for more natural backshore vegetation to develop following nourishment, or if in fact there would be any effect on those habitats of beach nourishment. This is particularly true in the SCBNP area as encroachment of the railroad provides a hard limit to backshore extent. Backshore riparian vegetation is likely important in providing not only shade for the upper shore but a source of insects to nearshore habitats. None of our data suggest any effect of nourishment at the SCBNP sites on these parameters, though we recognize it was not a specific design objective to improve backshore riparian vegetation. Outside of our transect locations we made anecdotal observations of nourishment storage in back beach locations that contributed to development of a beach berm, suggesting some functional improvement is possible. At most sites where alongshore drift is prominent, smaller amounts of nourishment material cannot persist long enough or with a large enough spatial footprint to create a back beach; thus, functions associated with marine shoreline buffers cannot develop waterward of the railroad grade.

A possible exception to this limitation is suggested by the Woodway slide (Deer Creek unarmored site), where the 'nourishment' was of a very large spatial scale and sediment volume. At this location, the site changed from an armored location to unarmored (in the sense of this study) as the slide material nourished the beach face. Over time a treed buffer spatially separated the railroad armor from the beach. Our results suggest that for physical parameters (beach width, slope, toe elevation, sand content at MLW), this site very much resembles other unarmored locations. Similarly, the wrack and log metrics resemble other unarmored beaches. However, the mid-shore biota in the Deer Creek unarmored samples do not cluster with the other unarmored sites and species richness was low, likely due to the clay-rich sediments brought by the slide. This site ended up being intermediate between armored and unarmored sites.

8 Conclusions and Recommendations

Our learning project used the Snohomish County Beach Nourishment Program as the centerpiece of a monitoring effort to assess the success of nourishment and other treatments in restoring a variety of beach functions. Based on prior data from comparisons of armored and unarmored beaches, we hypothesized that beach nourishment would change beach textures and profiles, in particular making beaches wider, less steep, and with more sand. At the nourished sites and in some cases in the downdrift areas, we found that beach width did increase and there was generally more sand, but these changes sometimes lasted only for months, and rarely longer than a few years. Changes in beach slope were negligible. Persistence of added sediment correlated with a variety of physical features; where there was a downdrift delta or another shoreform that blocked drift, the beach retained sediment for longer; beaches that had higher wave energy lost sediment more quickly; and beaches where the

railroad grade was relatively low on the shore and consisted of vertical armoring that reflected wave energy lost added sediment very rapidly. At some sites sediment was washed lower on the shore, visible in a signal of increased sand on mid-shore transects.

We expected that physical changes resulting from nourishment would result in increases in logs, wrack, and abundances of insects and benthic fauna, especially on the upper shore. Such results were found at only a few of the surveyed sites; at many sites the addition of sediment to the upper shore actually caused a decrease in invertebrates as their initial habitat was disturbed by this management measure. Our data thus suggest that, at least over a 3-year time frame following nourishment, managers cannot expect to see increases in beach-dependent biota such as insects and high-shore invertebrates that could provide trophic support for organisms such as juvenile salmonids feeding nearshore.

In the mid-shore, beaches where sand cover increased experienced a decline in flora and fauna, since mobile sand is a difficult habitat for most species. In general, nourishment of the upper shore had few impacts on the biota of the mid-shore; instead, chronic differences between armored and unarmored beaches tended to persist.

We further expected that the addition of fine sand to sediment-starved beaches in front of the railroad grade should encourage forage fish spawning. Some of our data suggest that this function was improved by beach nourishment, in that appropriate-sized sediments for forage fish spawning increased over variable time scales at or downdrift of the nourishment sites. Because actual spawning behavior is so unpredictable spatially, it is impossible to say that nourishment actually increased forage fish production, but the potential, i.e. suitable substrate, is clearly present.

Along heavily urbanized shorelines with little hope of complete restoration, such as along the BNSF railroad, nourishment can improve some structural and functional aspects of shorelines, but these improvements are unlikely to persist for longer than a few years when limited in scope and scale. This is at least the case with respect to the current test of beneficial re-use of Snohomish River sediments, but may not be true for beach nourishment generally as a regional restoration action. Limitations to benefits, such as application at more exposed locations and those relating to substrate size and area of treatment (leading to rapid loss) are informed by this study. Certainly, the use of a sediment mix including larger-sized material might have produced different results along the railroad armor, for example broader incidence of surf smelt spawning among sites, and greater persistence of emplaced materials on-site. Because our evaluation of beach nourishment is with reference to the efficacy of re-used fine material, more general recommendations about beach nourishment are not warranted.

Longer term monitoring may be needed to adequately assess alternative scales or scope of treatment, likely along with continued experimental nourishment interventions and maintenance. If nourishment were implemented at the scale of the Woodway slide, then we could confidently say that some structural and functional aspects of shorelines would persist for longer than a few years, as is observed at this unique site. However, our work indicates that benefits are uncertain, and there are treatment risks that undoubtedly depend on many interacting factors

operating at short (e.g., variability across months in beach substrate size) and longer time frames (e.g., shoreform topography) that likely would further interact with the scale of treatment or type of nourishment material used.

Restoration alternatives should be explored, such as improving areas where coastal streams are routed under the railroad through culverts that may be undersized or in poor condition. Additionally, in situations where armor can be removed, targeting efforts at the base of feeder bluffs that are updrift of armored sites will provide natural sediment input to beaches downdrift ([ESRP Beach Strategies](#)). Additional application of beach nourishment material likely constitutes a beneficial re-use of dredged material, and results from this study can help inform siting of similar treatments. However, because of the spatially limited and short-term success we observed in improvement of beach functions, sediment nourishment should not be considered in isolation as an optimal management action or measurement of performance for most restoration programs.

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Appendix A.

Table A1. Summary of types of sampling done at each site. Sites are arranged from South to North which is also the direction of drift. 13Ar and Un also had seasonal wrack sampling 2017-2019.

UW Site Name	SnoCo Site ID	Treatment	Years Beach Profiles	Years Wrack Studies	Years MHW Sediments	Forage Fish Sampling/ Sediment	Years MLW Biota/ Sediment
Deer Creek Ar		None	2016-9	2016-9			2016-9
Deer Creek Un	(Woodway)	None	2016-9	2016-9			2016-9
Meadowdale Ar		None	2016-9	2016-9			2016-9
Meadowdale Un		None	2016-19	2016-19			2016-19
Picnic Pt Un		None	2016-19	2016-19			2016-19
Picnic Pt Ar		None	2016-19	2016-19			2016-19
Shipwreck Un		None	2016-19	2016-19			2016-19
Shipwreck Ar		None	2016-19	2016-19			2016-19
2 Un		None	2016-19	2013, 2016-19			2016-19
2 Ar	2S7	Nourished	2016-19	2013, 2016-19		2011-20	2016-19
--	2N7	Downdrift				2011-20	
--	5S7	Nourished				2011-20	
--	5N7	Downdrift				2011-20	
6 Ar		Nourished	2016-19	2013, 2016-19			2016-19
6 Un	6S7	Downdrift	2016-19	2013, 2016-19		2011-20	2016-19
--	9S7	Nourished				2011-20	
--	9N7	Downdrift				2011-20	
9 Un		Nourished	2015, 16, 18, 19	2013, 2015-19	2015, 7, 8, 9	2011-20	2016-19
9 Ar		Downdrift	2015, 16, 18, 19	2013, 2015-19	2015, 7, 8, 9		2016-19
--	12N7	Downdrift				2011-20	
--	12S7					2011-20	
13 Ar	HP7	Nourished	2015-19	2013, 2015-19	2017, 8, 9	2011-20	2016-19
13 Un	13S7, 13S 10	Downdrift	2015-19	2013, 2015-19	2015, 7, 8, 9	2011-20	2016-19
--	13N7, 13N 10	Downdrift				2011-20	

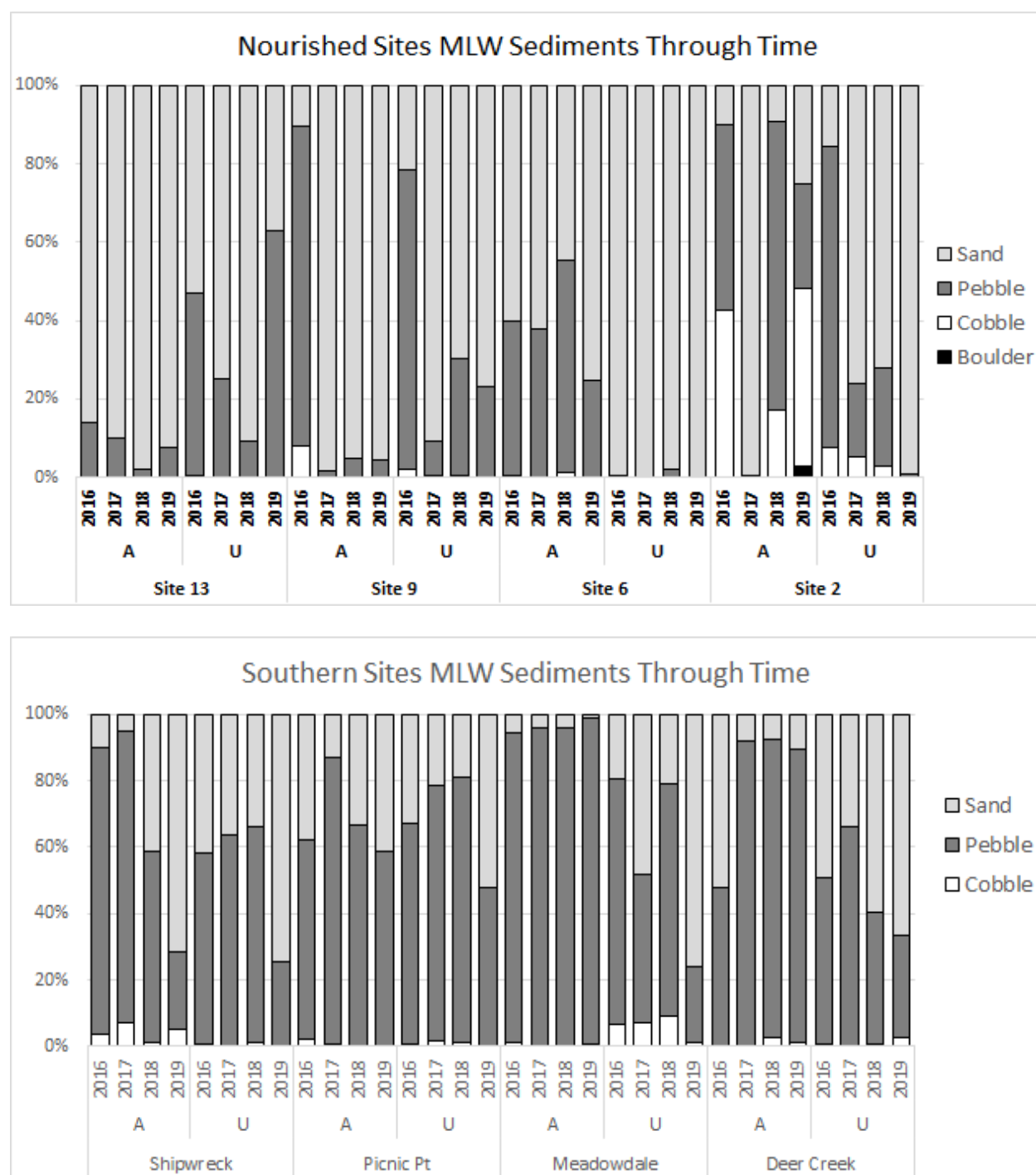


Figure A1. Surface sediment composition at all sites and dates sampled.

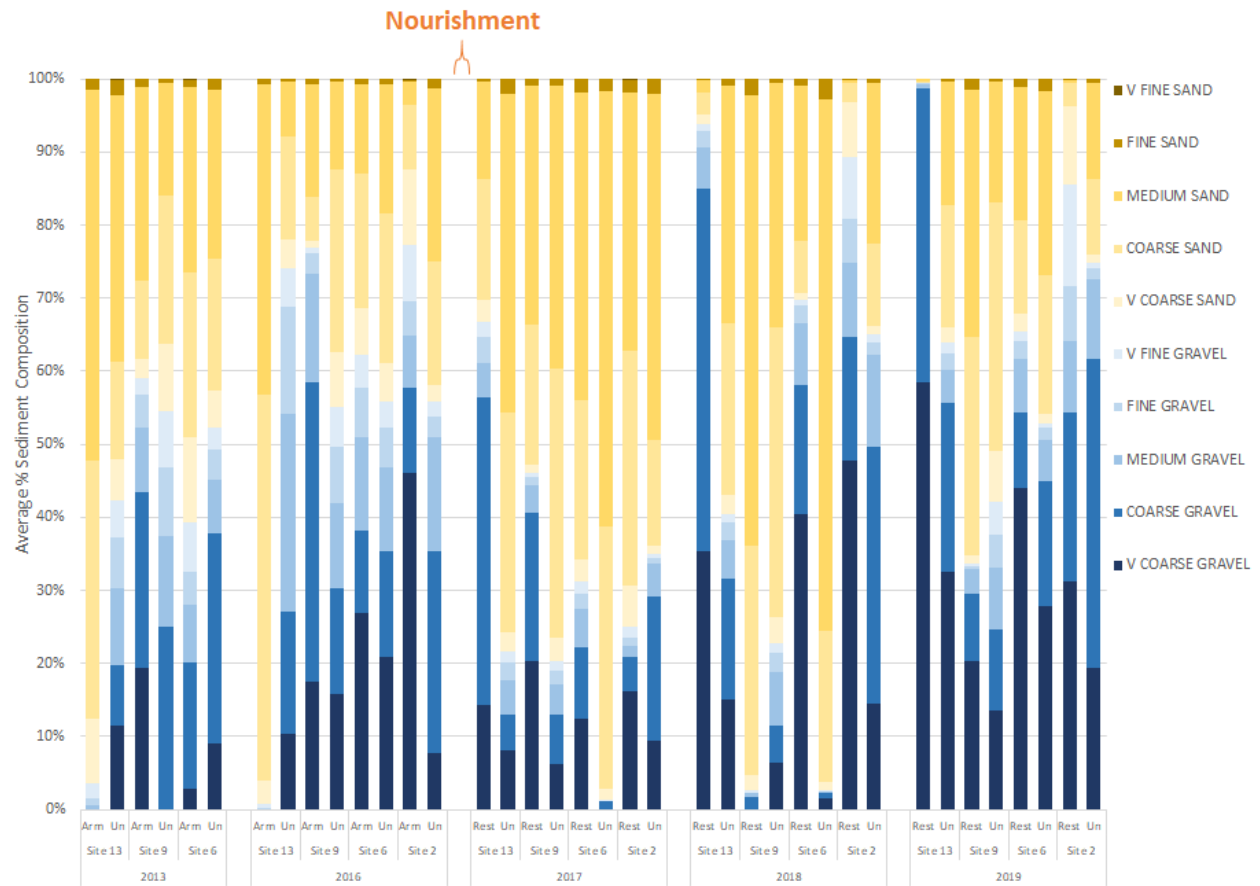


Figure A2. Percent composition of sediment sizes from the wrackline at nourished sites.

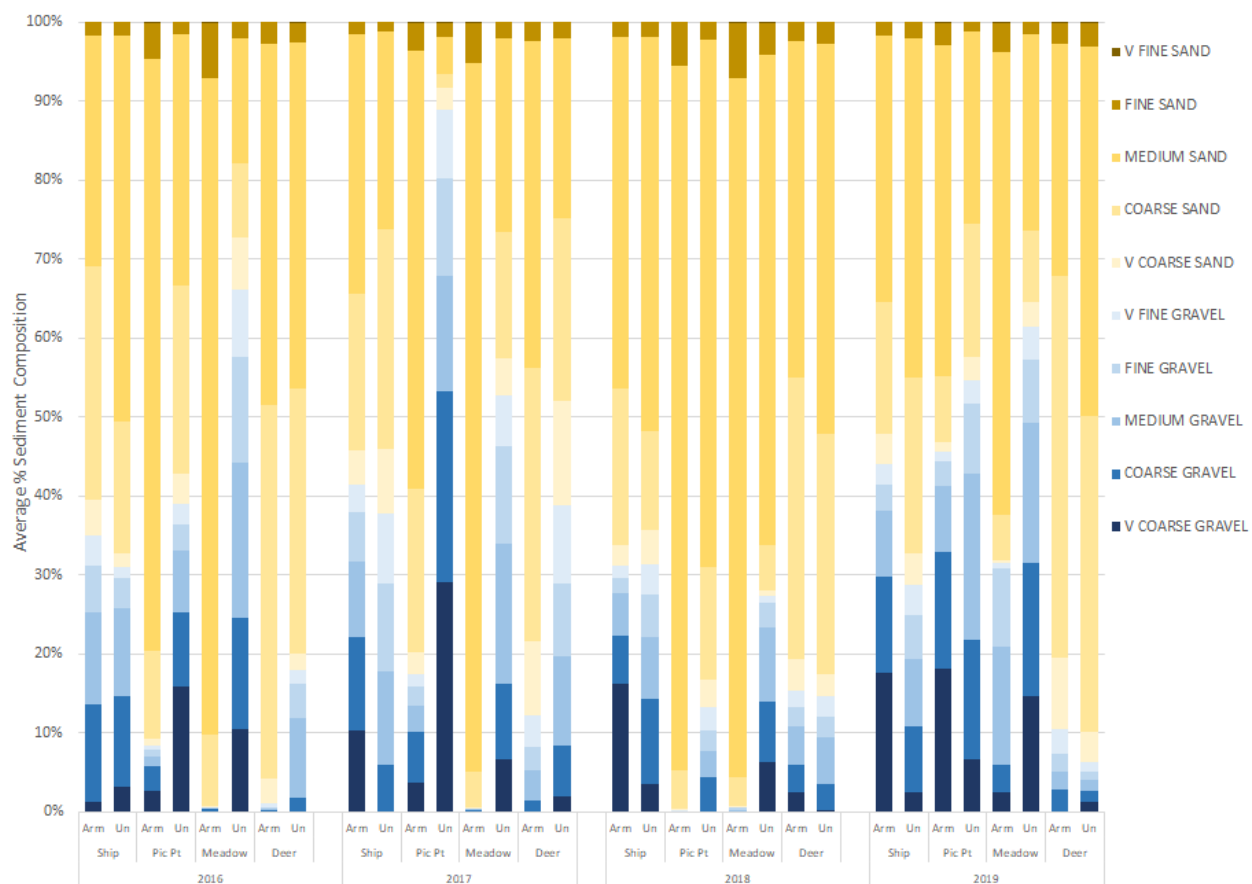


Figure A3. Percent composition of sediment sizes from the wrackline at southern sites.

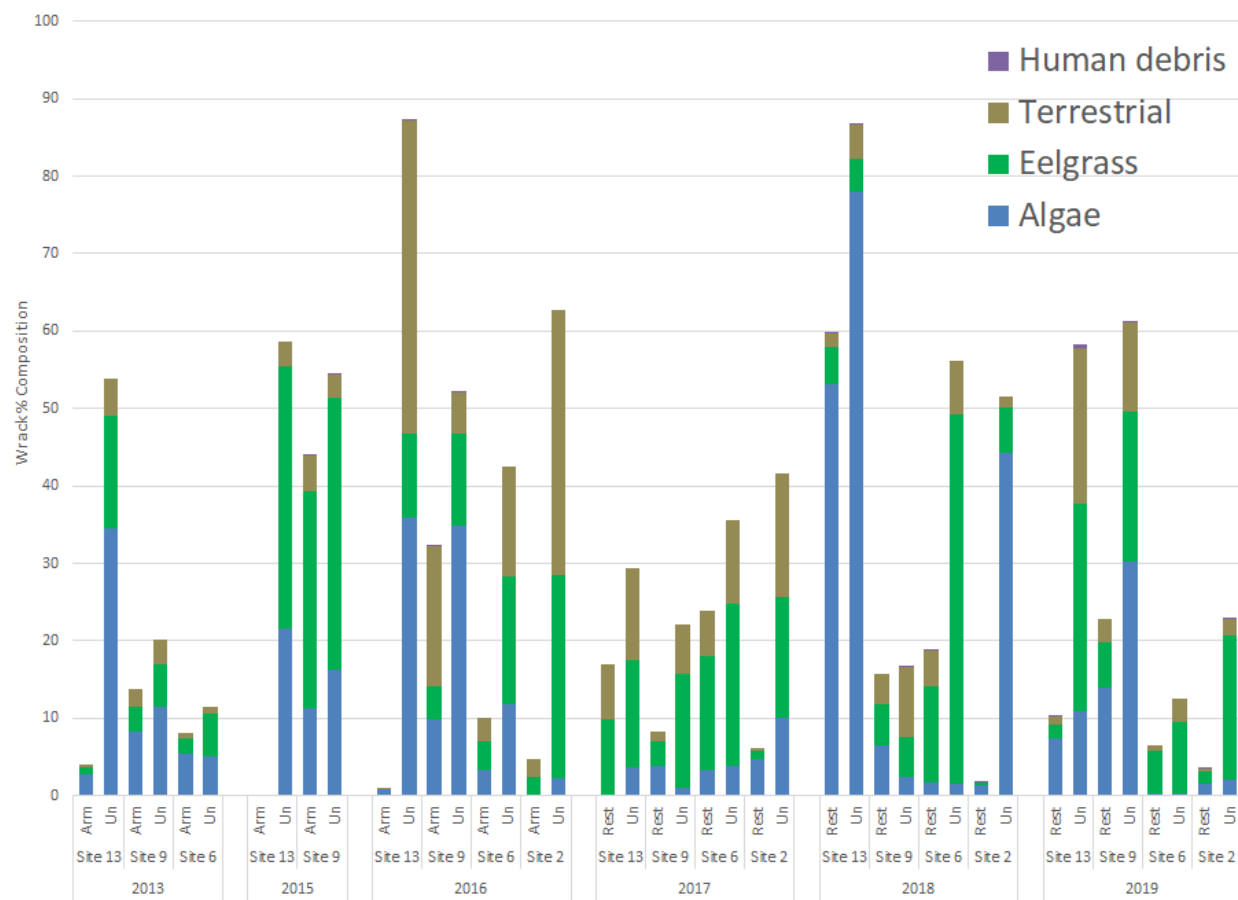


Figure A4. Percent cover of wrack at nourished sites.

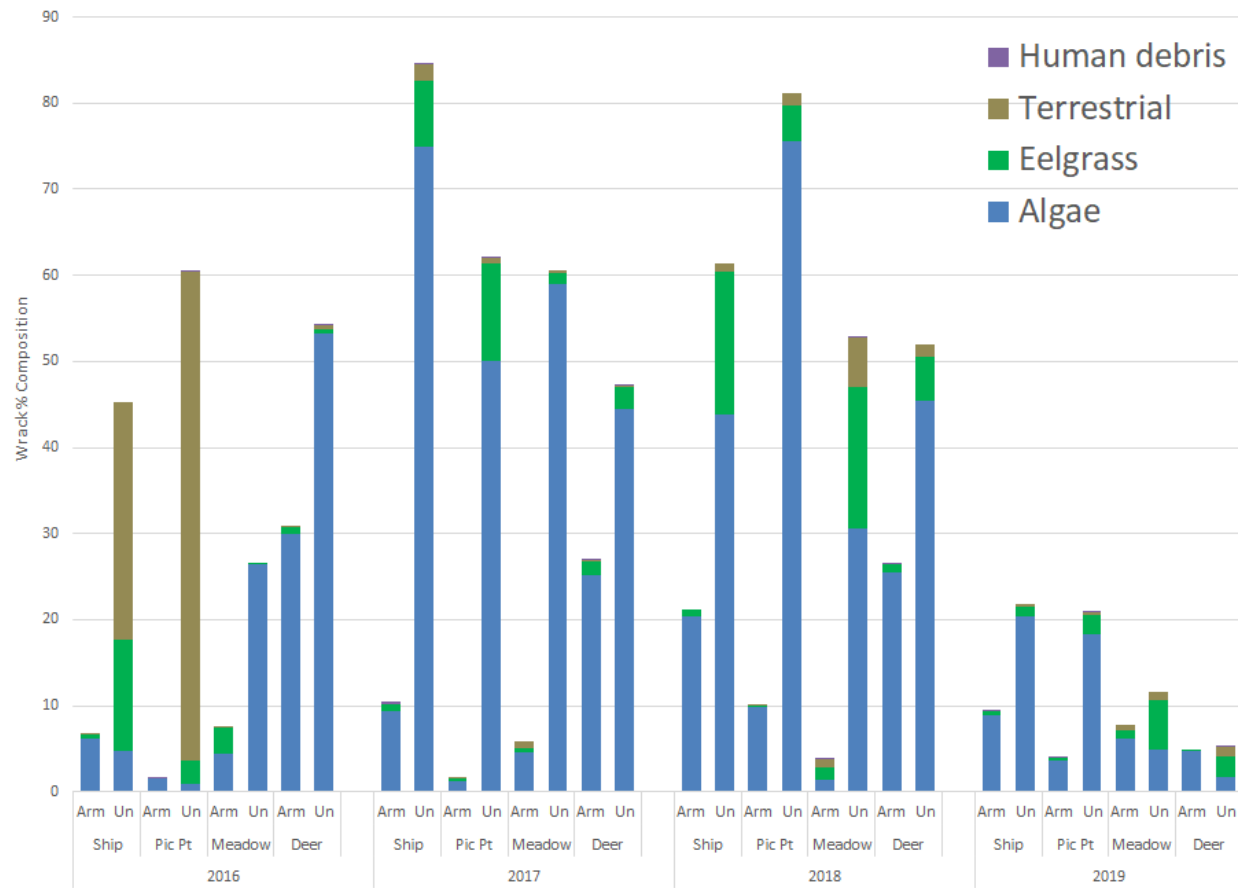


Figure A5. Percent cover of wrack at southern sites.

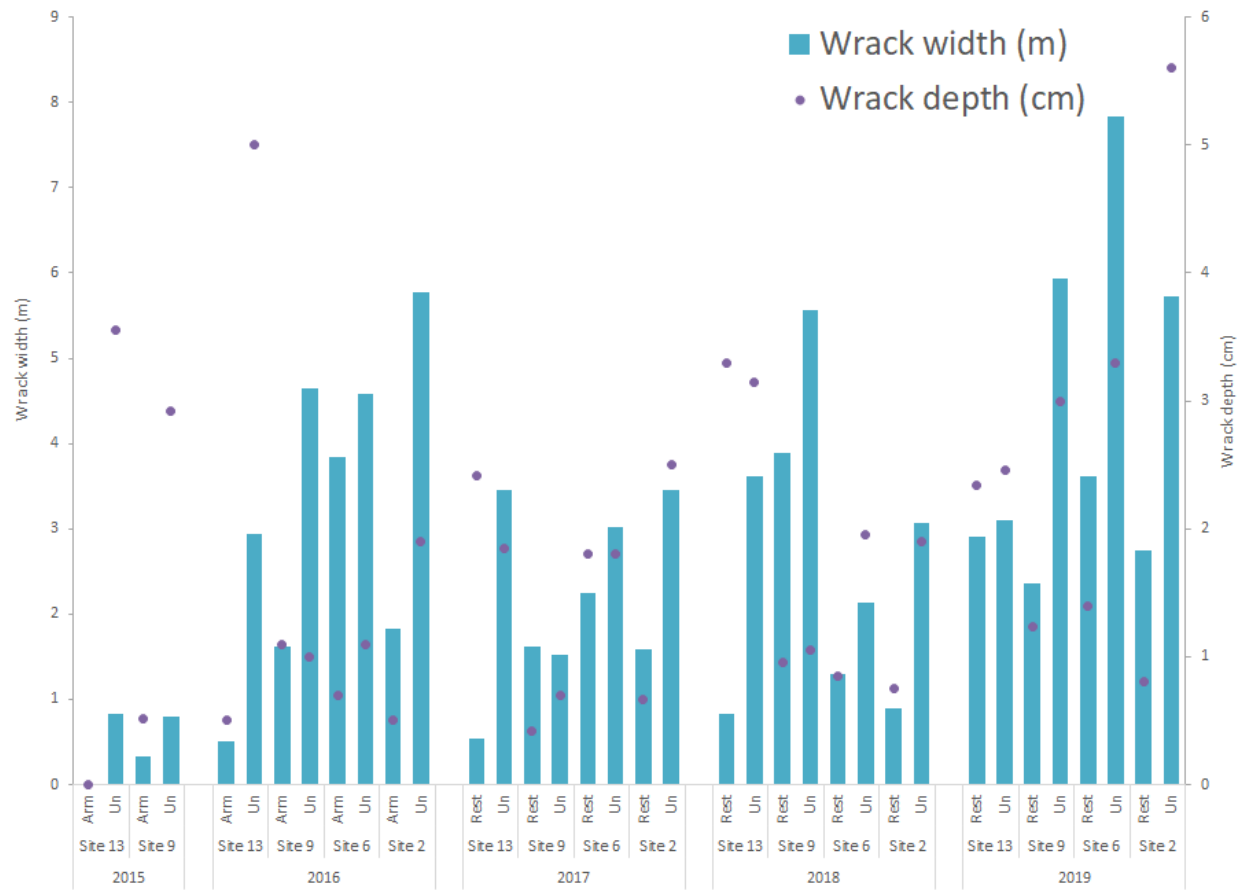


Figure A6. Wrack width and depth at nourished sites.

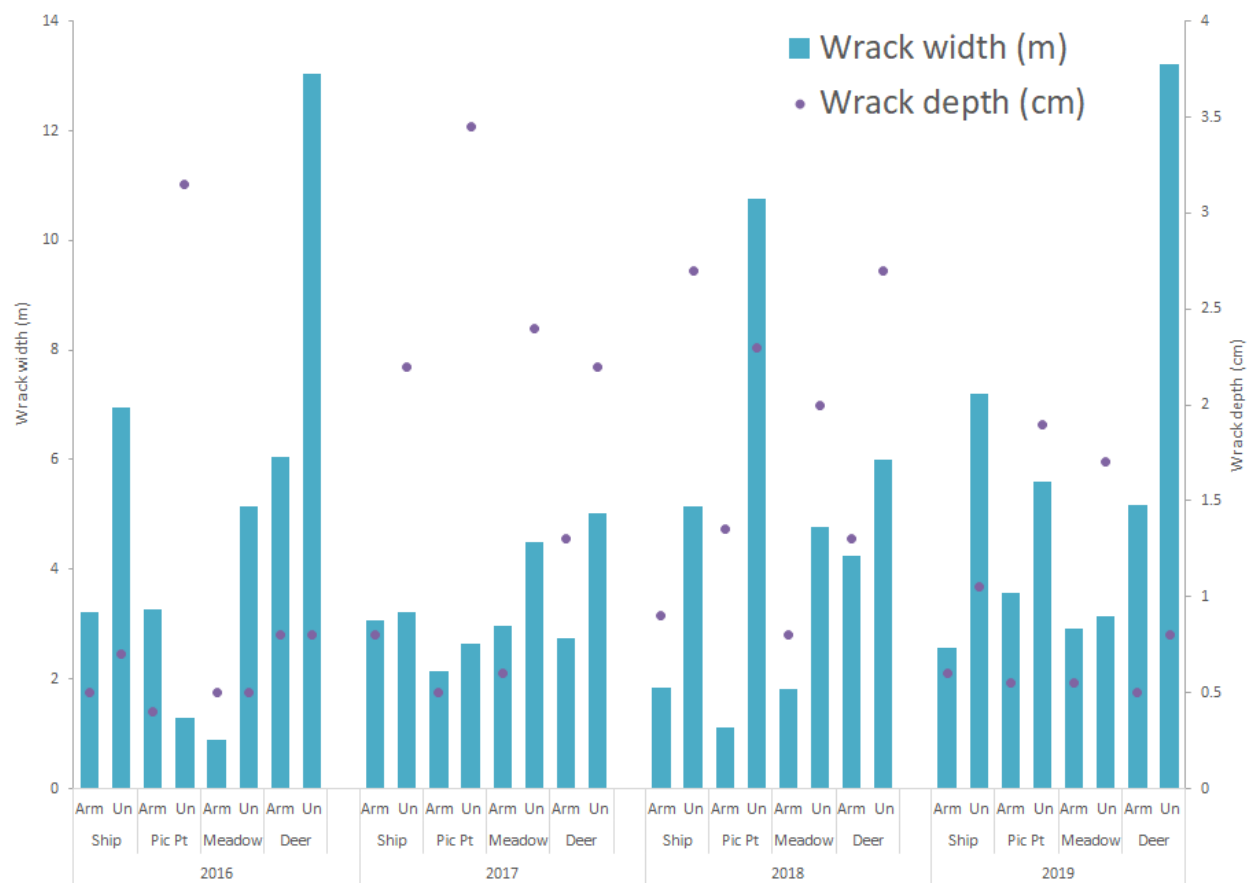


Figure A7. Wrack width and depth at southern sites.

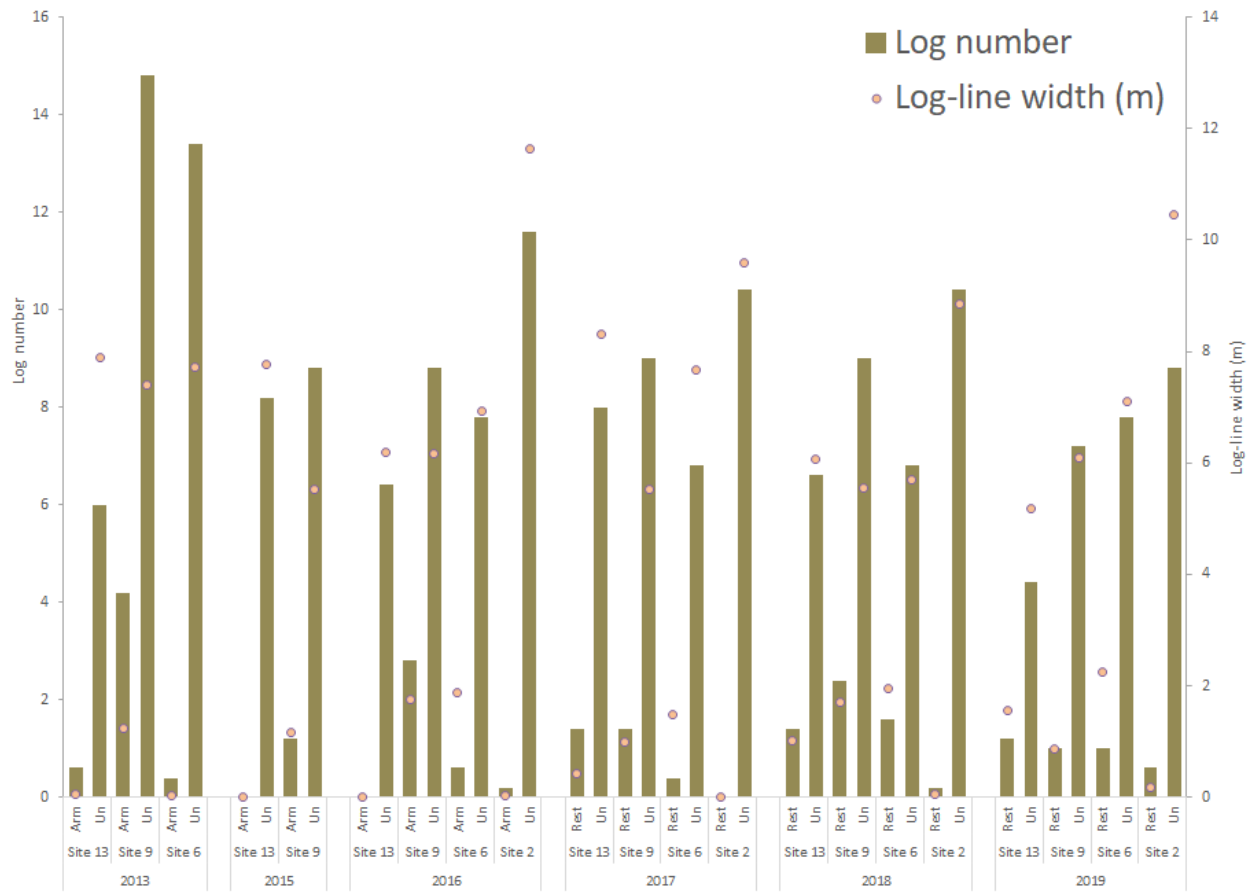


Figure A8. Log number at logline width at nourished sites.

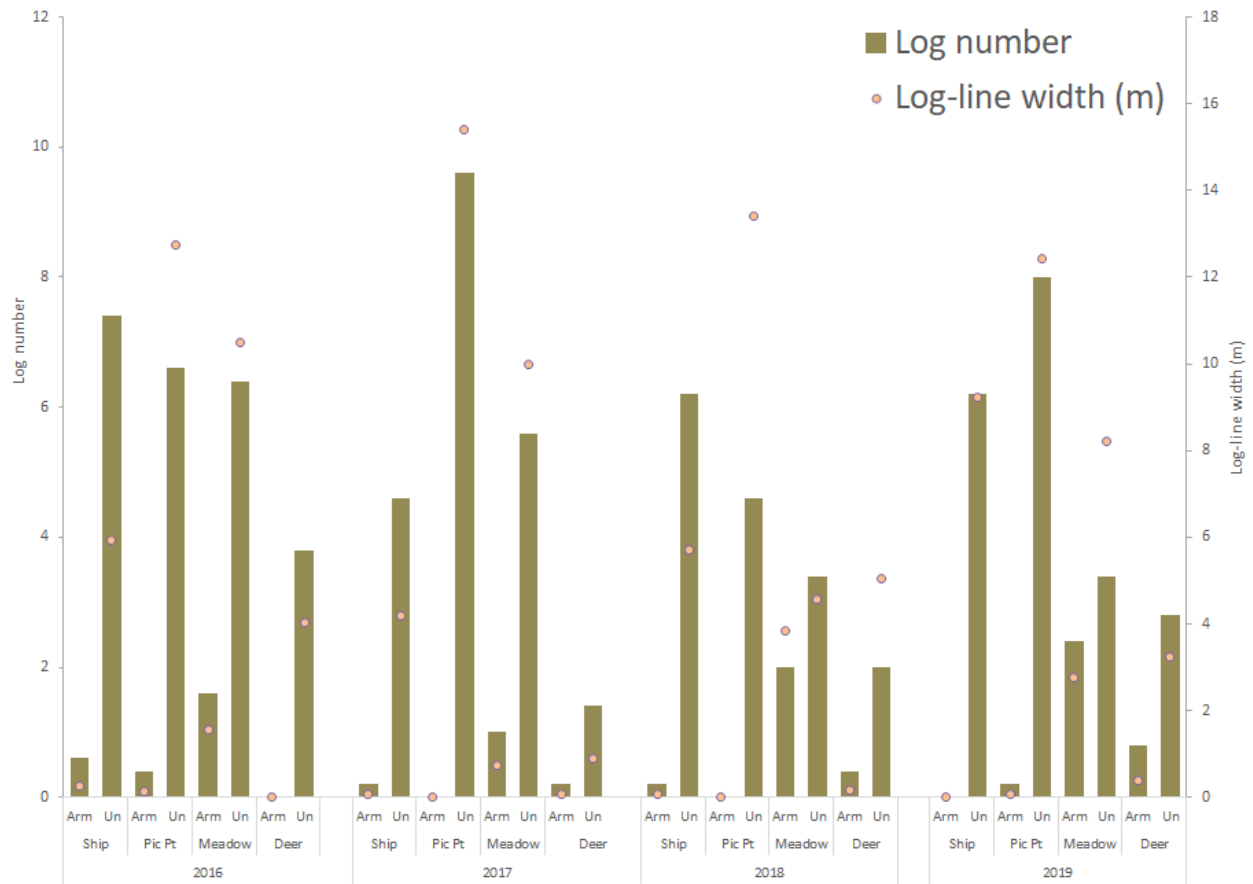


Figure A9. Log number at logline width at southern sites.

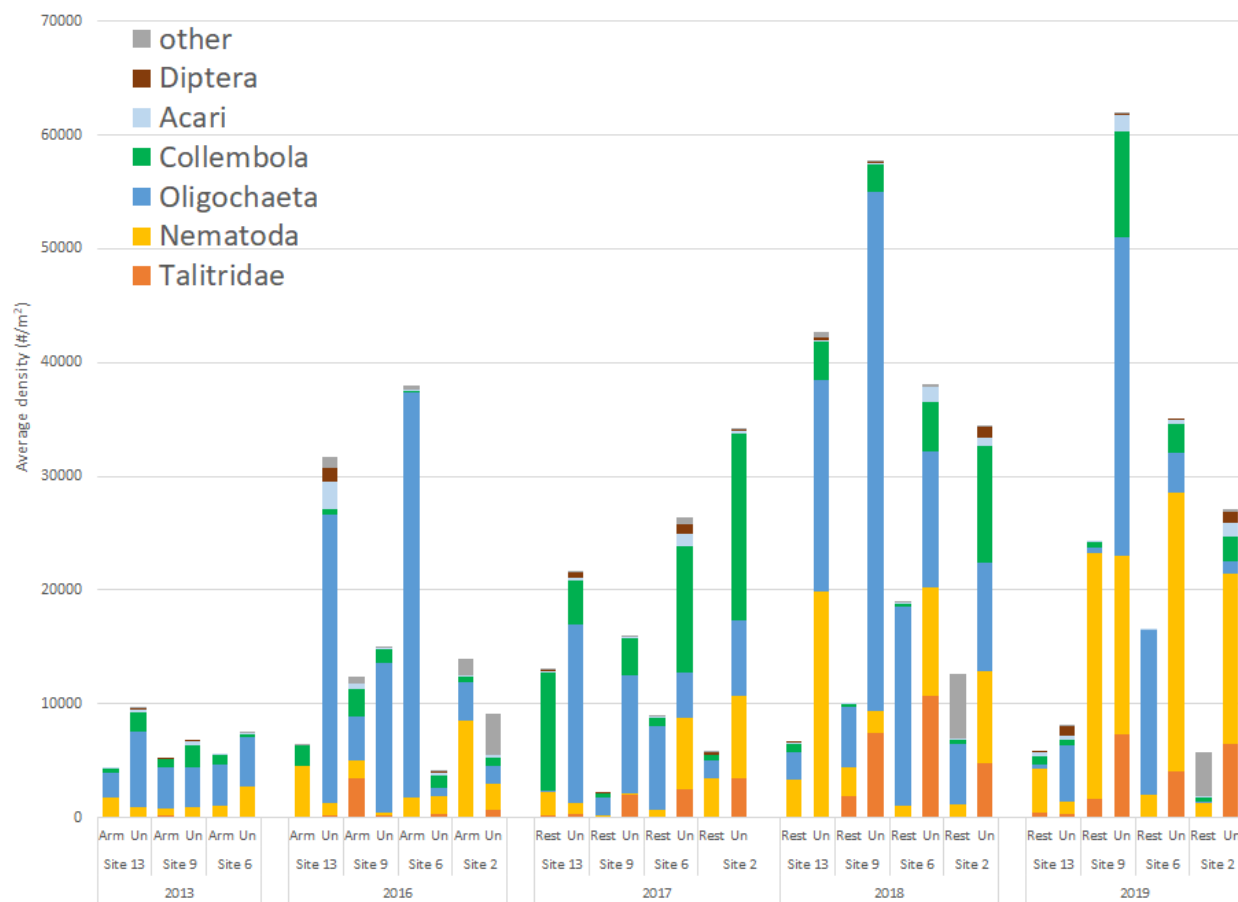


Figure A10. Invertebrates from wrackline cores at nourished sites.

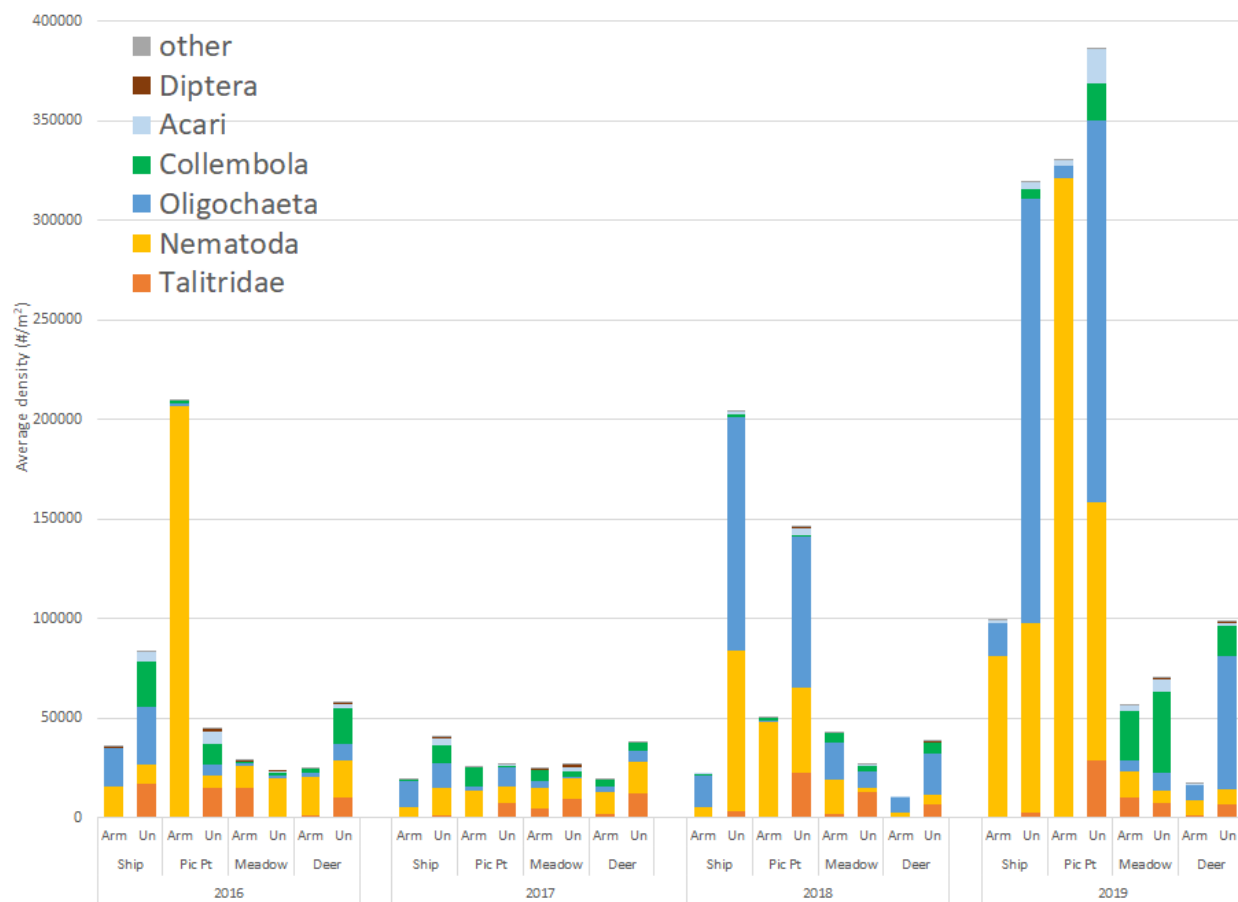


Figure A11. Invertebrates from wrackline cores at southern sites.

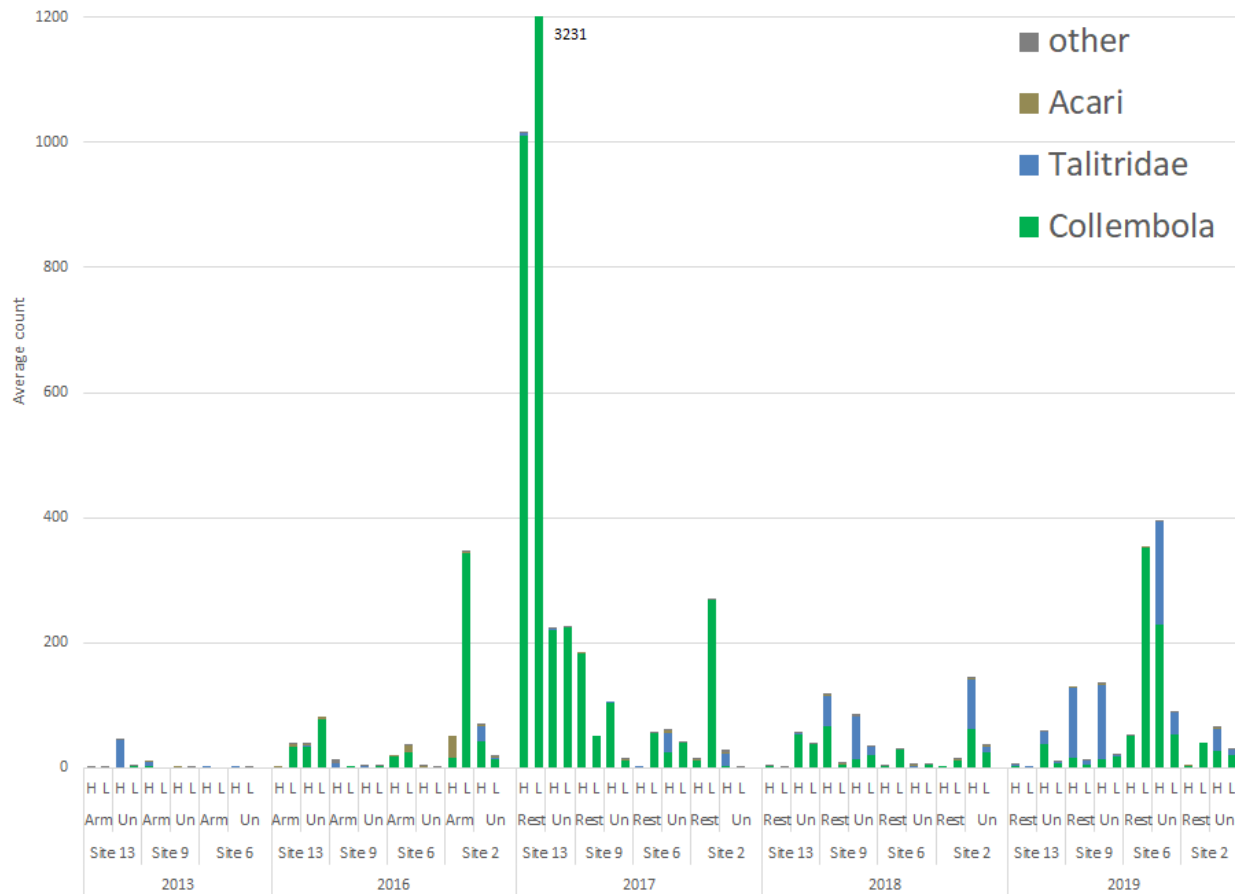


Figure A12. Mobile invertebrates from pitfall traps at nourished sites, for high and low elevations.

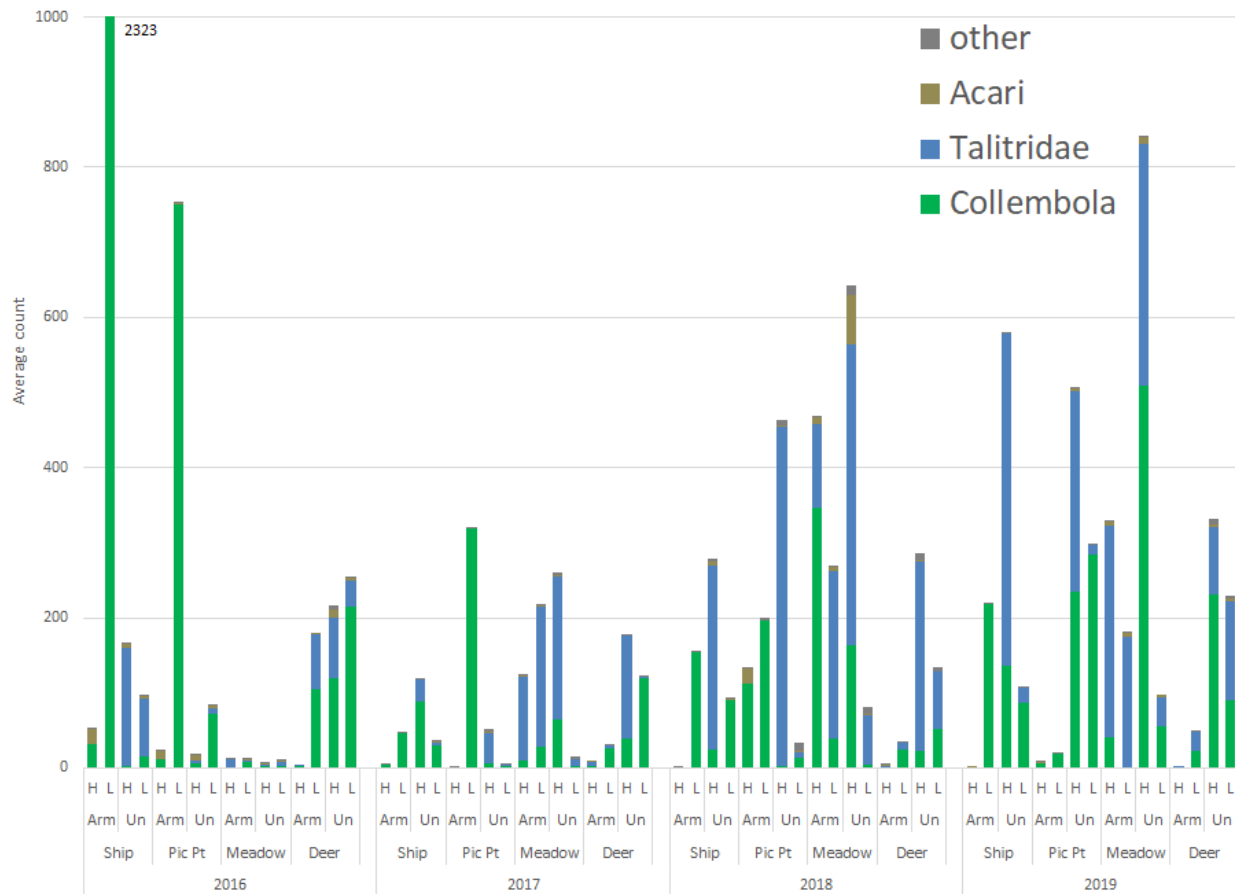


Figure A13. Mobile invertebrates from pitfall traps at southern sites, for high and low elevations.

Appendix B.

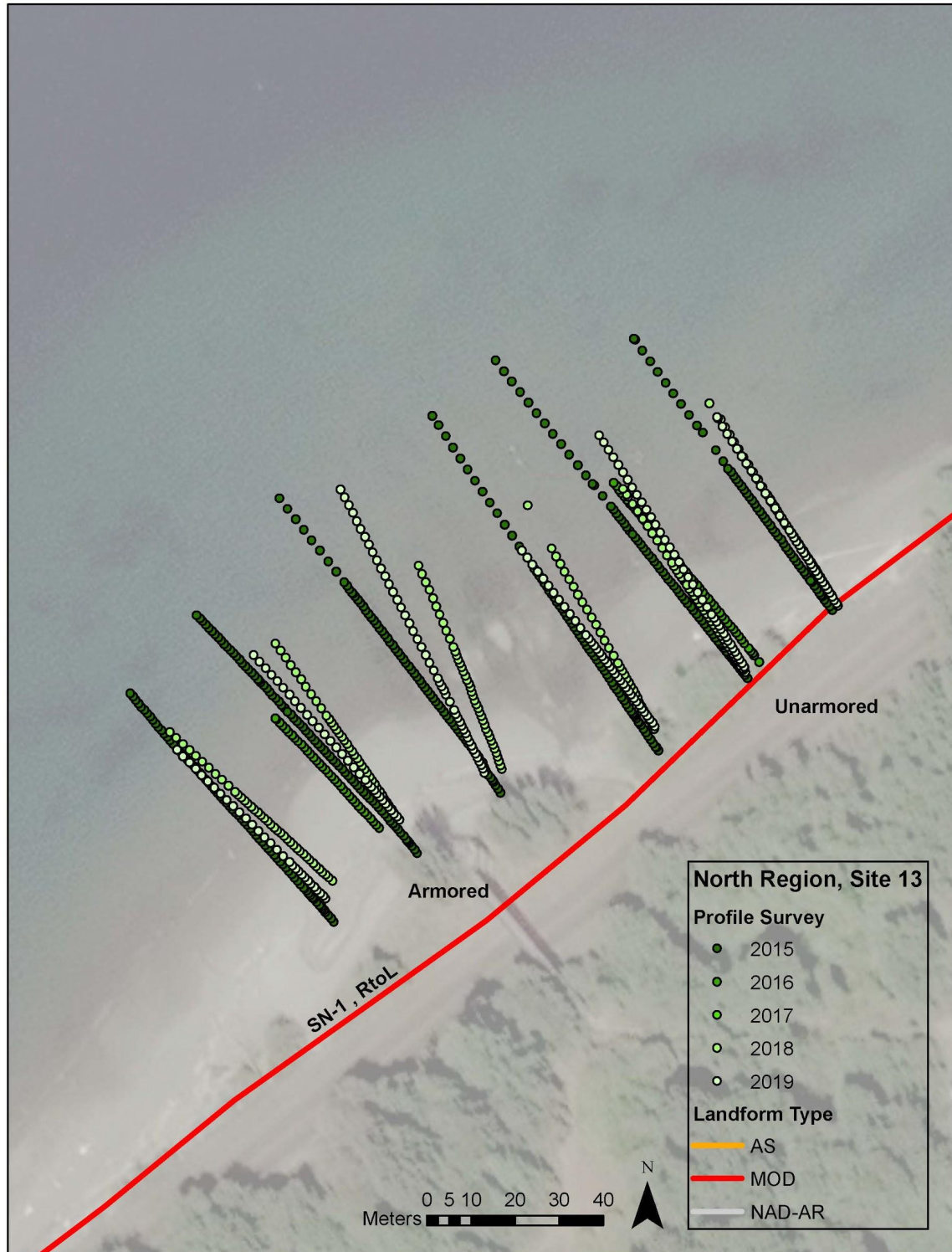


Figure B1. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

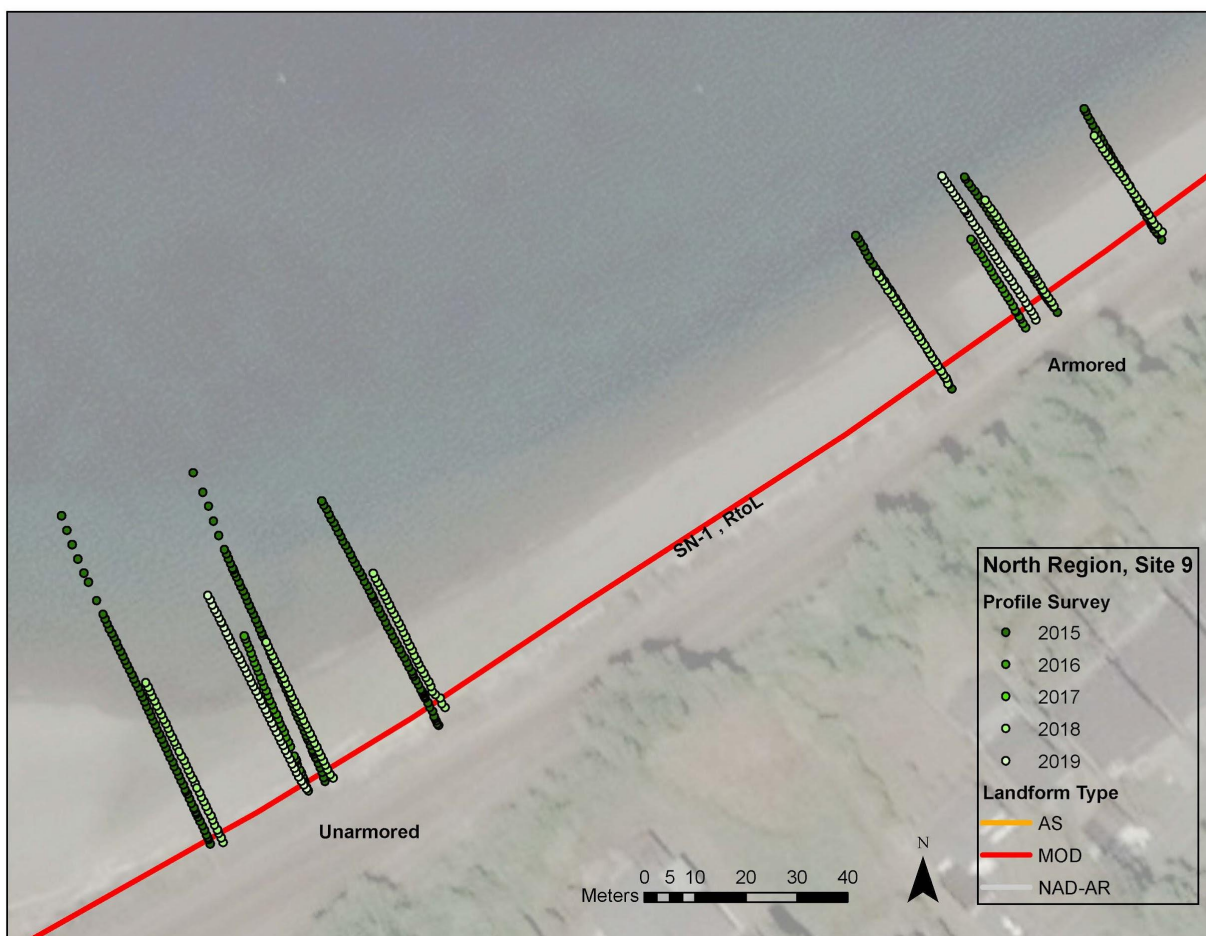


Figure B2. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

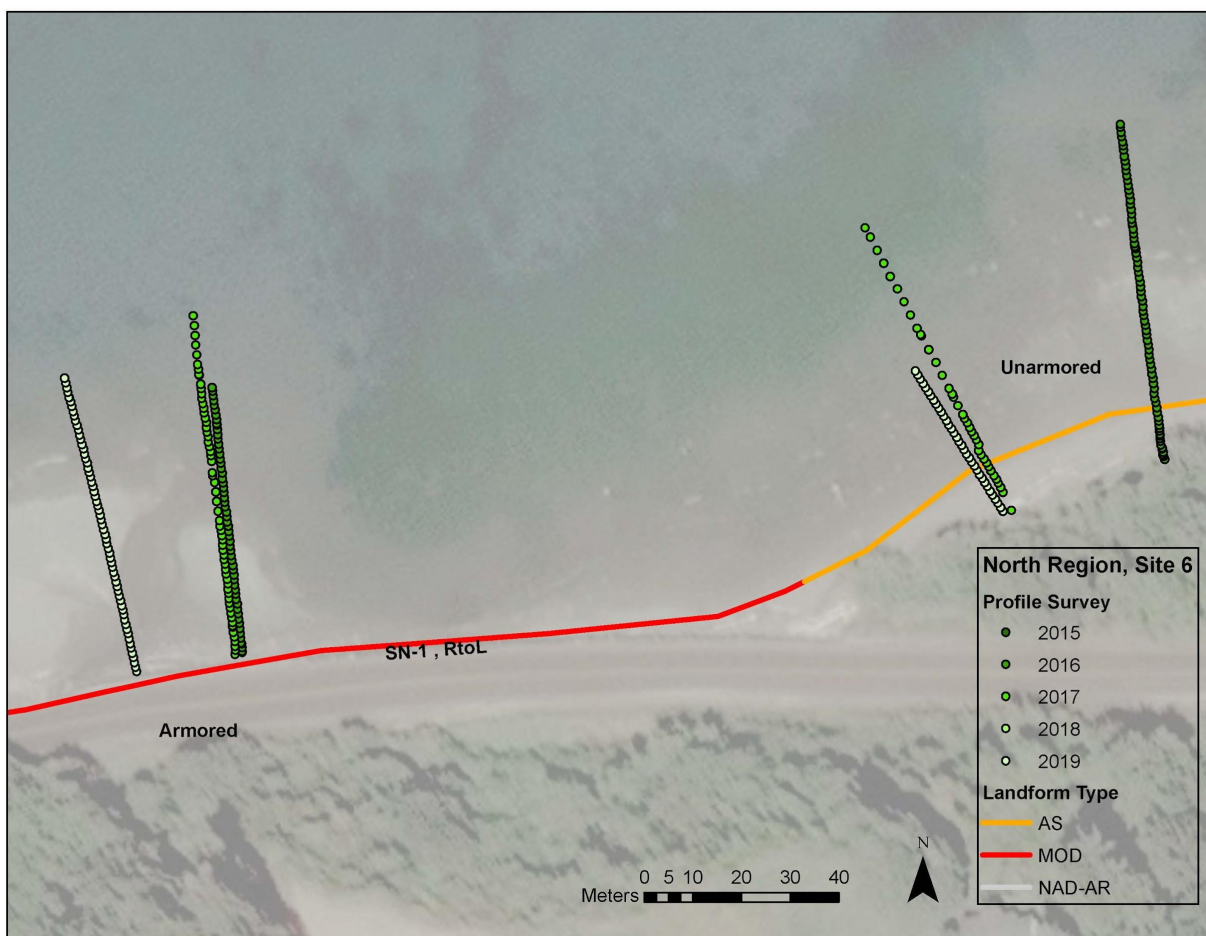


Figure B3. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

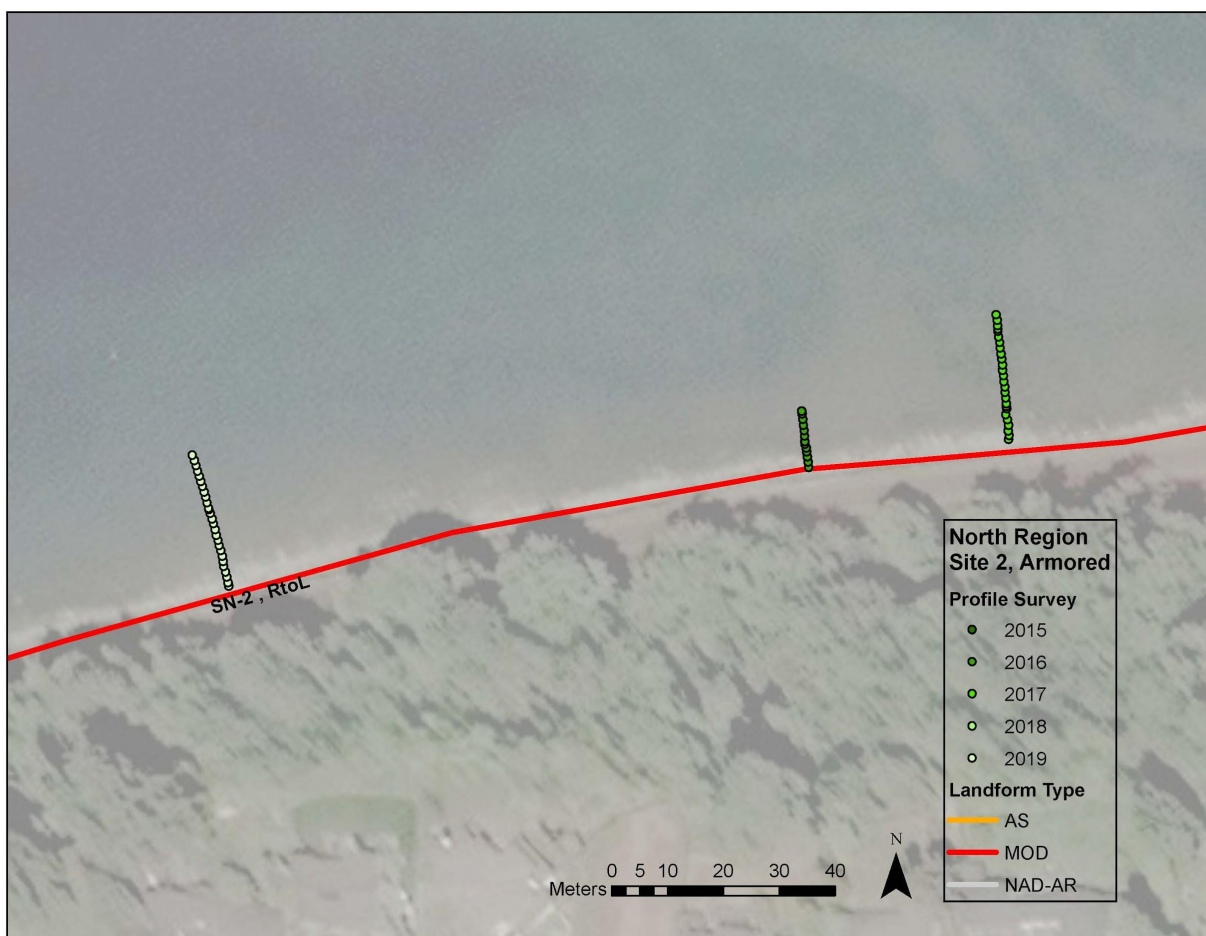


Figure B4. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.



Figure B5. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

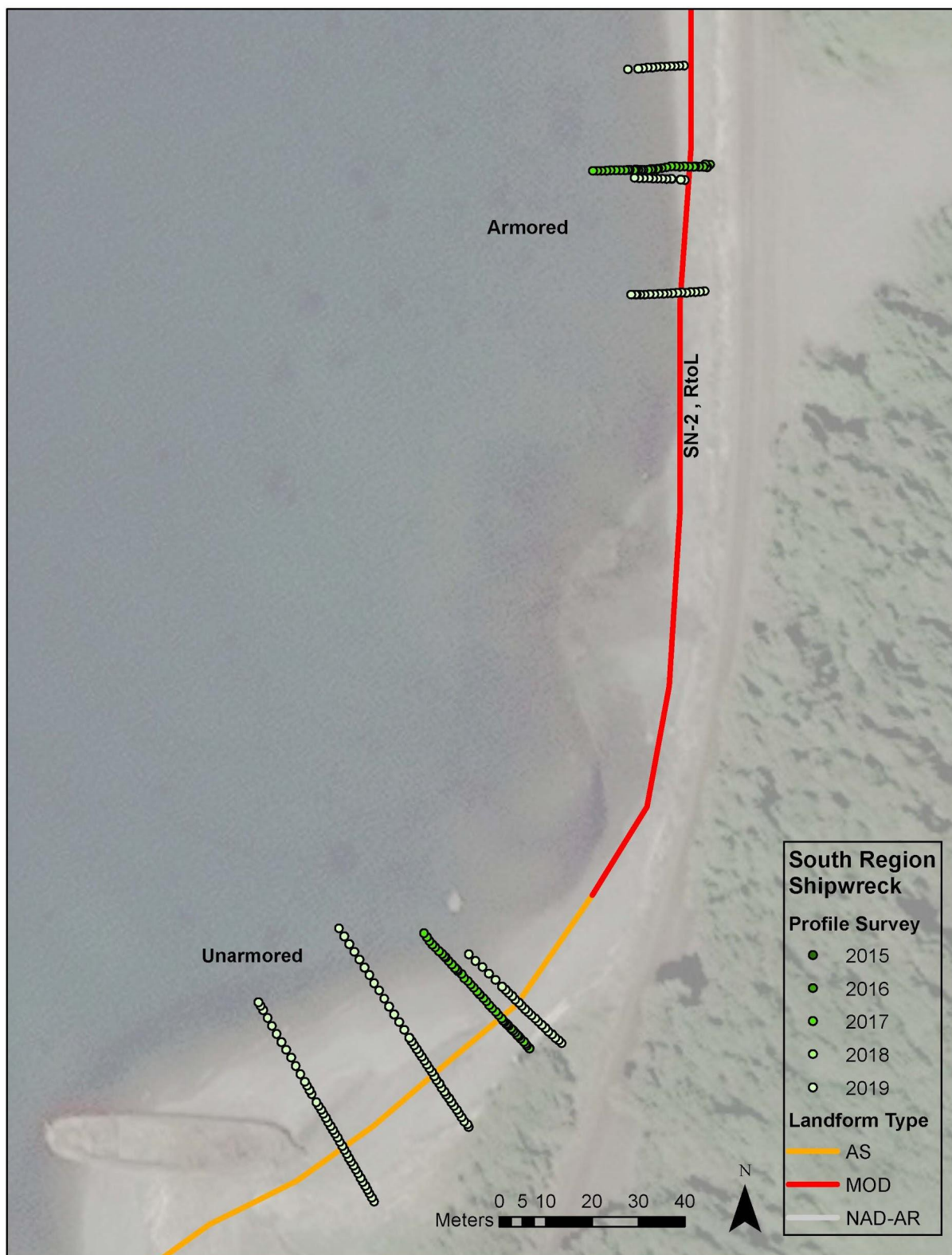


Figure B6. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

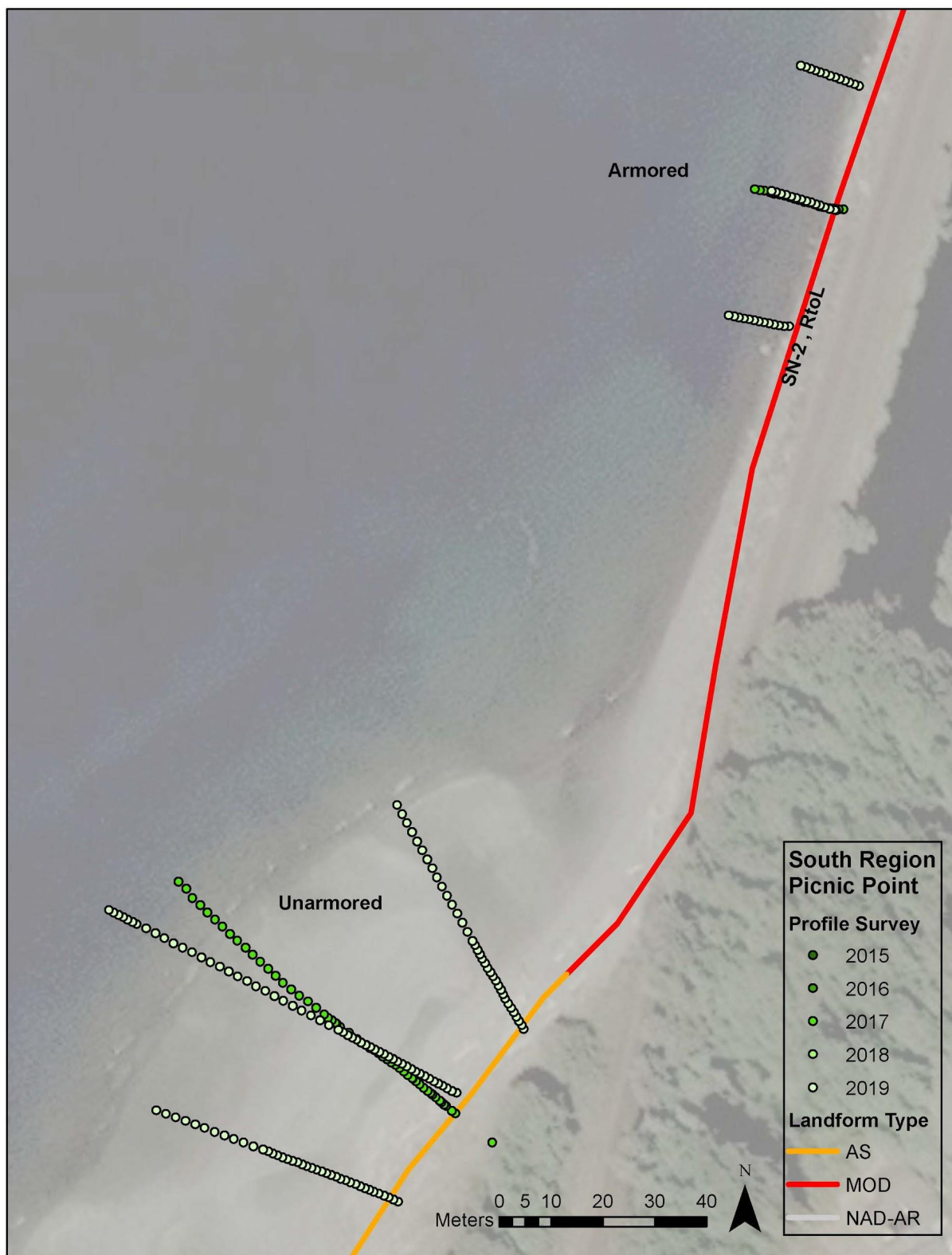


Figure B7. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

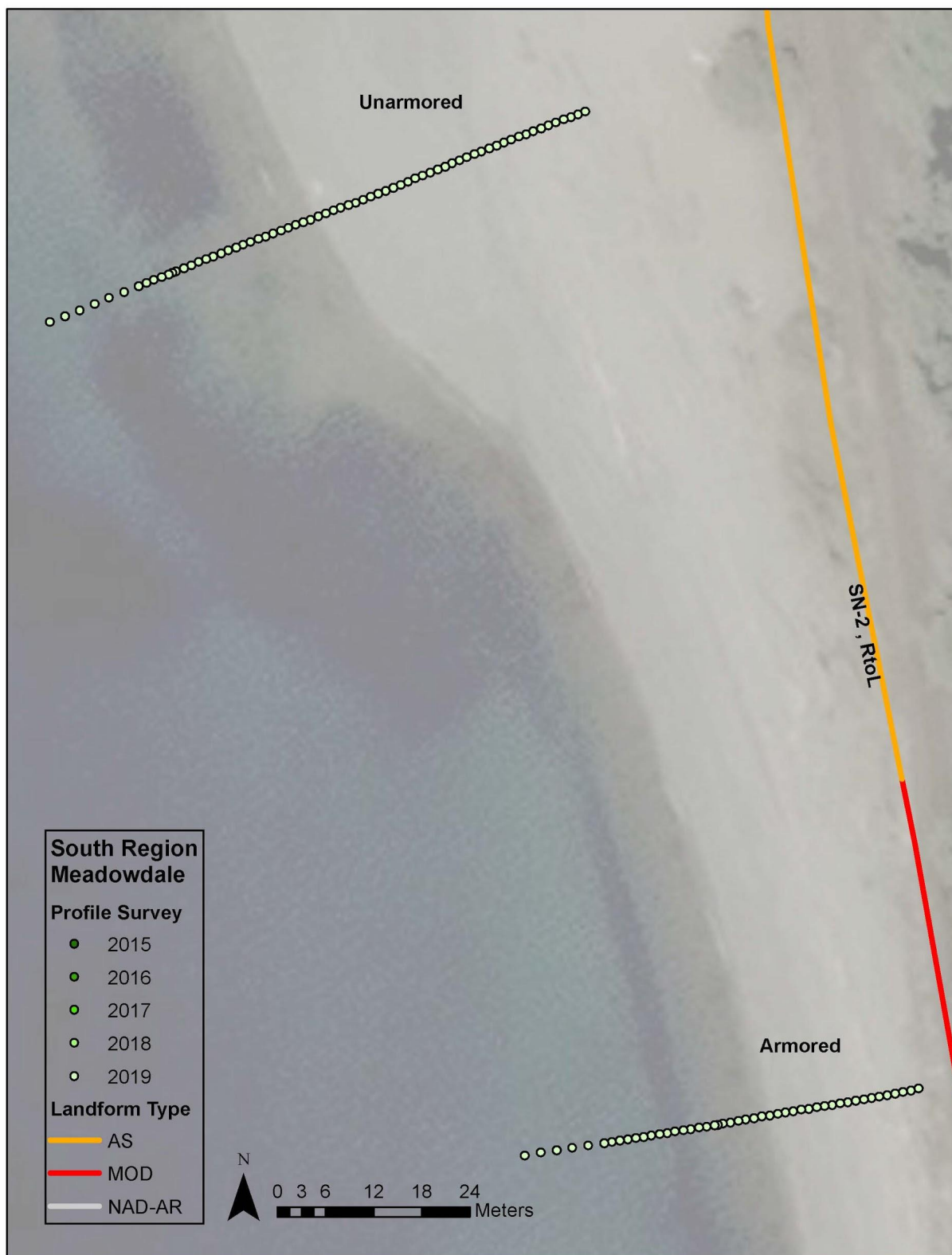


Figure B8. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

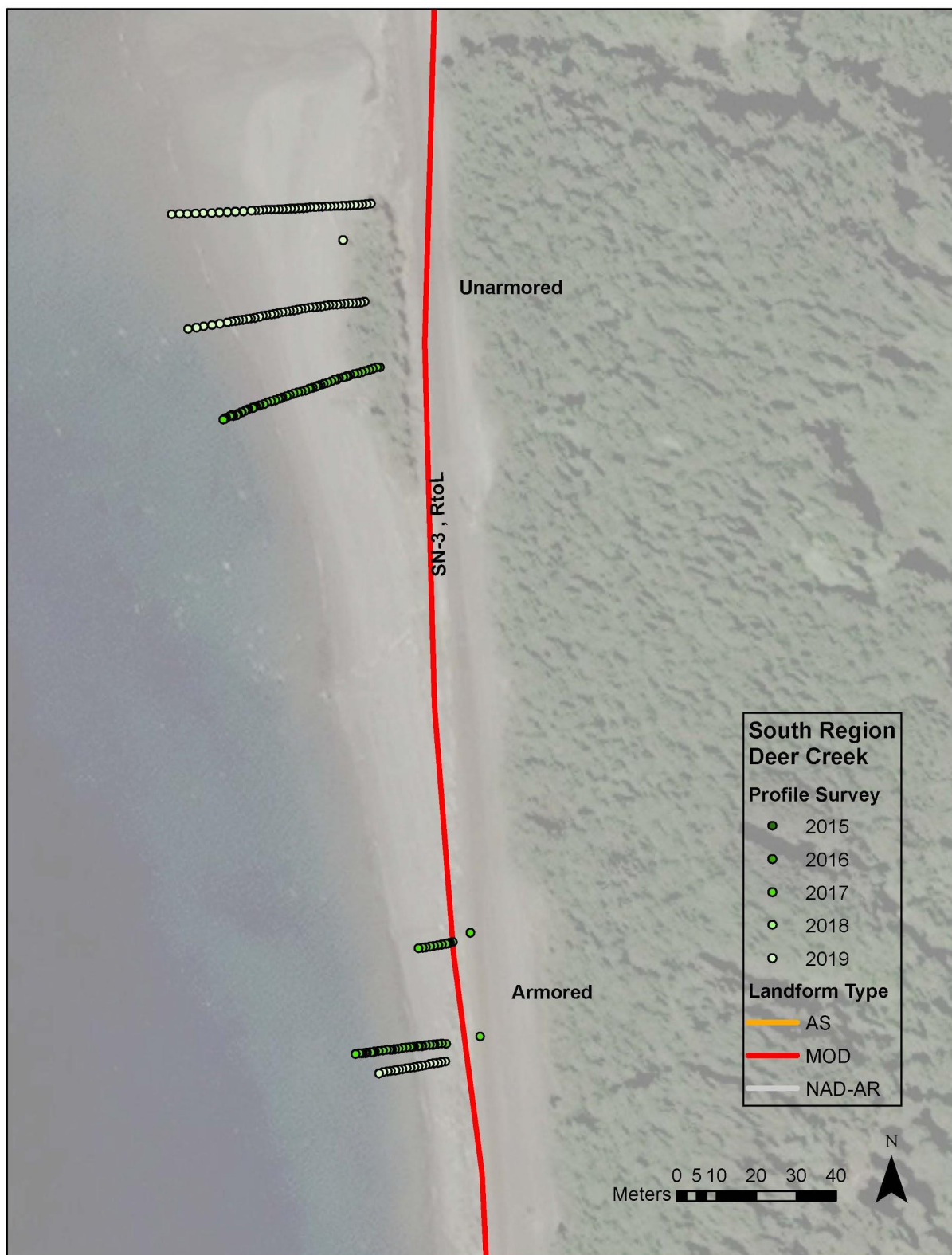


Figure B9. Location of profile survey points, by survey year, collected with Trimble RTK GPS. At least one profile was collected at center of 50-m sample transect each survey year.

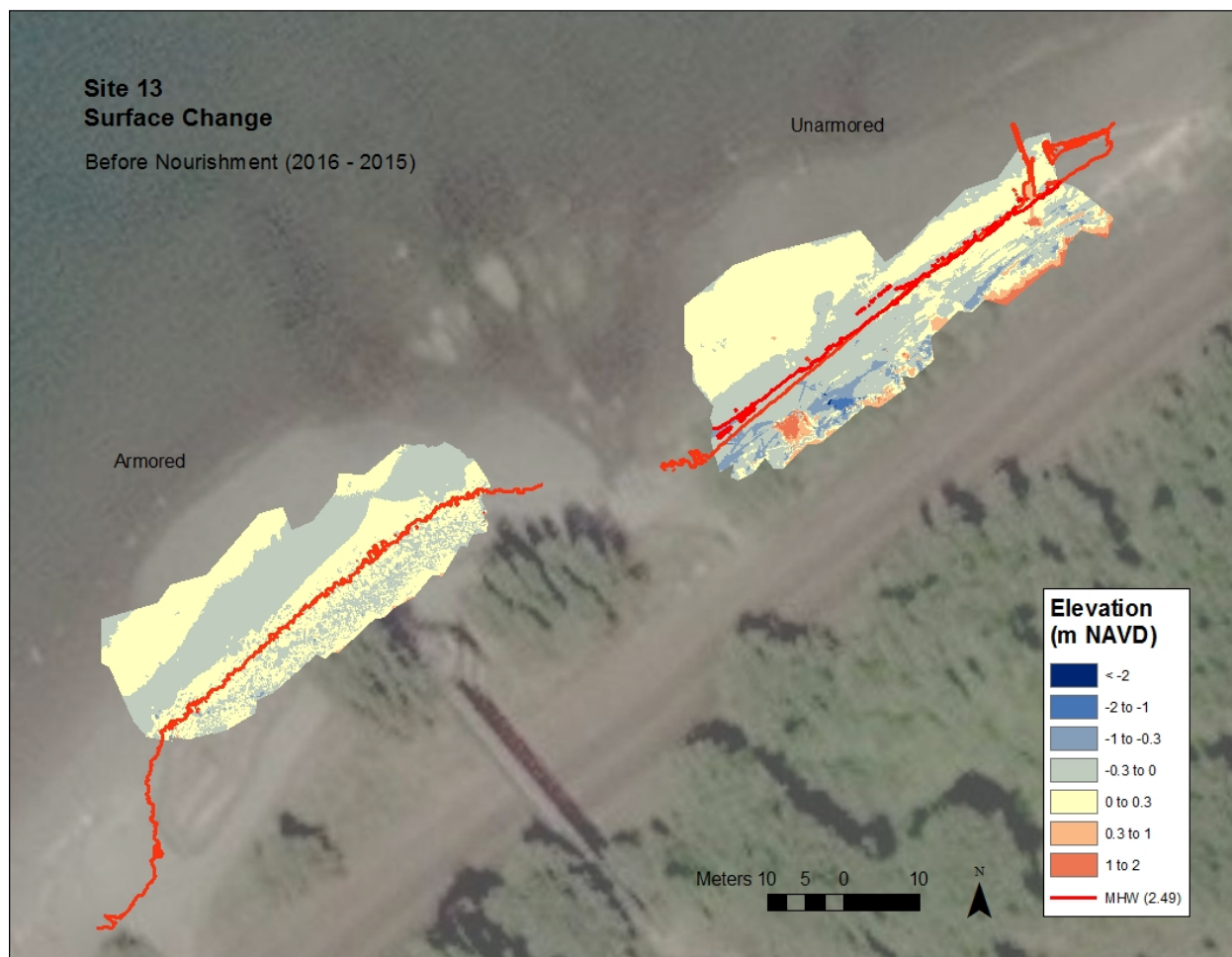


Figure B10. Change in beach surface elevations before nourishment only at site 13, in Snohomish County, WA. Change is measured as difference in elevation (m NAVD) $t_{2016} - t_{2015}$. MHW is denoted as solid lines before nourishment.

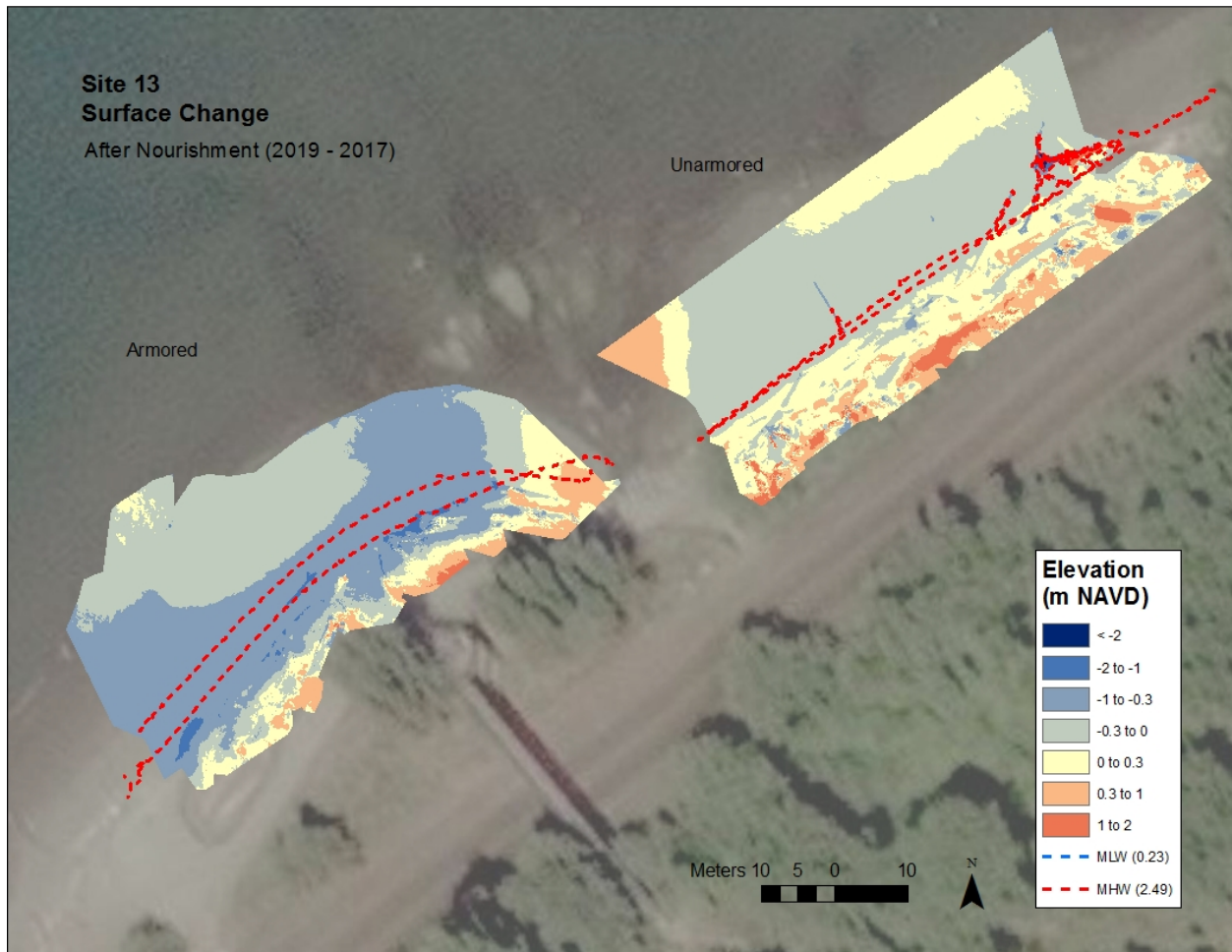


Figure B11. Change in beach surface elevations after nourishment only at site 13, in Snohomish County, WA. Change is measured as difference in elevation (m NAVD) $t_{2019} - t_{2017}$. MHW is denoted as dashed lines after nourishment.

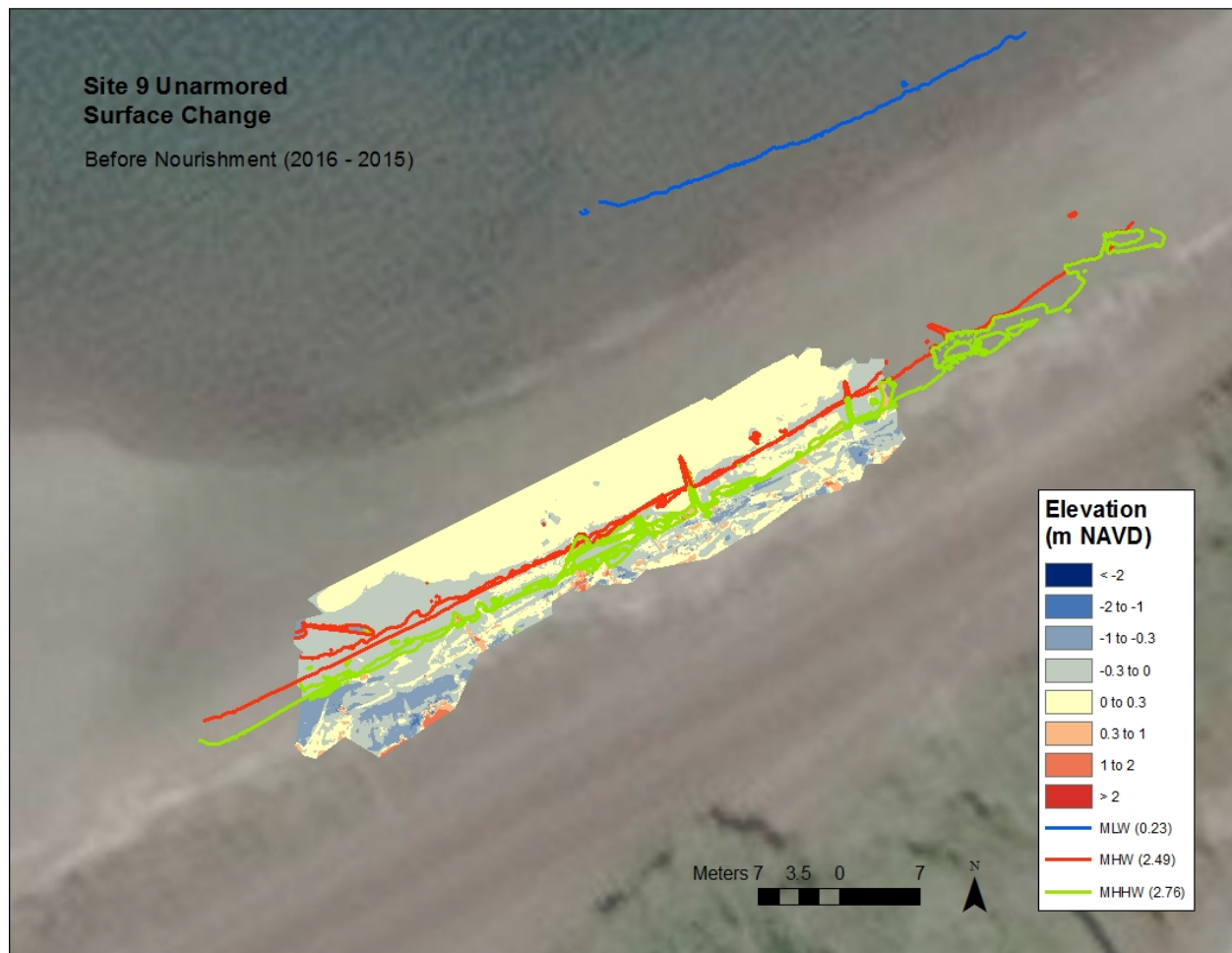


Figure B12. Change in beach surface elevations before nourishment only at site 9 armored. Change is measured as difference in elevation (m NAVD) $t_{2016} - t_{2015}$. Tidal datums (MHHW, MHW, MLW) are denoted as solid lines before nourishment.



Figure B13. Change in beach surface elevations year two post-nourishment at site 9 armored. Change is measured as difference in elevation (m NAVD) $t_{2018} - t_{2016}$. Tidal datums (MHHW, MHW, MLW) are denoted as solid lines before nourishment, i.e. 2016, and dashed lines after nourishment, i.e. 2019.

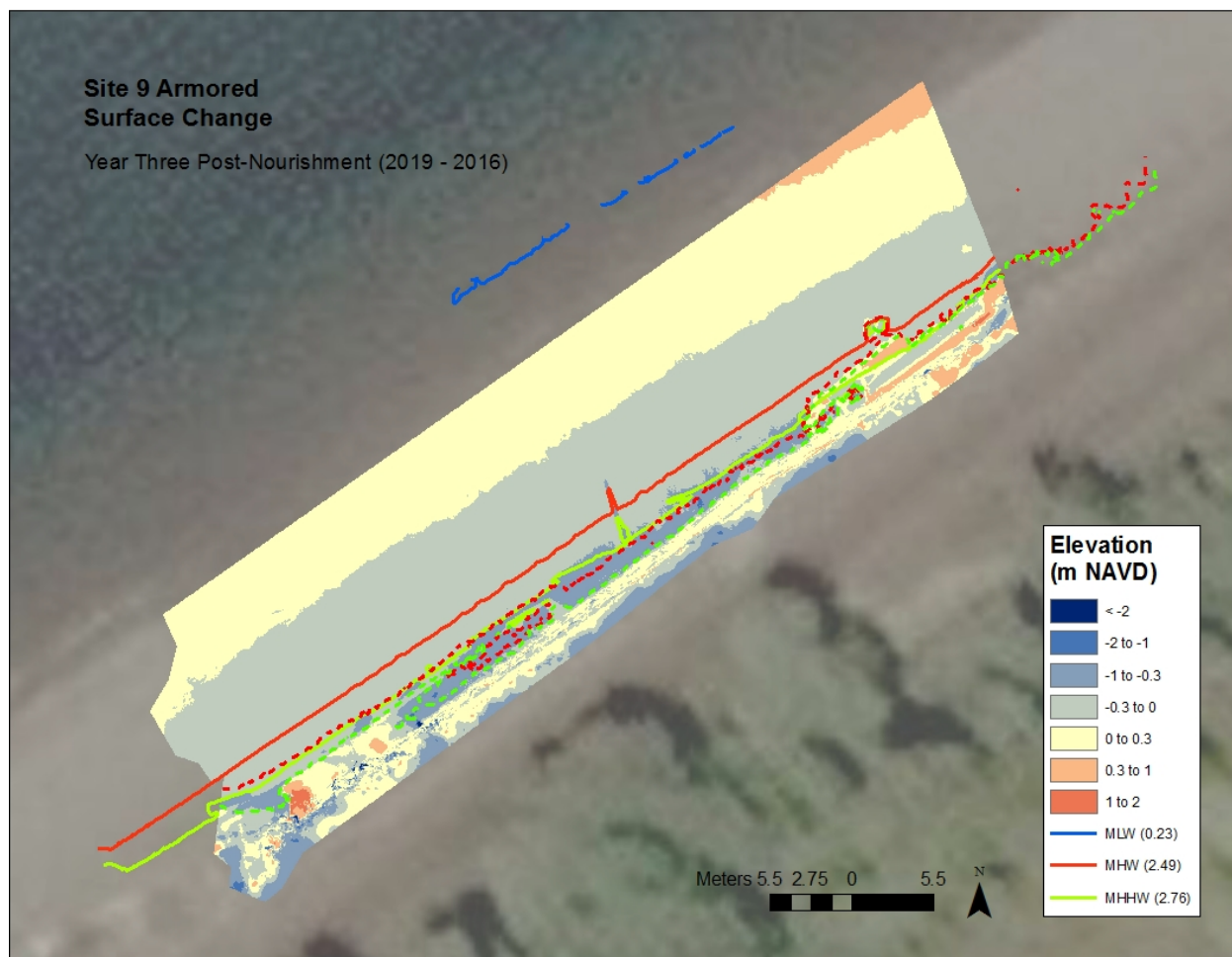


Figure B14 Change in beach surface elevations year three post-nourishment at site 9 armored. Change is measured as difference in elevation (m NAVD) $t_{2019} - t_{2016}$. Tidal datums (MHHW, MHW and MLW) are denoted as solid lines before nourishment, i.e. 2016, and dashed lines after nourishment, i.e. 2019.

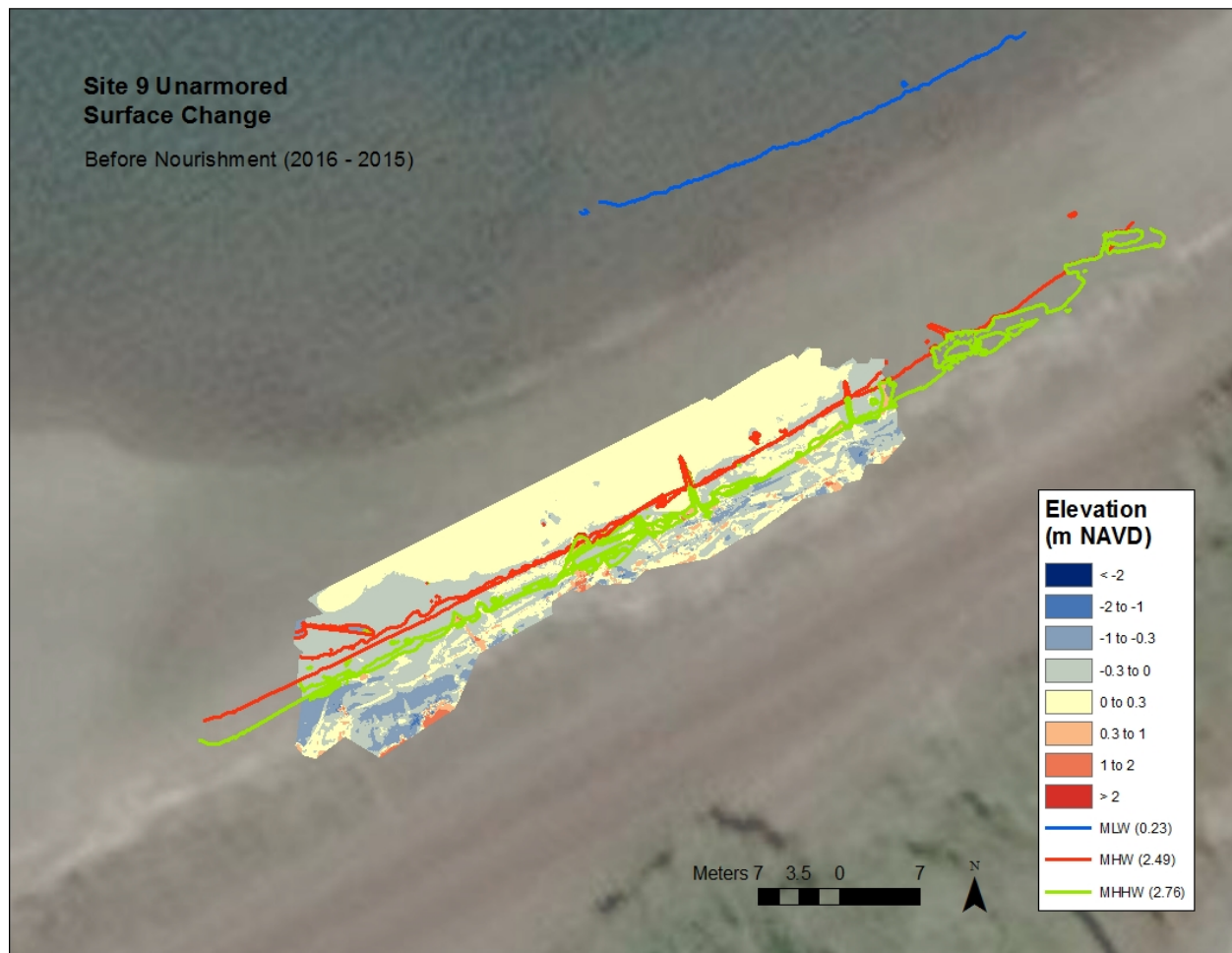


Figure B15. Change in beach surface elevations before nourishment only at site 9 unarmored. Change is measured as difference in elevation (m NAVD) $t_{2016} - t_{2015}$. Tidal datums (MHHW, MHW and MLW) are denoted as solid lines before nourishment.

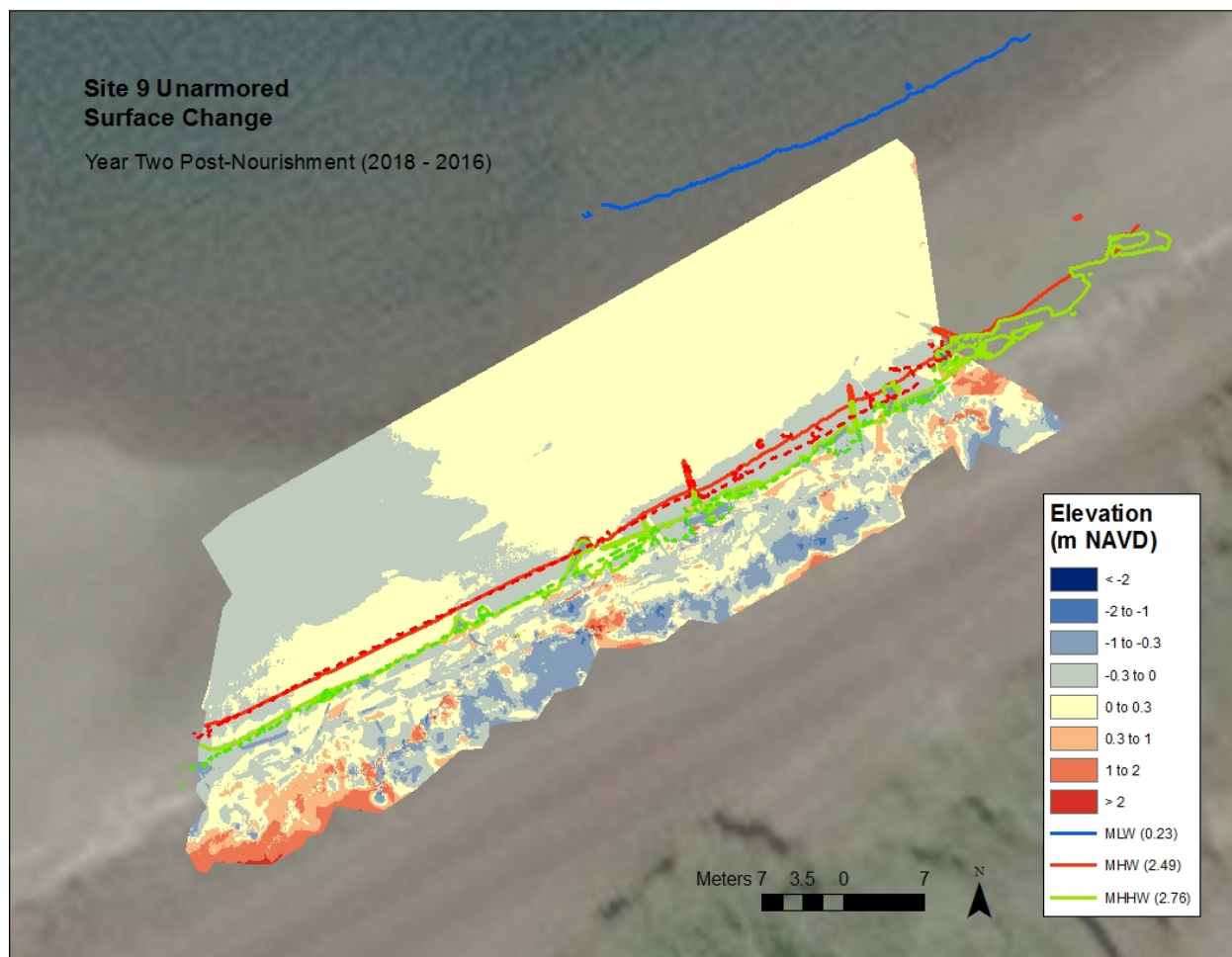


Figure B16. Change in beach surface elevations year two post-nourishment at site 9 unarmored. Change is measured as difference in elevation (m NAVD) $t_{2018} - t_{2016}$. Tidal datums (MHHW, MHW and MLW) are denoted as solid lines before nourishment, i.e. 2016, and dashed lines after nourishment, i.e. 2018.

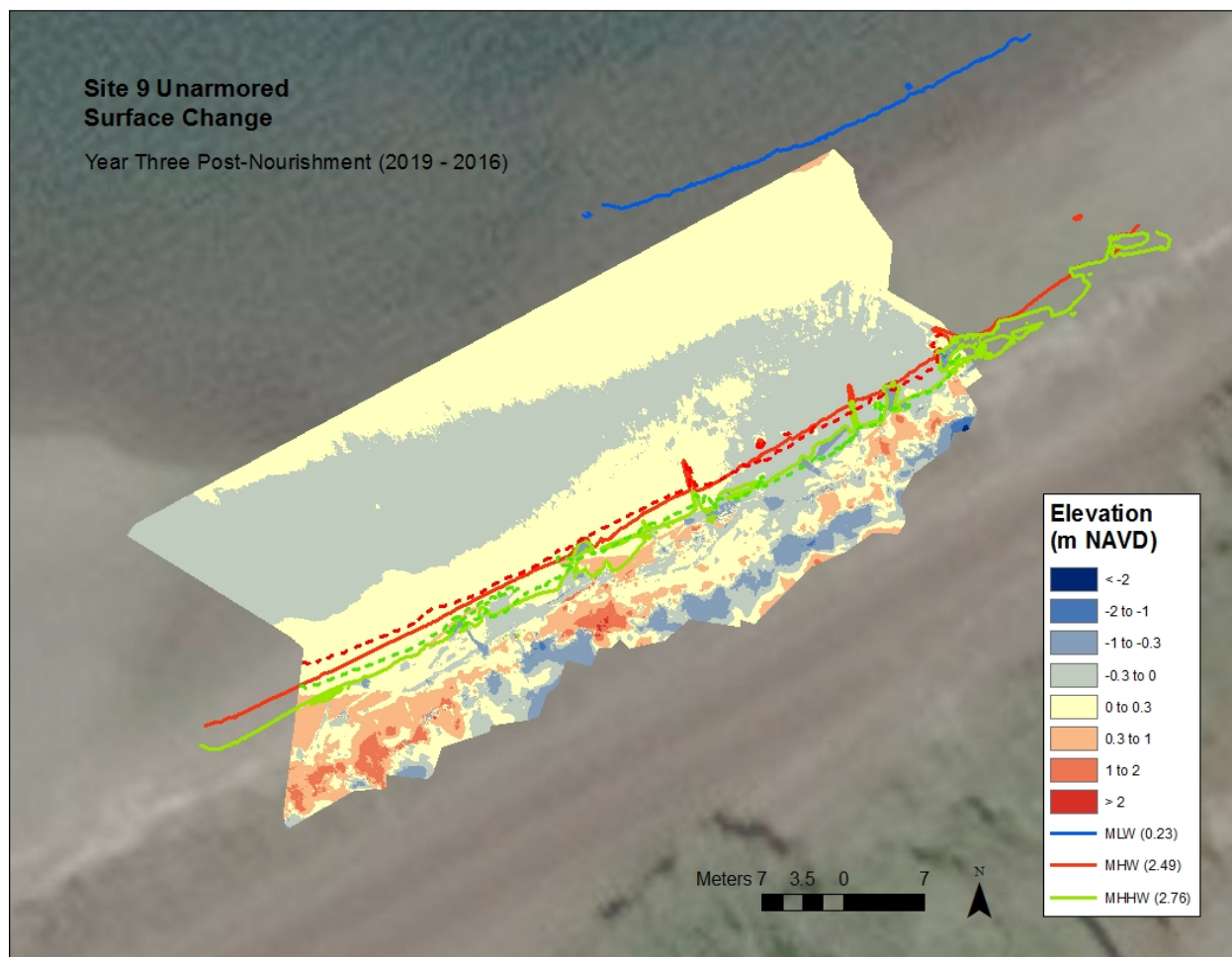


Figure B17. Change in beach surface elevations year two post-nourishment at site 9 unarmored. Change is measured as difference in elevation (m NAVD) $t_{2019} - t_{2016}$. Tidal datums (MHHW, MHW and MLW) are denoted as solid lines before nourishment, i.e. 2016, and dashed lines after nourishment, i.e. 2019.

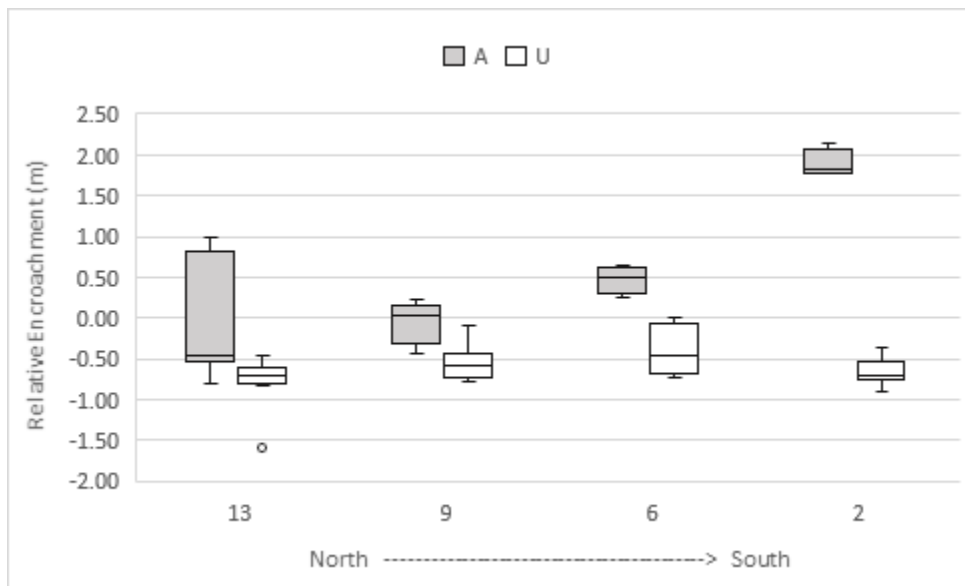


Figure B18. Range of relative encroachment (m + MLLW) measured at each Nourished site 13, 9, 6, and 2 in Snohomish County, WA. Values are averaged across all years sampled, 2015 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair.

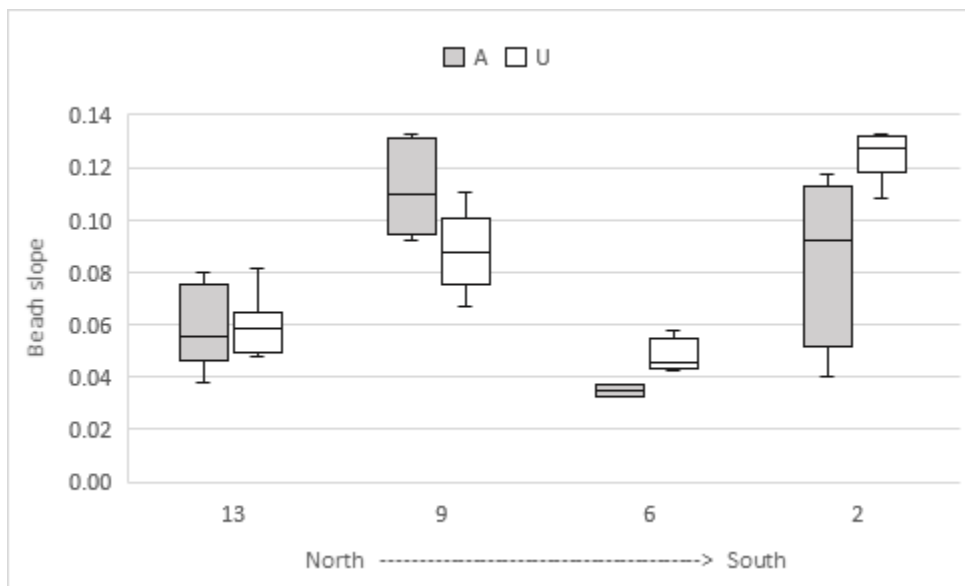


Figure B19. Range of beach slope (m) measured at each Nourished site 13, 9, 6, and 2 in Snohomish County, WA. Values are averaged across all years sampled, 2015 - 2019, where shaded plots represent armored pair and open plots represent unarmored pair.

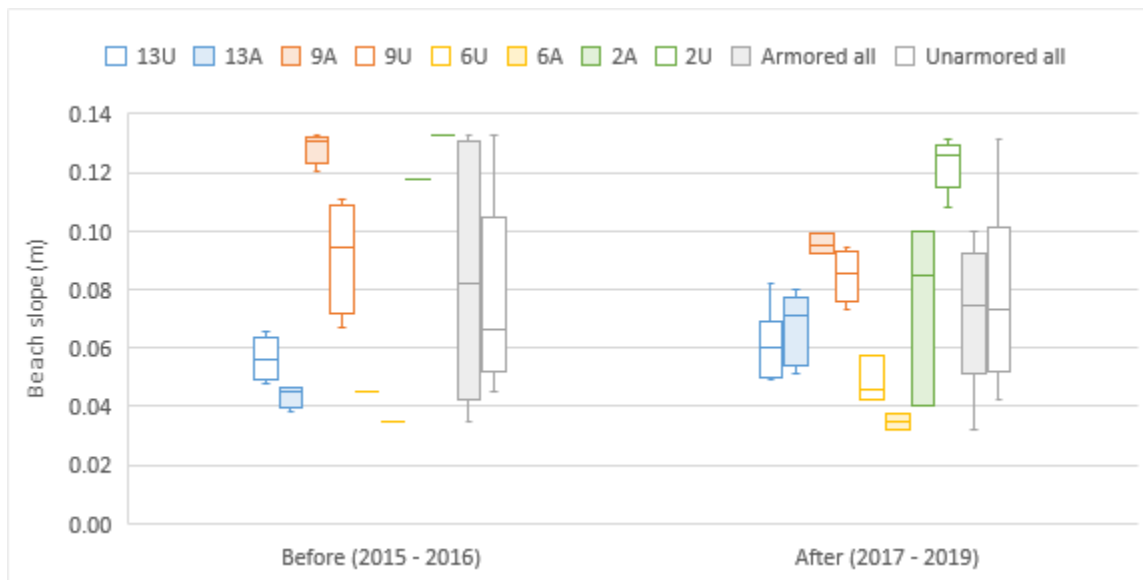


Figure B20. Range of beach slope (m) measured at each North site 13, 9, 6 and 2 in Snohomish County, WA. Profiles were surveyed before (2015 to 2016) and after (2017 to 2019) beach nourishment, at armored, A, locations (shaded plots) and unarmored, U, locations (open plots).

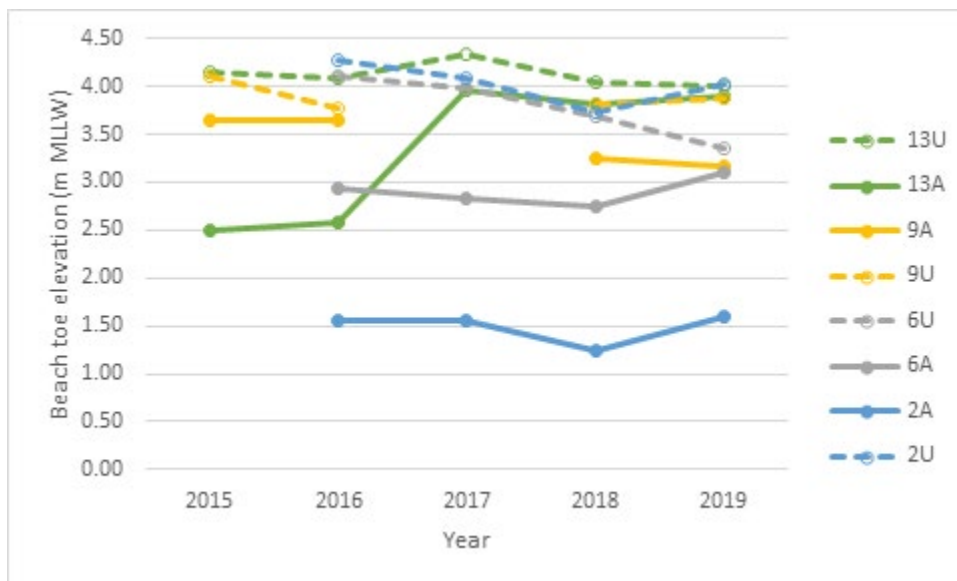


Figure B21. Average beach toe elevation (m MLLW) measured at each North site pair in Snohomish County, WA; where solid lines represent armored locations and dashed lines represent unarmored locations. Beach nourishment occurred between survey years 2016 and 2017.

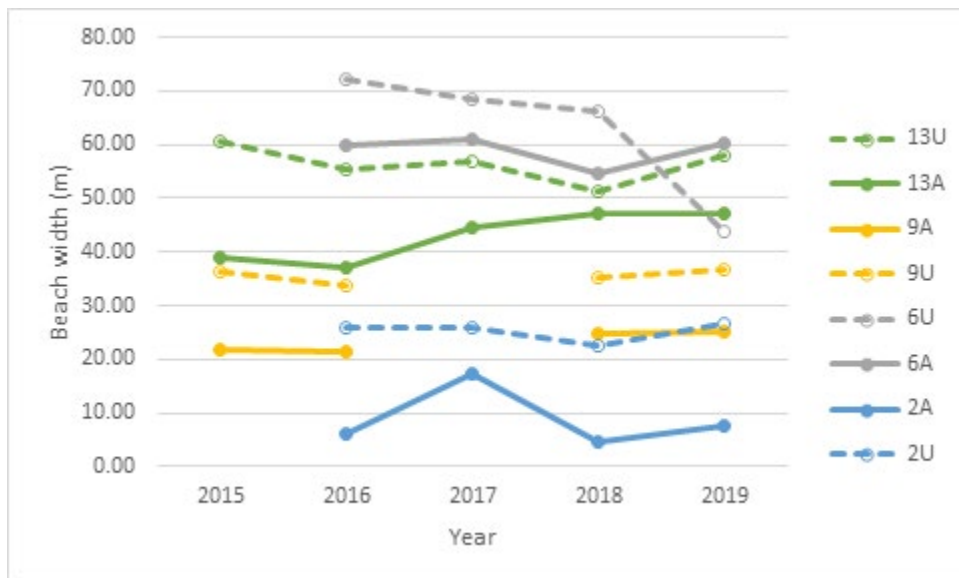


Figure B22. Average beach width (m) measured at each North site pair in Snohomish County, WA; where solid lines represent armored locations and dashed lines represent unarmored locations. Beach nourishment occurred between survey years 2016 and 2017.



Figure B23. Average beach slope (m) measured at each North site pair in Snohomish County, WA; where solid lines represent armored locations and dashed lines represent unarmored locations. Beach nourishment occurred between survey years 2016 and 2017.

Table B1. Sediment grain-size composition by percent weight averaged before (2015 – 2016) and after (2017-2019) beach nourishment. Surface and sub-surface samples were collected at Nourished sites 13 and 9 in Snohomish County, WA.

			Before (2015 - 2016)				After (2017 - 2019)			
	Site	Strata	Sand	Granule	Pebble	Cobble	Sand	Granule	Pebble	Cobble
Surface	13	A					10.2	2.4	87.4	0.0
		U	15.8	3.7	80.6	0.0	61.4	1.0	37.6	0.0
		Total	15.8	3.7	80.6	0.0	35.8	1.7	62.5	0.0
	9	A	17.0	7.0	75.9	0.0	79.6	0.8	19.6	0.0
		U	28.5	9.2	62.2	0.0	63.6	3.0	33.4	0.0
		Total	22.8	8.1	69.1	0.0	71.6	1.9	26.5	0.0
	Total		20.4	6.6	72.9	0.0	53.7	1.8	44.5	0.0
Sub-surface	13	A					37.1	6.2	56.7	0.0
		U	38.9	6.8	54.4	0.0	63.7	3.1	33.2	0.0
		Total	38.9	6.8	54.4	0.0	50.4	4.7	45.0	0.0
	9	A	44.1	6.6	49.3	0.0	80.1	1.8	18.0	0.0
		U	40.5	5.2	46.8	7.5	64.4	6.3	29.4	0.0
		Total	42.3	5.9	48.1	3.7	72.3	4.0	23.7	0.0
	Total		41.2	6.2	50.2	2.5	61.3	4.3	34.3	0.0
Total			30.8	6.4	61.5	1.2	57.5	3.1	39.4	0.0

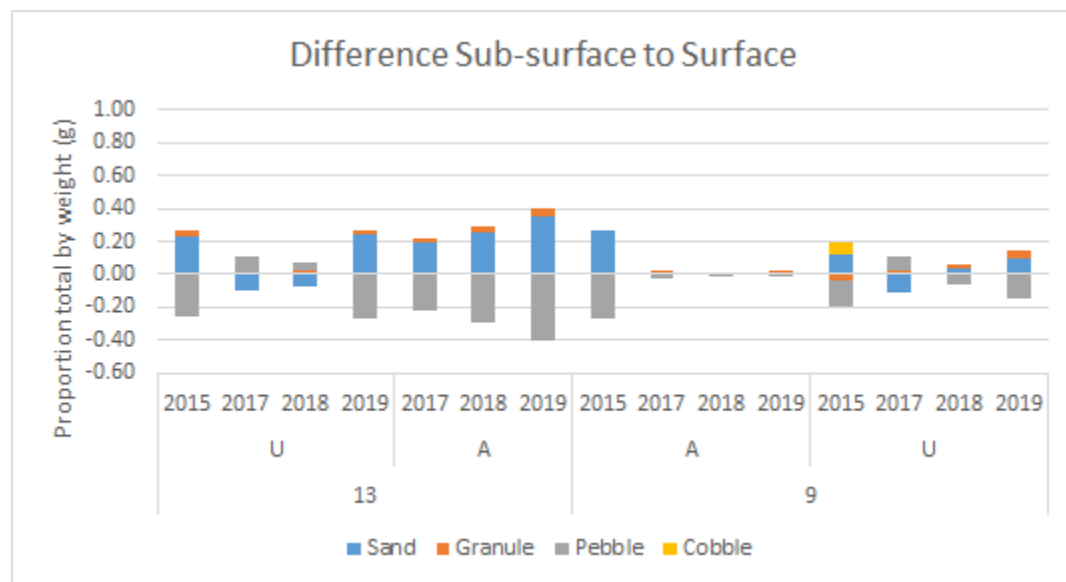


Figure B24. Difference in proportion total weight of surface and sub-surface sediment samples collected at MHW at Nourished sites 13 and 9 in Snohomish County, WA. Sediment sizes are binned by sand (< 2mm), granule (2 - 4 mm), pebble (4 - 64 mm) and cobble (> 64 mm).

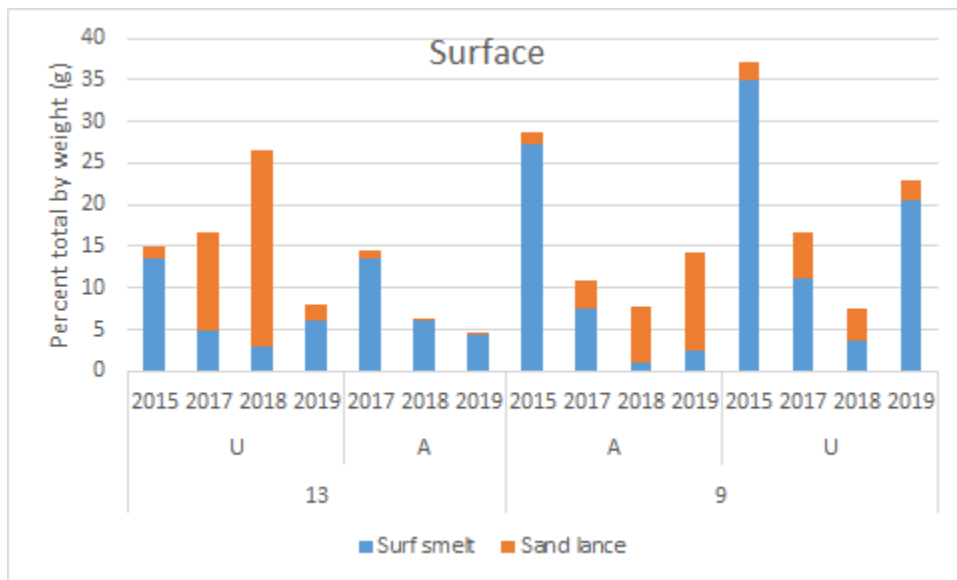


Figure B25. Surface sediment grain size composition by percent total weight, suitable for forage fish. Samples were collected at MHW at nourished region sites 13 and 9 from 2015 to 2019, in Snohomish County, WA. Sediment sizes are binned by surf smelt (1 to 7 mm) and Pacific sand lance (0.2 to 0.4 mm).

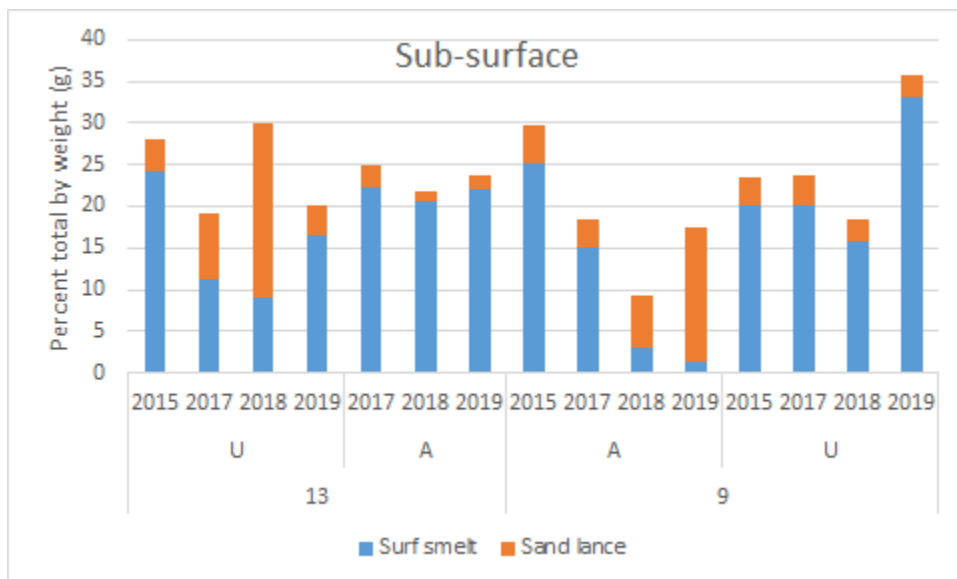


Figure B26. Sub-surface sediment grain size composition by percent total weight, suitable for forage fish. Samples were collected at MHW at nourished region sites 13 and 9 from 2015 to 2019, in Snohomish County, WA. Sediment sizes are binned by surf smelt (1 to 7 mm) and Pacific sand lance (0.2 to 0.4 mm).

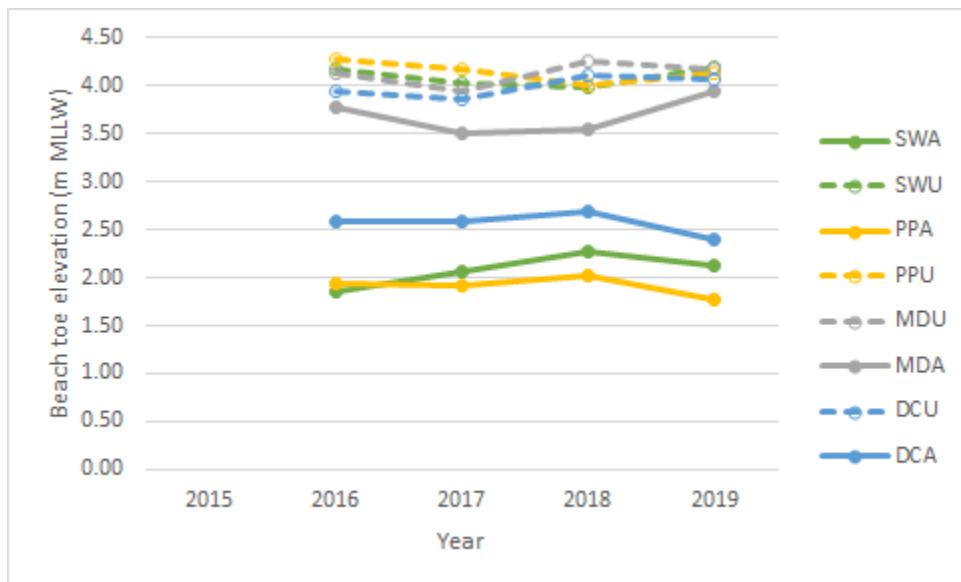


Figure B27. Average beach toe elevation (m +MLLW) measured at each South site pair in Snohomish County, WA; where solid lines represent armored locations and dashed lines represent unarmored locations. Note that lines are organized by northness with SWA being the most north site.

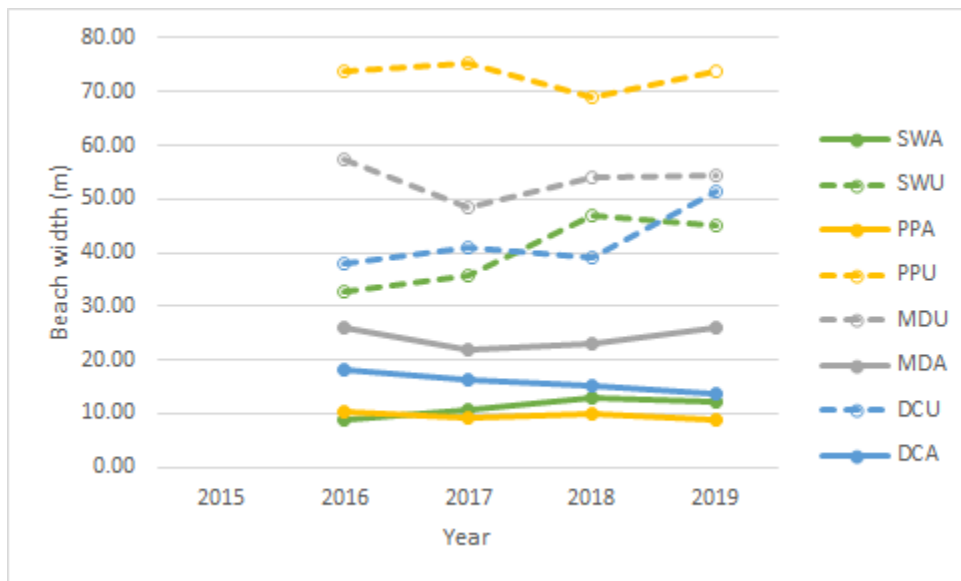


Figure B28. Average beach width (m) measured at each South site pair in Snohomish County, WA; where solid lines represent armored locations and dashed lines represent unarmored locations. Note that lines are organized by northness with SWA being the most north site.

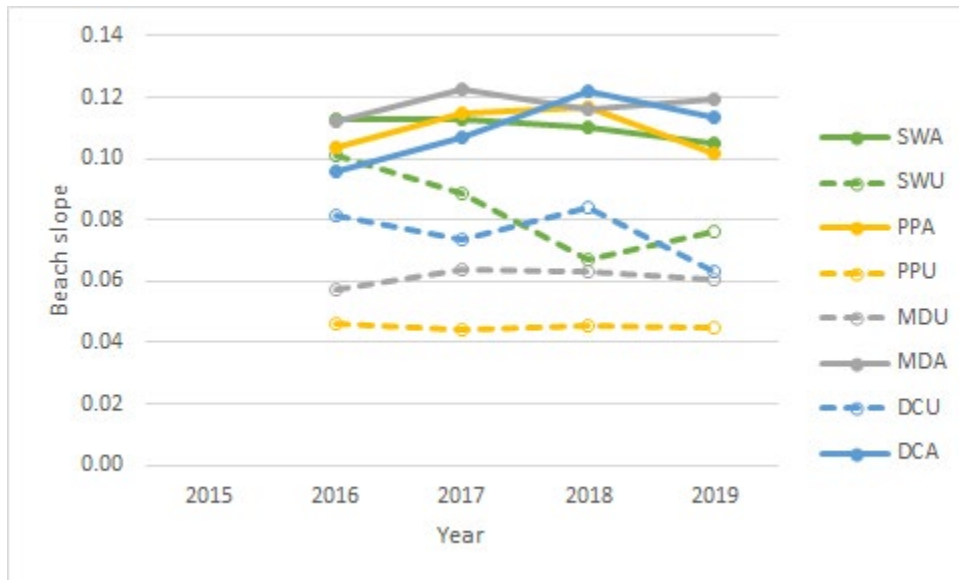


Figure B29. Average beach slope (m) measured at each South site pair in Snohomish County, WA; where solid lines represent armored locations and dashed lines represent unarmored locations. Note that lines are organized by northness with SWA being the most north site.

Table B2. Average, minimum and maximum values of beach profile parameters measured across sites 2015 to 2019 in the South Region, Snohomish County, WA. Values are summarized by treatment status (before or after nourishment) and strata (armored or unarmored). Note however, that no treatment (i.e. beach nourishment) was actually completed at South sites and are only categorized for comparison.

		Before (2015 - 2016)			After (2017 - 2019)		
		Armored	Unarmored	Total	Armored	Unarmored	Total
Toe (m +MLLW)	Average	2.54	4.13	3.34	2.42	4.10	3.28
	Minimum	1.85	3.94	1.85	1.66	3.86	1.66
	Maximum	3.78	4.27	4.27	3.94	4.27	4.27
RE (m +MLLW)	Average	0.79	-0.80	-0.01	0.91	-0.77	0.04
	Minimum	-0.47	-0.95	-0.95	-0.62	-0.94	-0.94
	Maximum	1.48	-0.60	1.48	1.67	-0.52	1.67
Width (m)	Average	15.86	50.54	33.20	13.87	54.29	34.69
	Minimum	8.85	32.80	8.85	7.47	35.90	7.47
	Maximum	26.09	73.97	73.97	25.89	81.20	81.20
Slope (m)	Average	0.11	0.07	0.09	0.11	0.06	0.09
	Minimum	0.10	0.05	0.05	0.10	0.04	0.04
	Maximum	0.11	0.10	0.11	0.12	0.09	0.12

APPENDIX C.

Substrate Size Favorability and Forage Fish Egg Count

Substrate Size Favorability

Monthly surf smelt substrate size favorability by site.

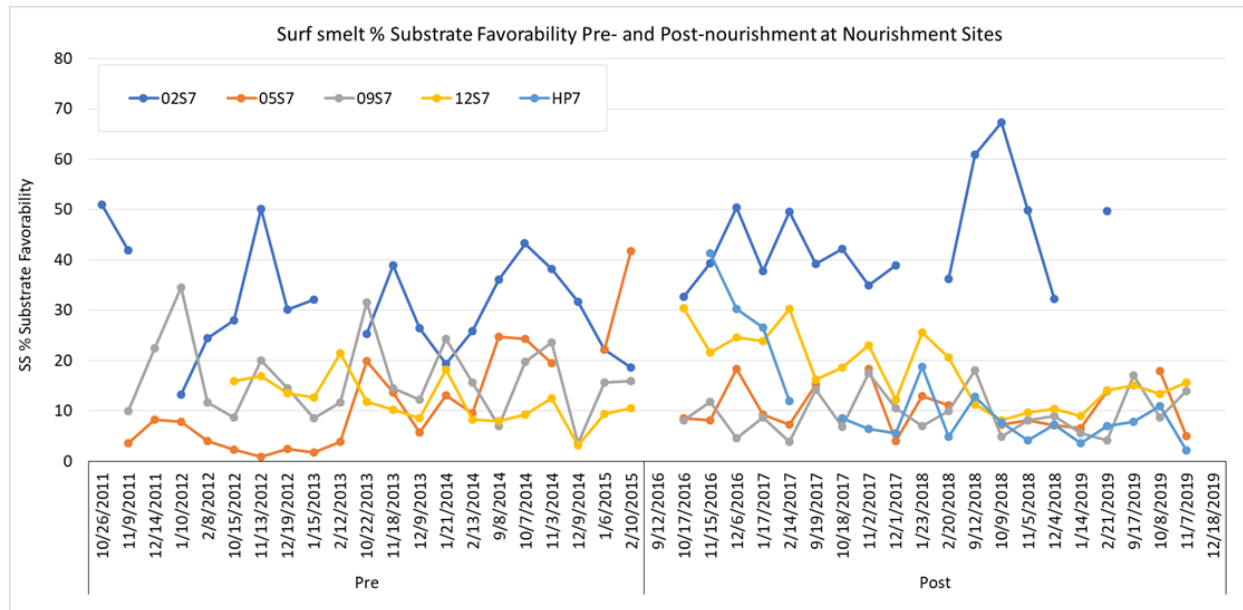


Fig. C1. Monthly surf smelt substrate size favorability for nourished or treated sites at Howarth Park.

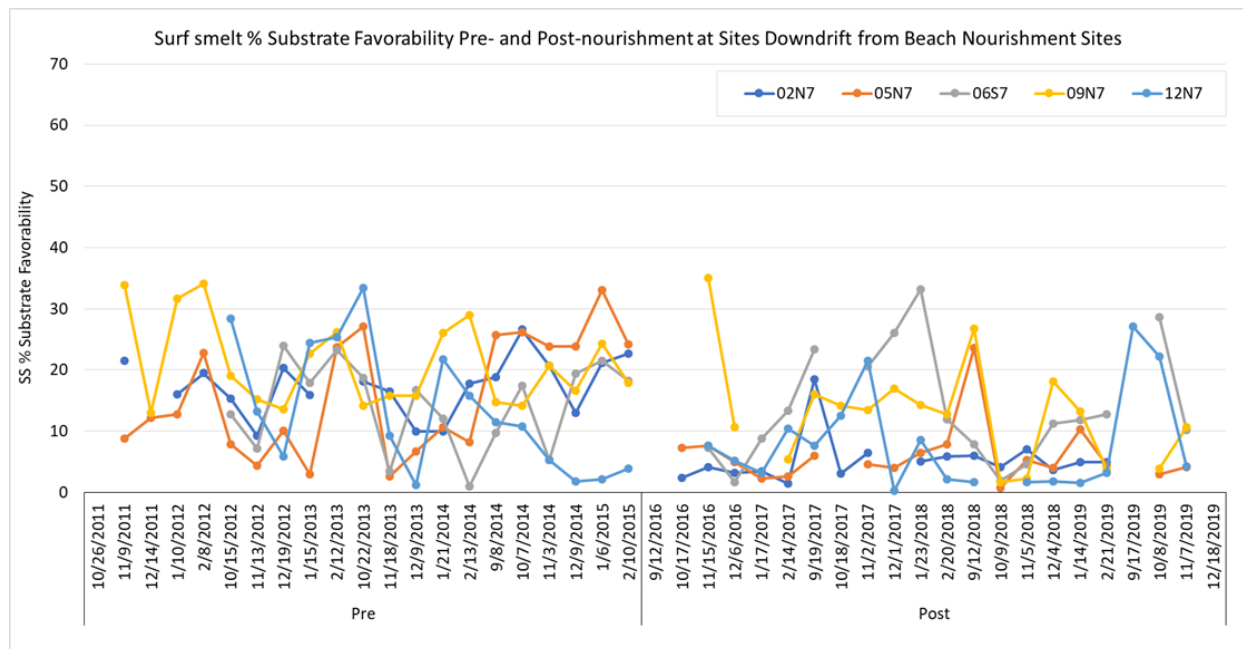


Fig. C2. Monthly surf smelt substrate size favorability for sites downdrift of beach nourishment locations.

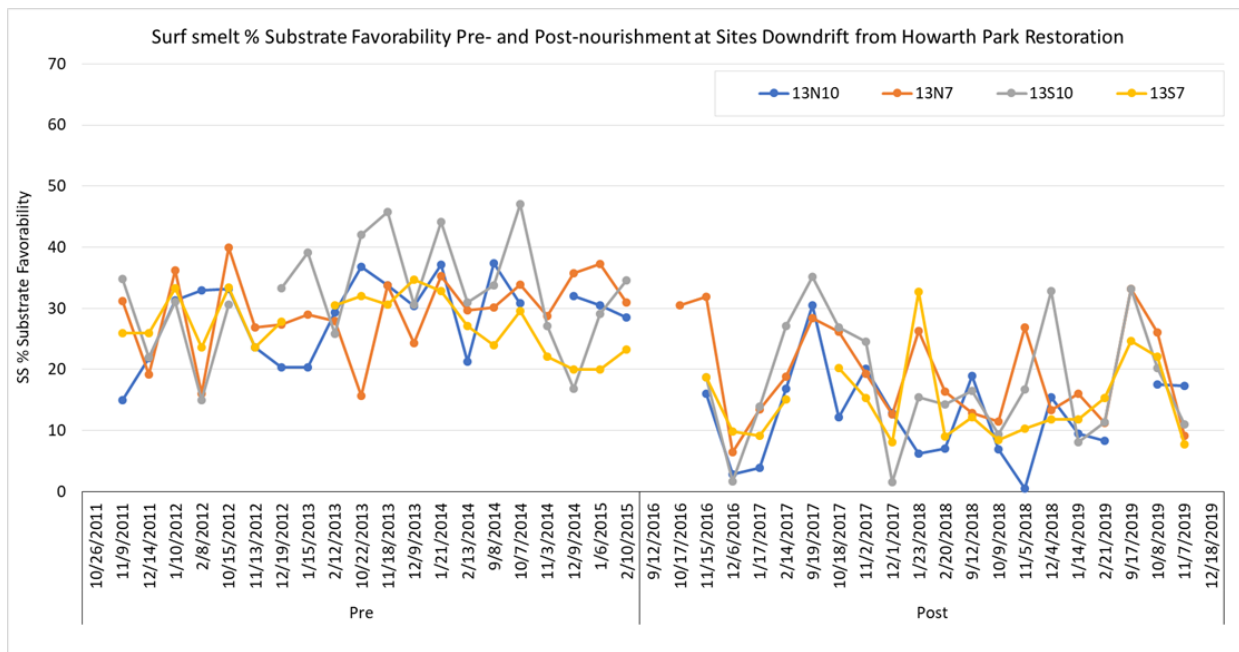
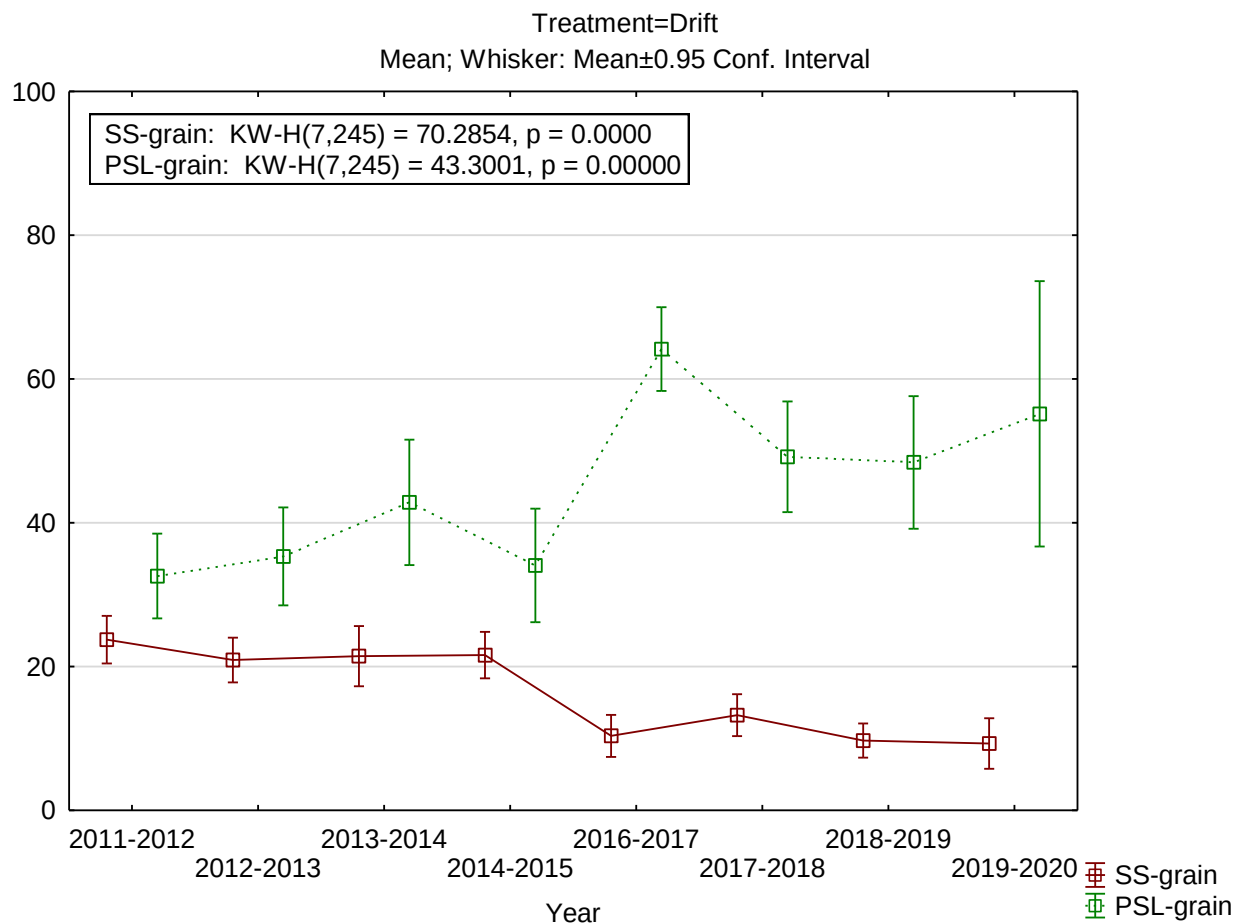


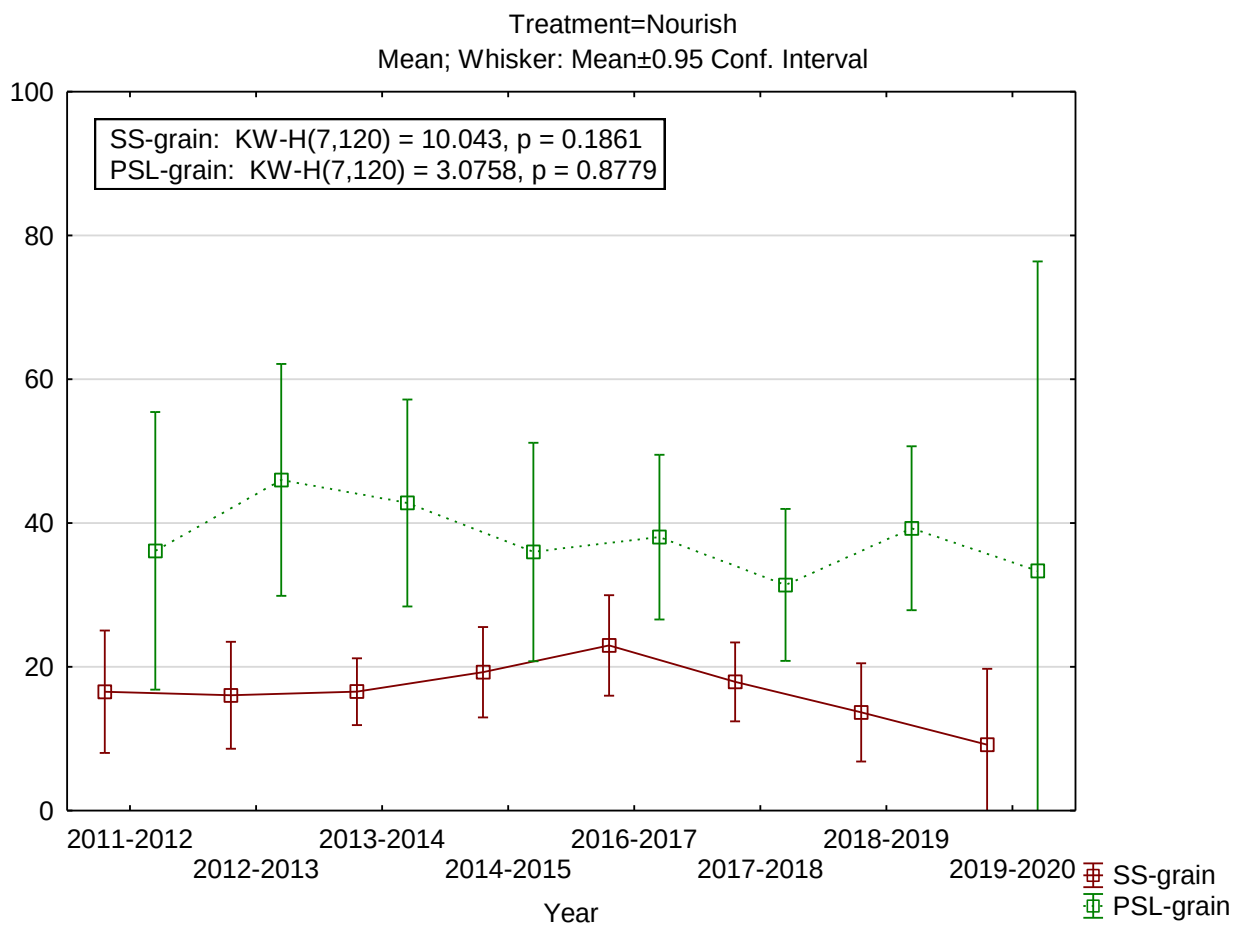
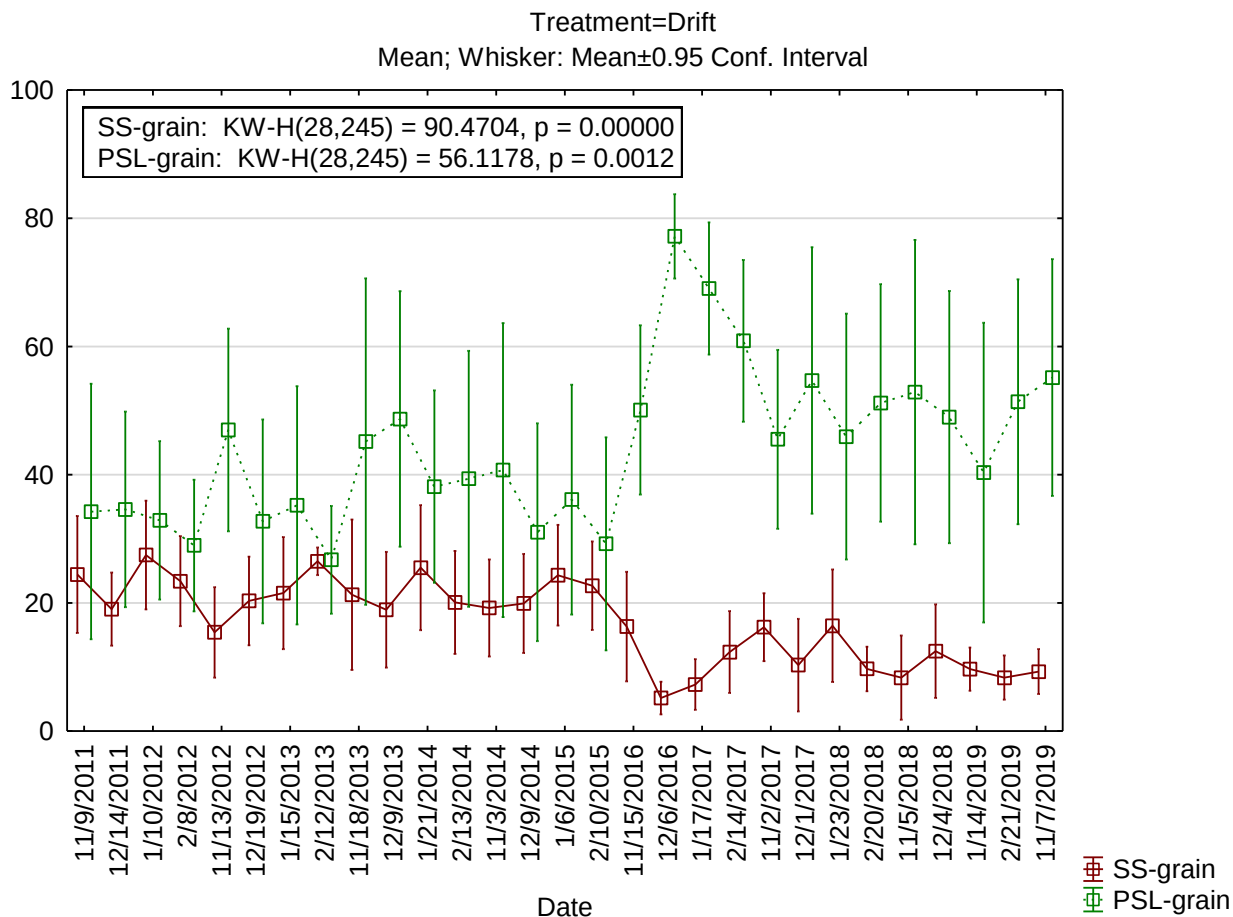
Fig. C3. Monthly surf smelt substrate size favorability for sites downdrift of Howarth Park restoration.

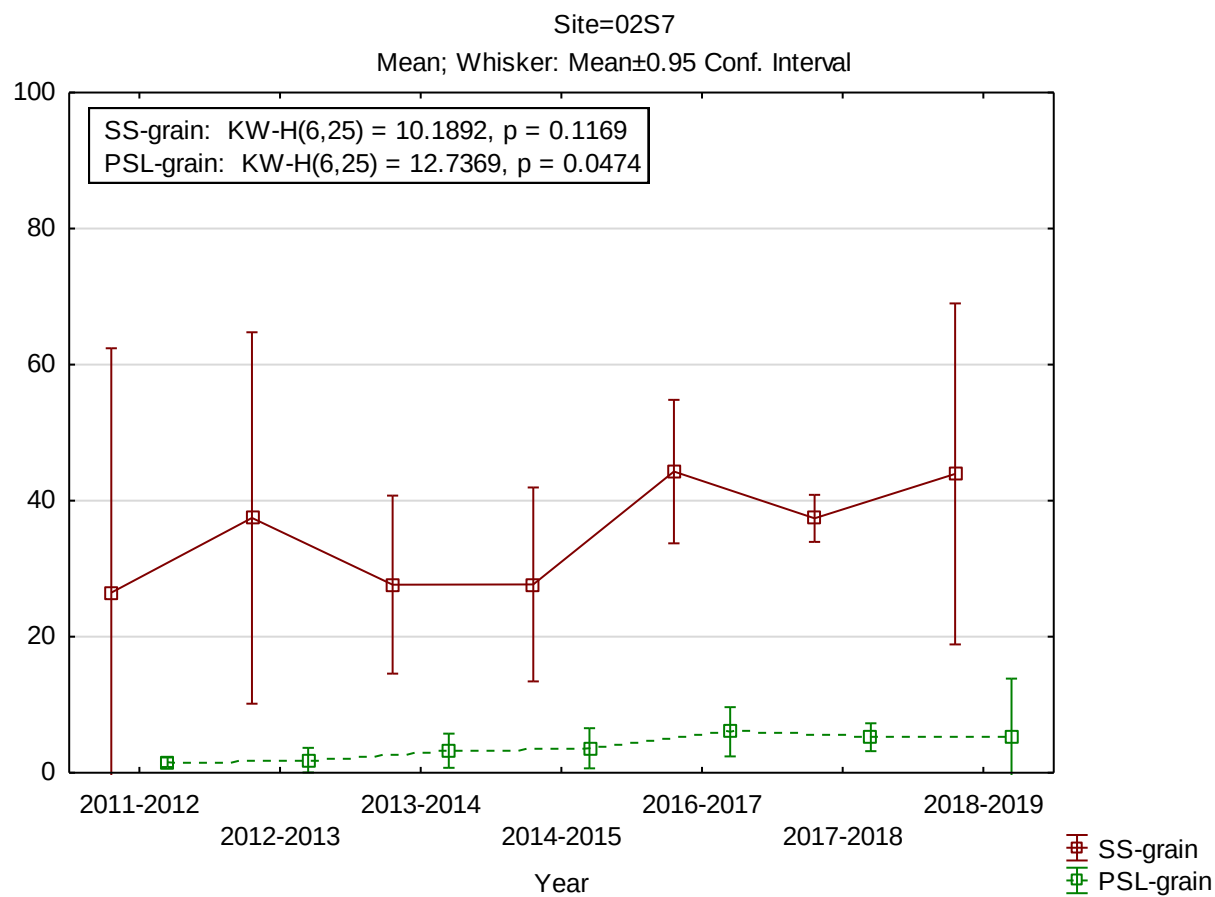
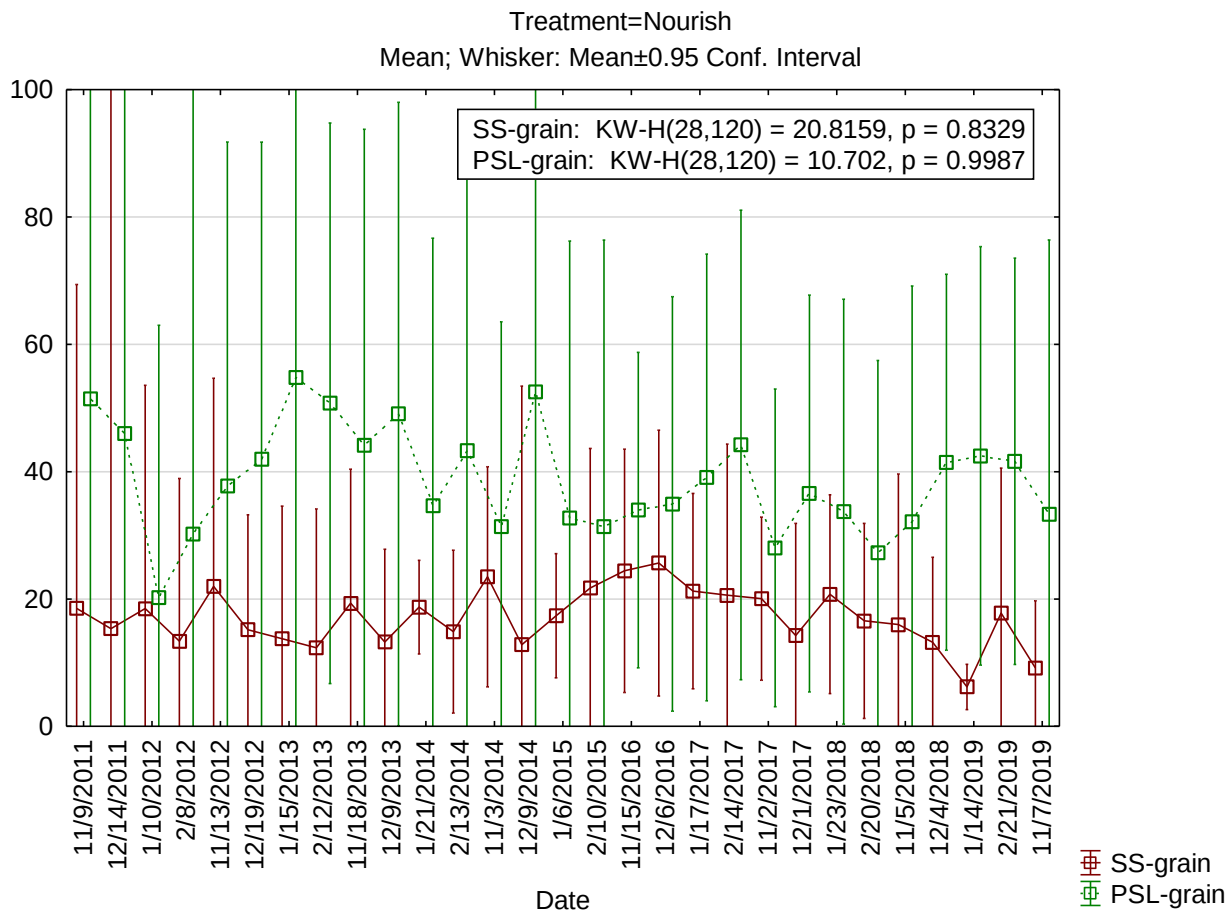
Results for PSL and SS substrate size favorability (y-axis) by year for treatments types (Drift and Nourish for year and month), then by site (for year) with non-parametric Kruskal-Wallis test for Year.

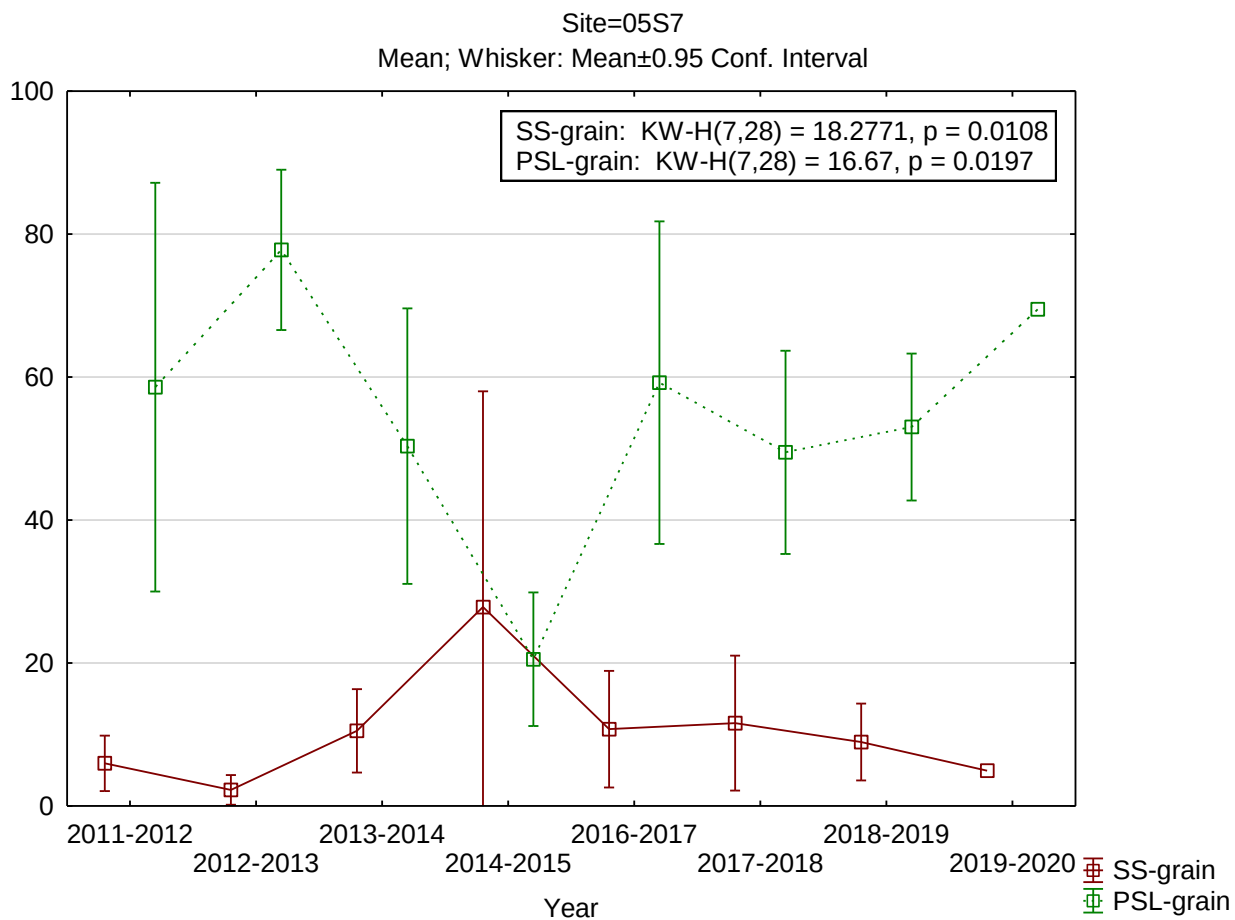
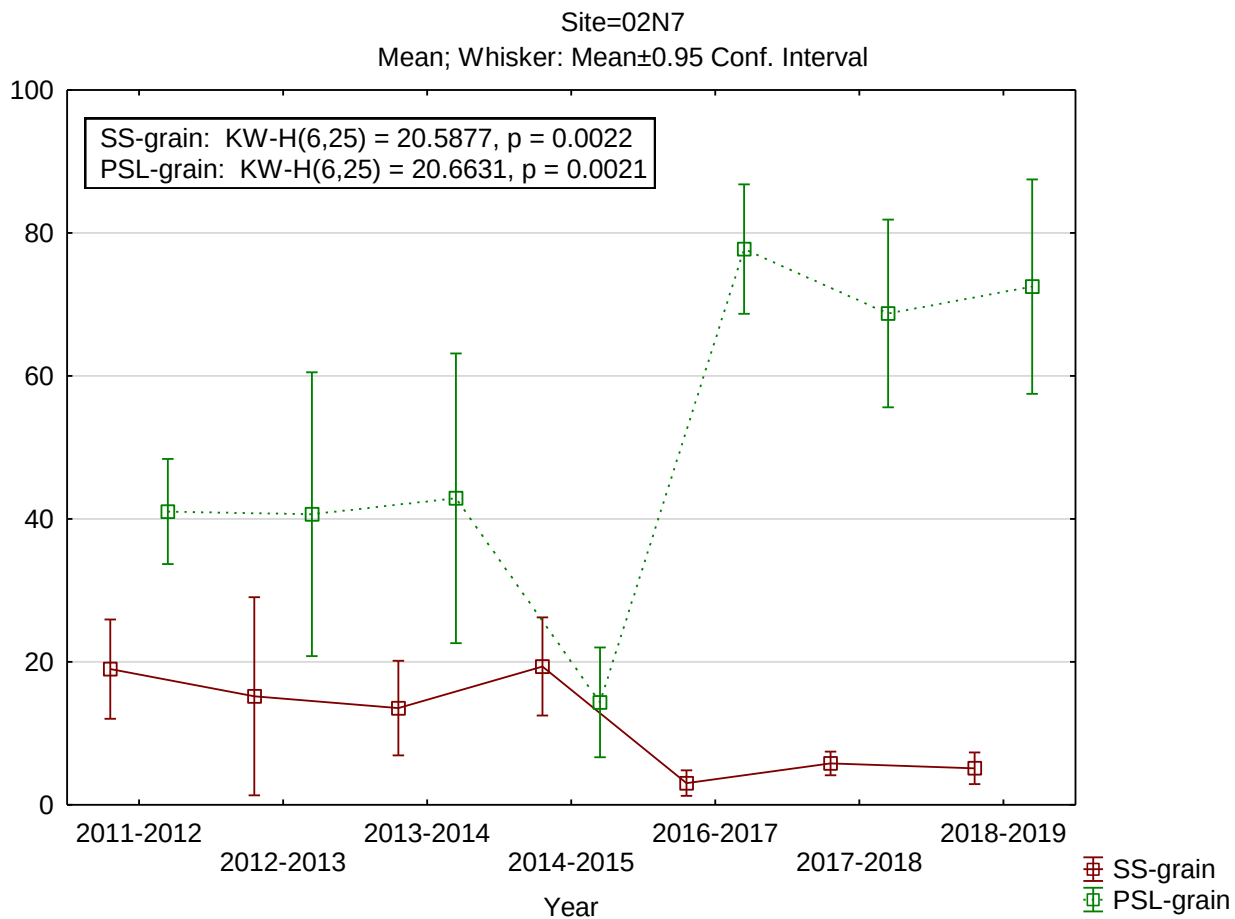
Pre-project Years are 2011-2015. Post-project years are 2016-2020.

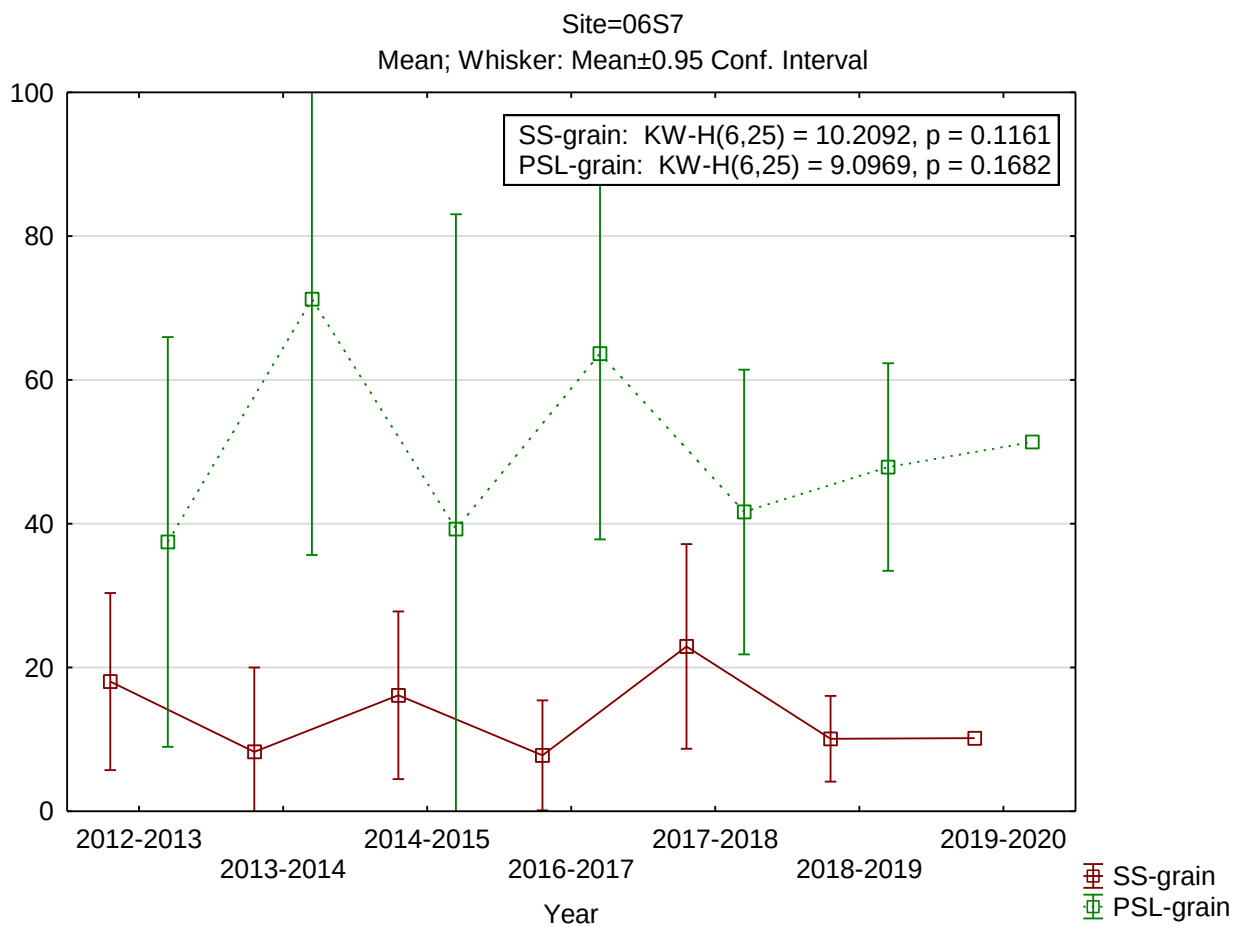
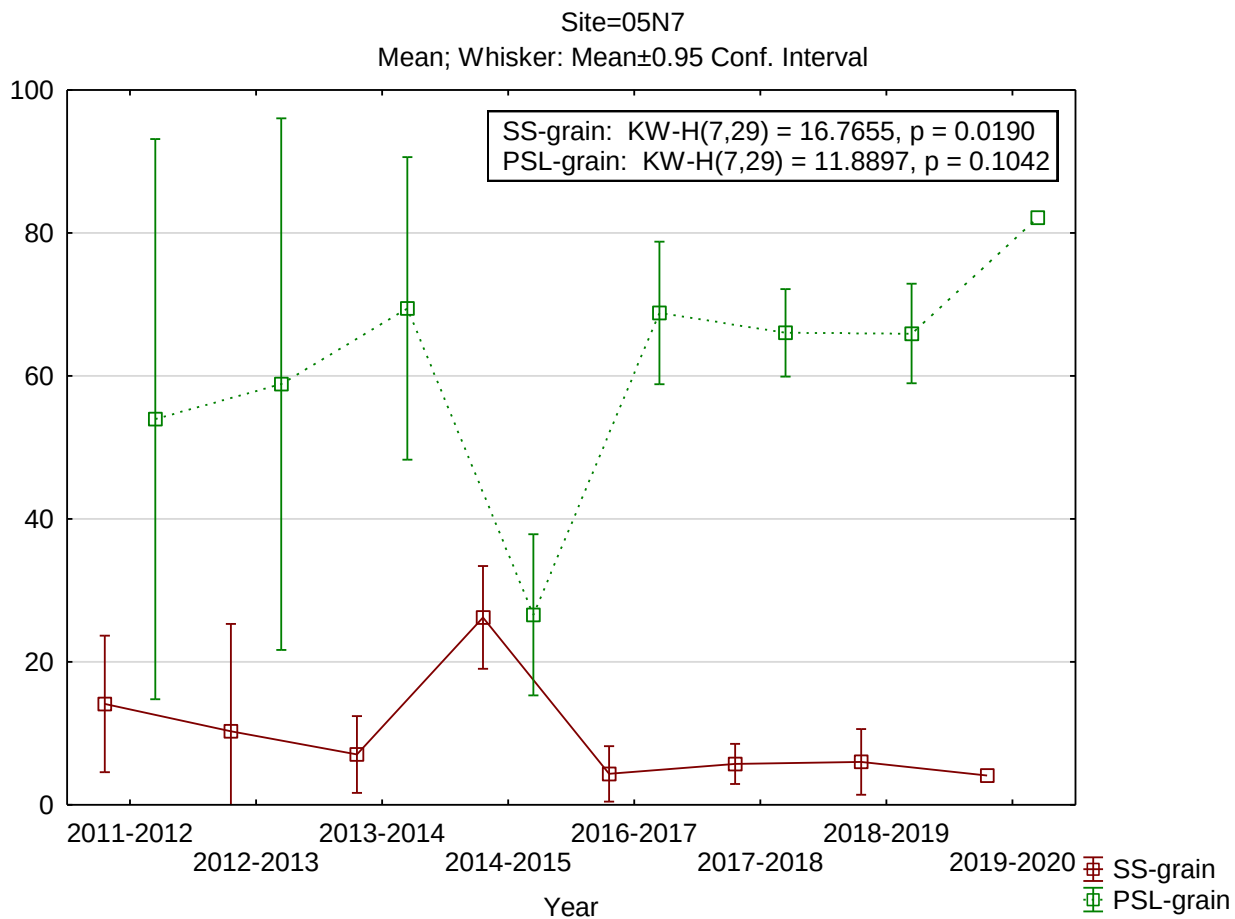
Figs. C4-C21.

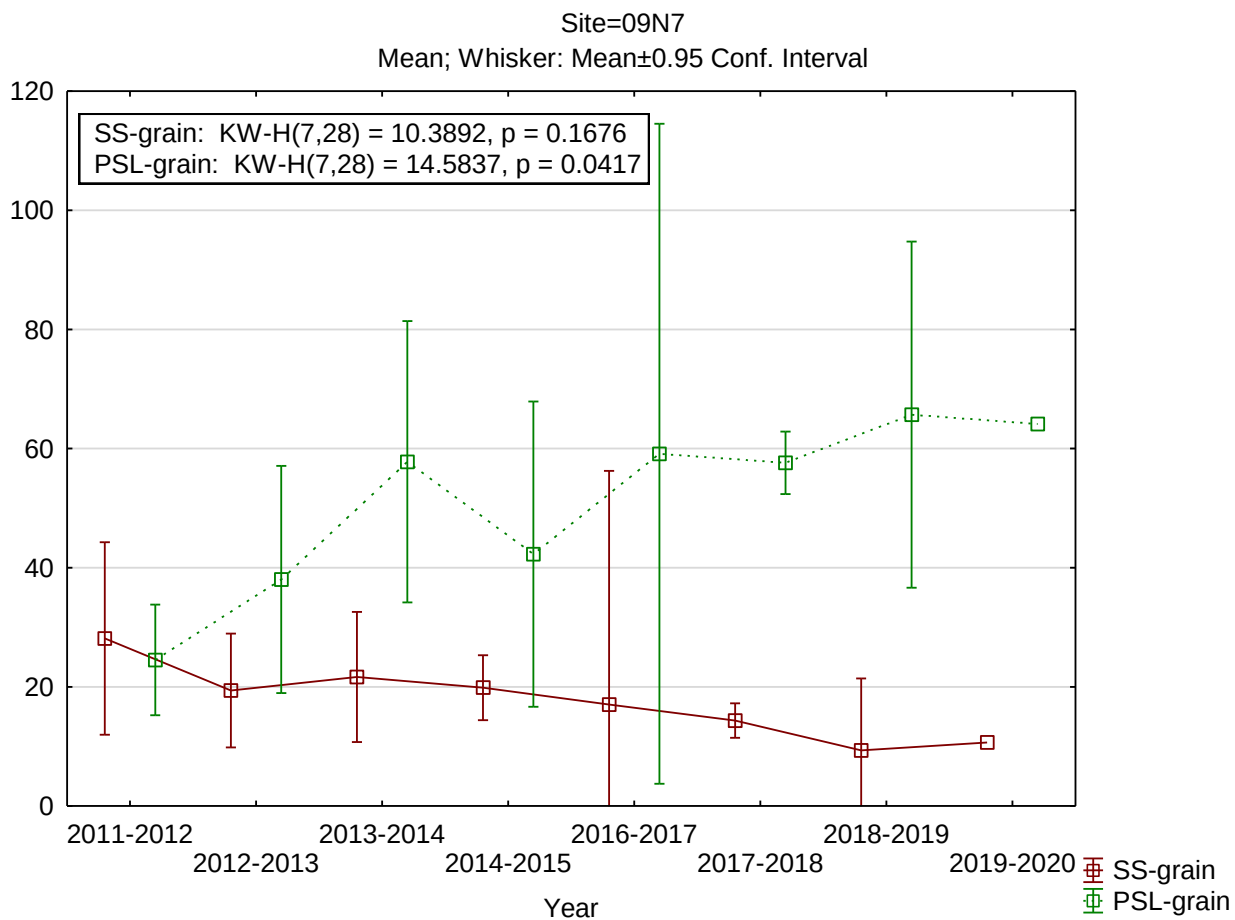
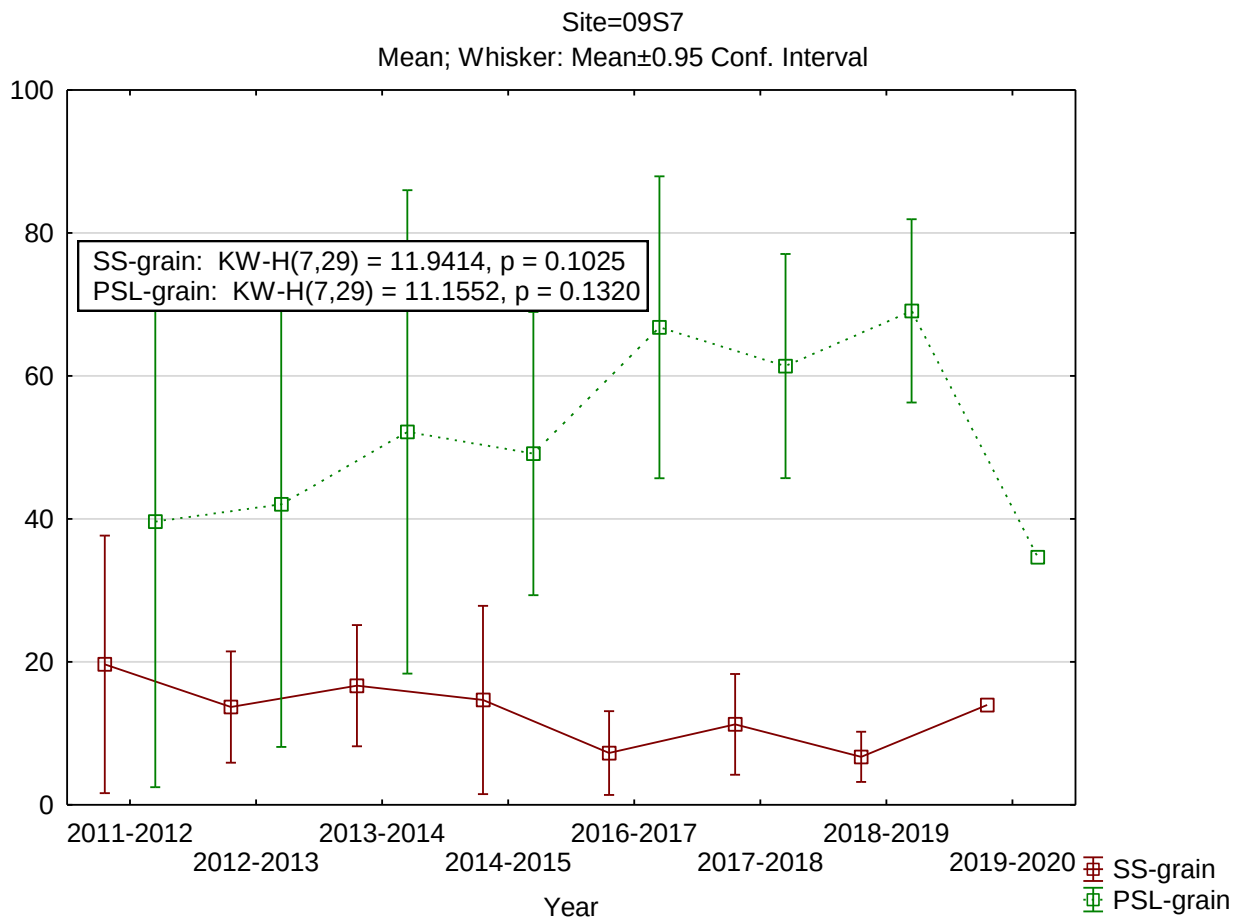


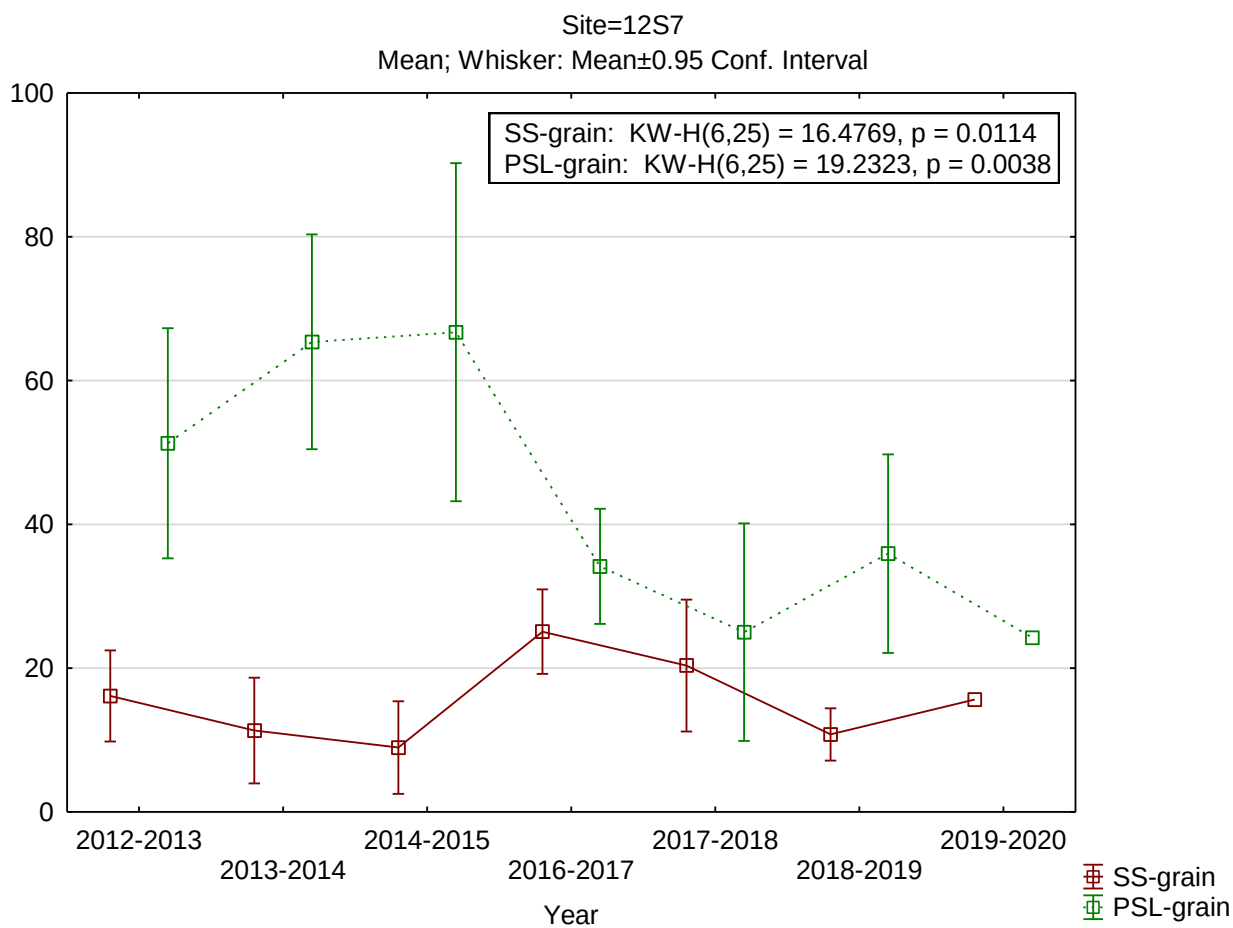
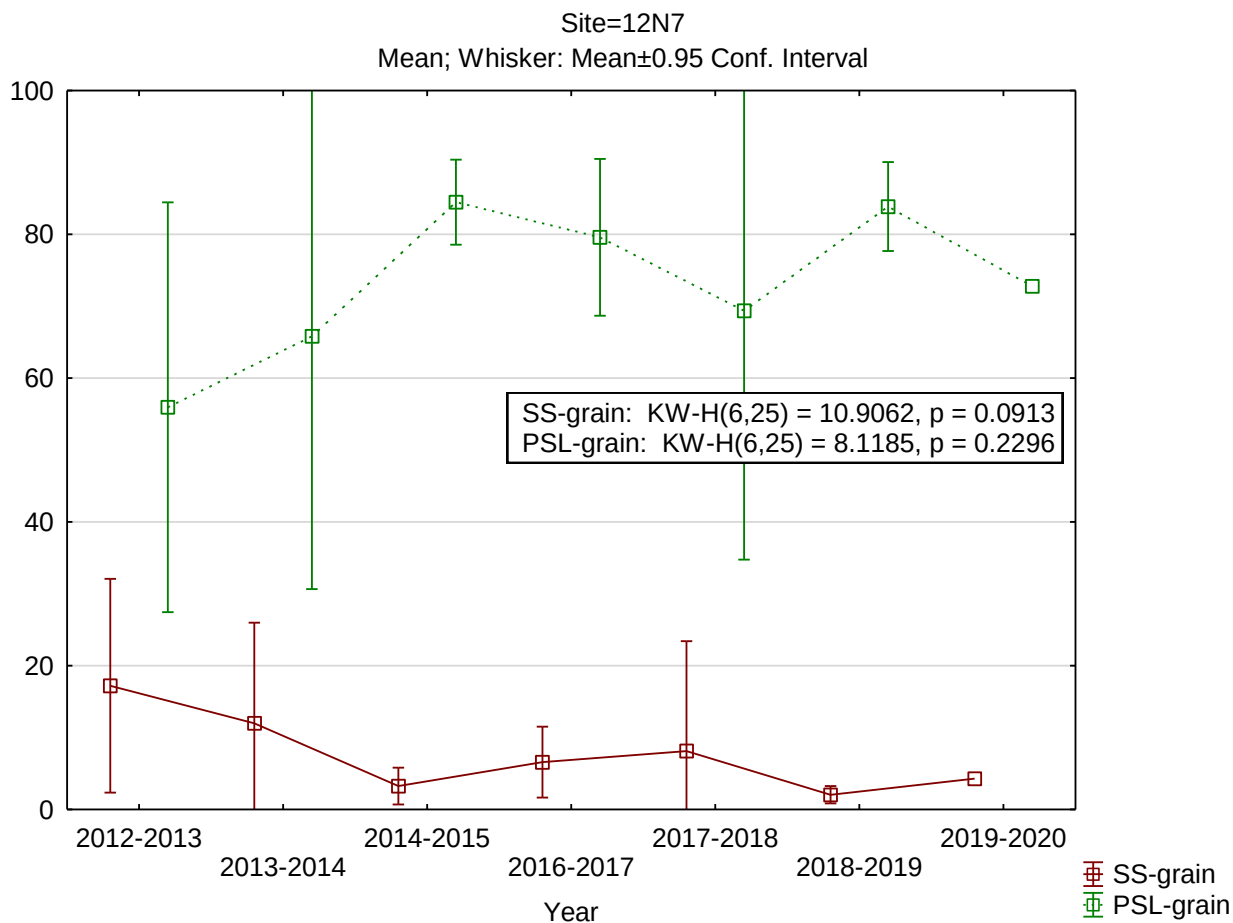


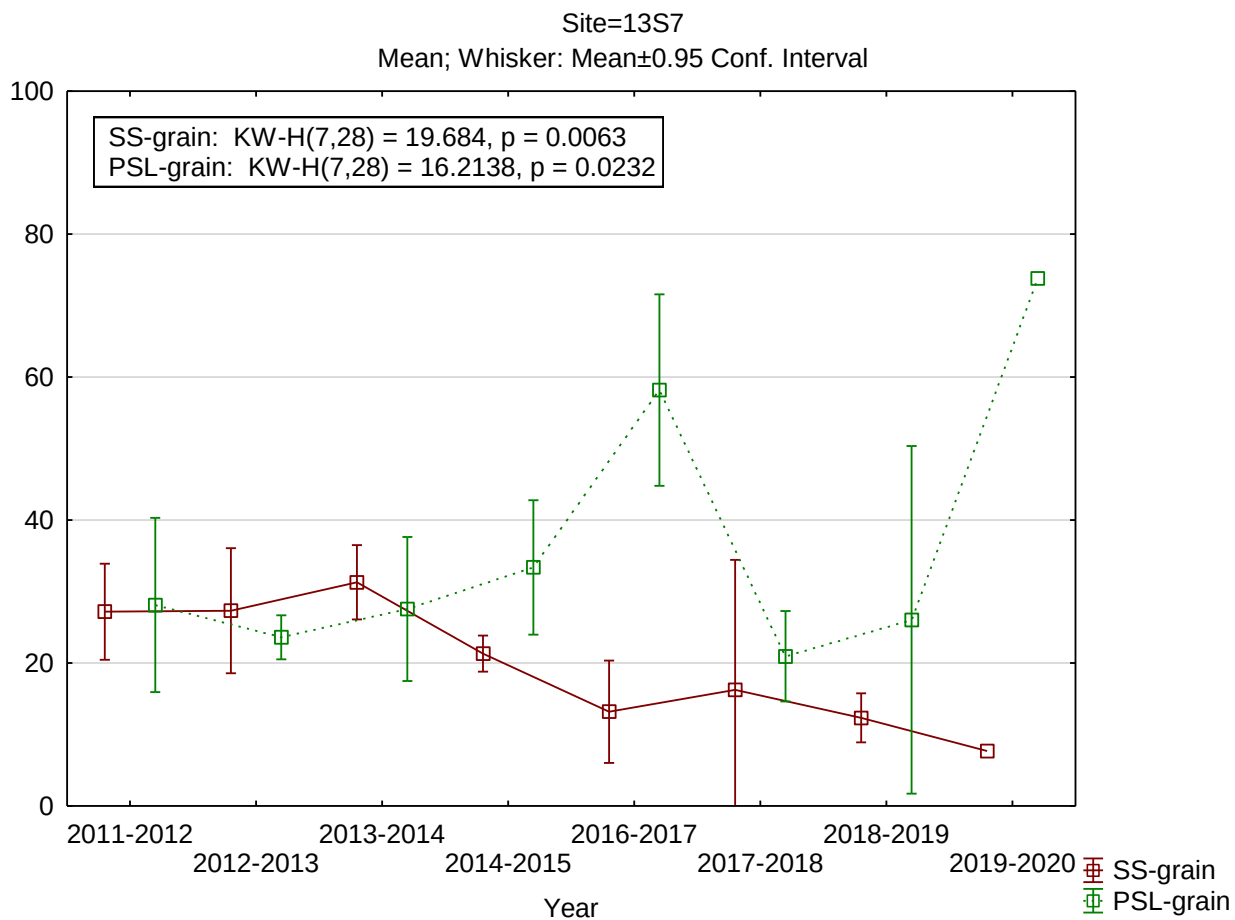
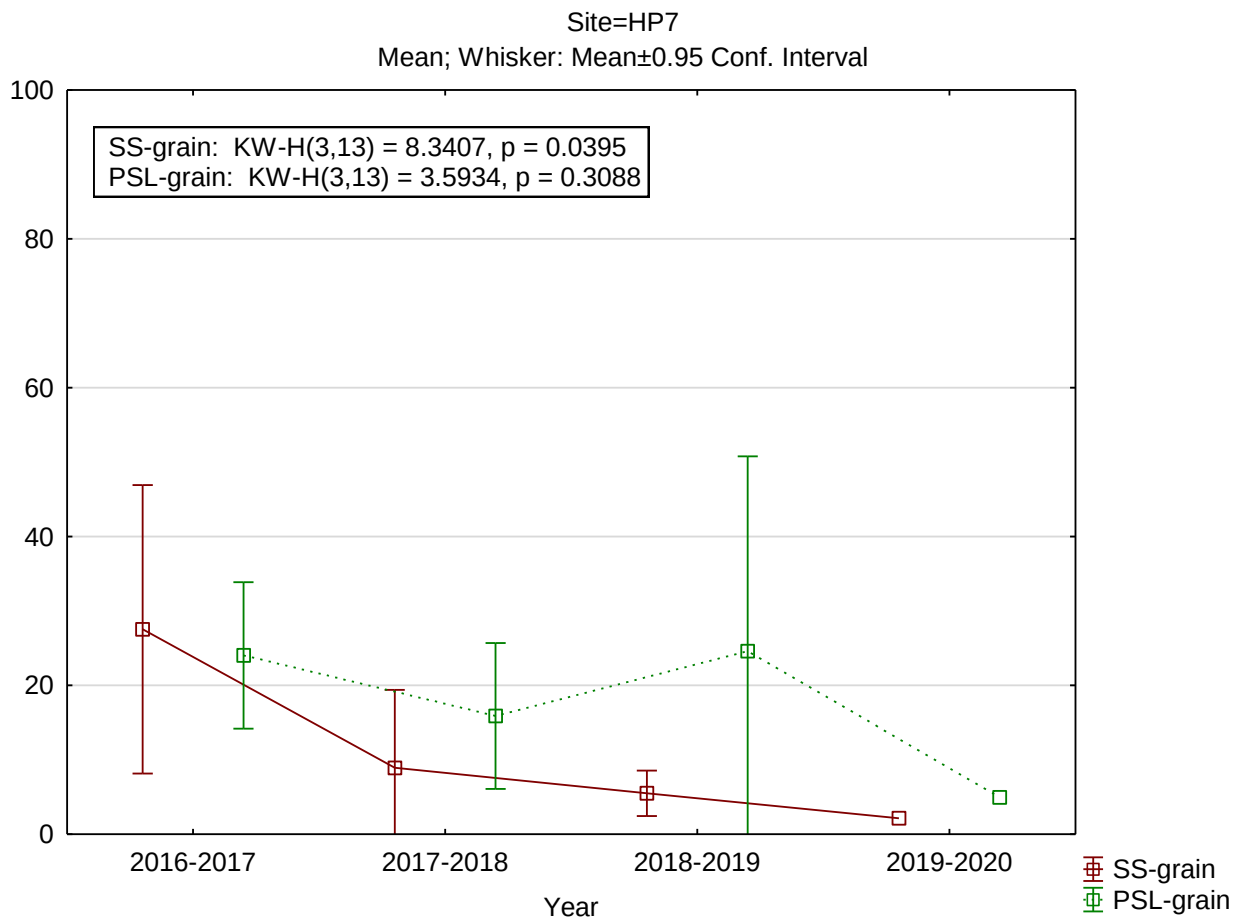


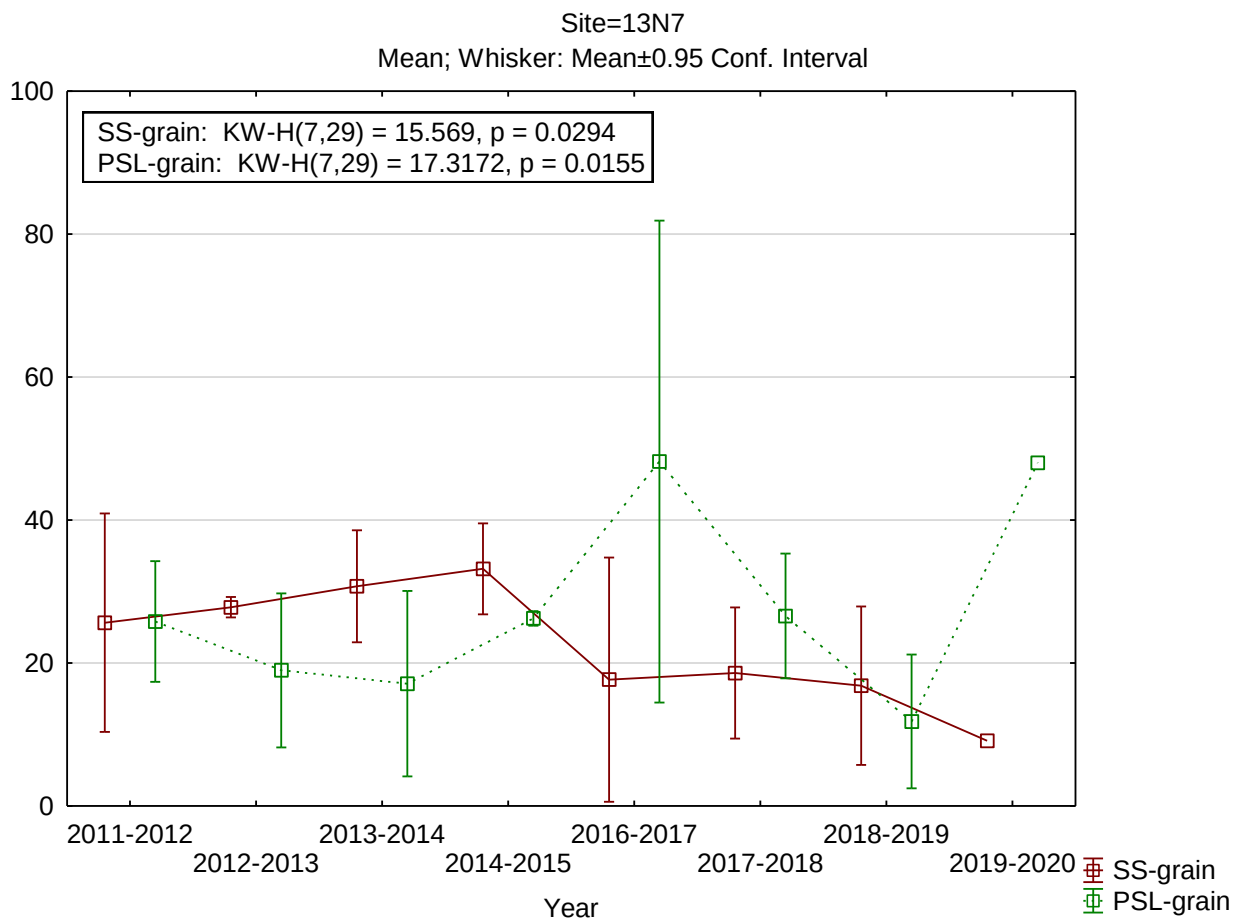
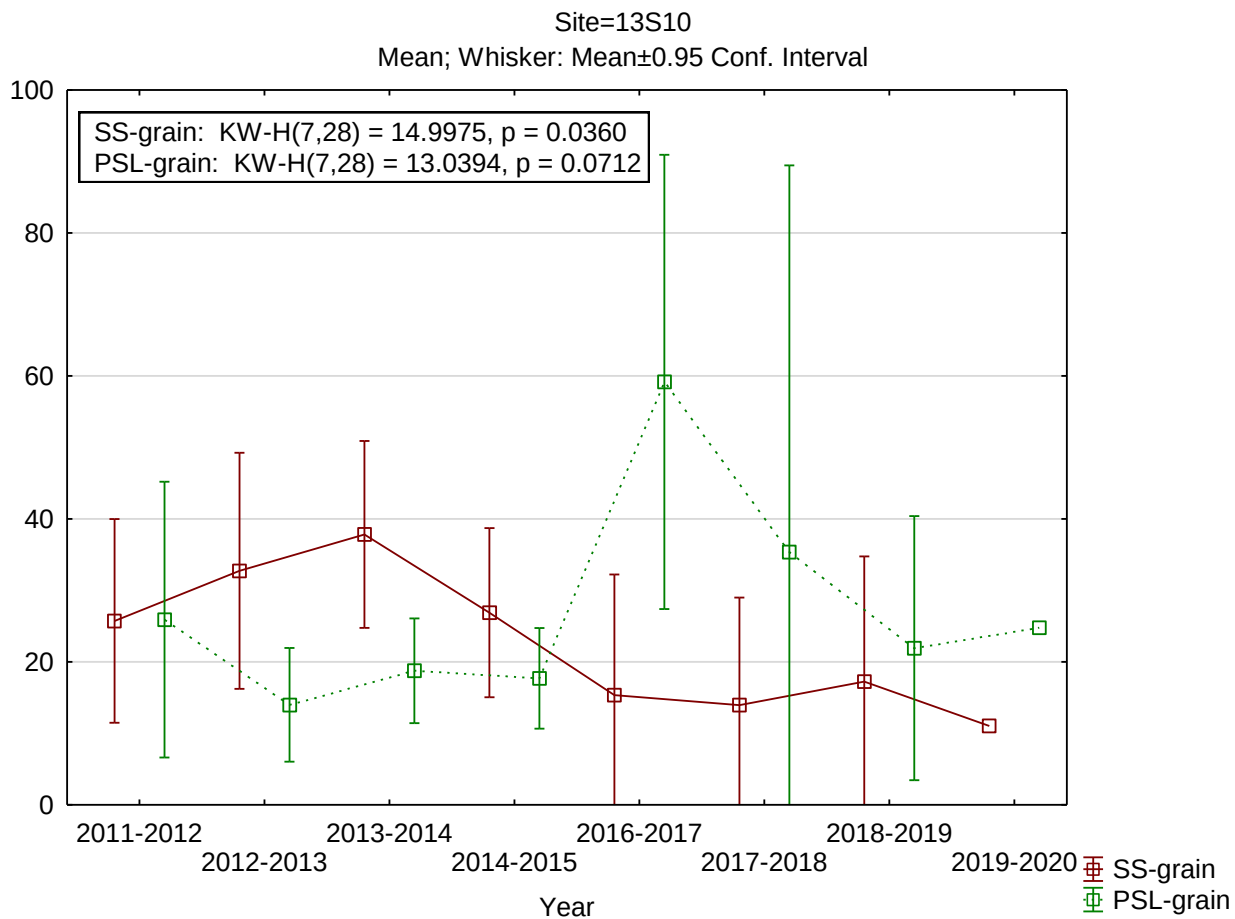






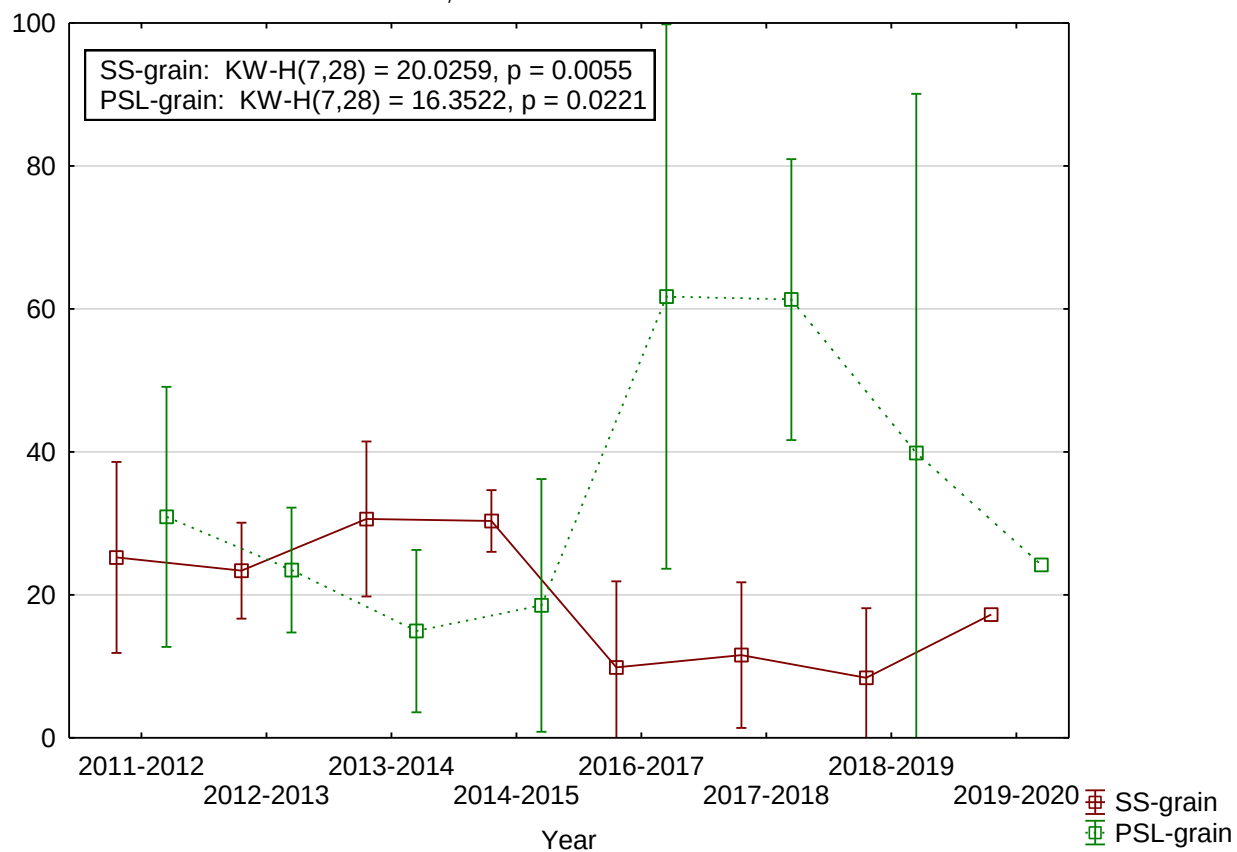






Site=13N10

Mean; Whisker: Mean $\pm$ 0.95 Conf. Interval



Wilcoxon Matched Pairs test between paired Nourished and Drift sites by date (x-axis) pre- and post-nourishment. The example below shows for Sites 5S and 5N that pre-project there were no differences in PSL grain size by date. Post-nourishment, 5N had significantly greater PSL substrate size favorability than 5S, likely due to a downdrift effect from nourishment. All other paired comparisons by date pre- and post-nourishment are included in Table C1 below. Sites 13S and 13N are excluded due their position downdrift from Howarth Park, which was a different type of treatment than sites influenced by nourishment - 2, 5, 6, 9, and 12.

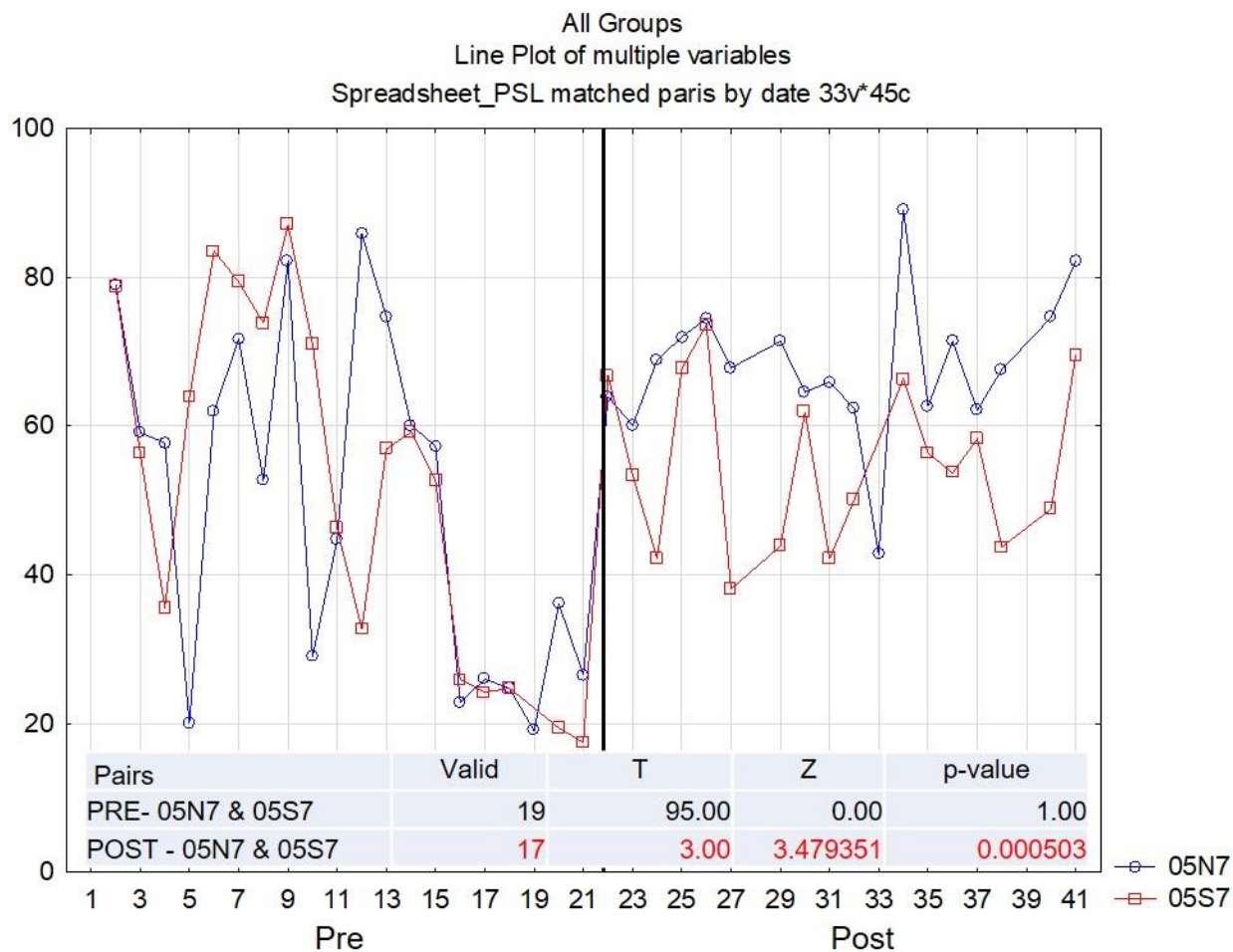


Fig. C22. Monthly PSL grain size matched pair values for sites 5S7 and 5N7, demonstrating significant difference post-nourishment in 5N7 downdrift PSL grain size compared to 5S7.

Table C1. Wilcoxon matched pairs tests for paired nourish and downdrift sites. Results showing a significant post-restoration interaction effect are bolded.

All Groups Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid	T	Z	p-value
02N7	& 02S7	32	0.00	4.936520	0.000001
05N7	& 05S7	36	174.0000	2.497981	0.012491
05N7	& 06S7	33	157.0000	2.206677	0.027337
05S7	& 06S7	31	217.0000	0.607493	0.543524
09N7	& 09S7	37	254.0000	1.470913	0.141316
12N7	& 12S7	34	80.00000	3.718492	0.000200
PrePost=Pre Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid	T	Z	p-value

02N7 & 02S7	18	0.00	3.723555	0.000196
05N7 & 05S7	19	95.00000	0.00	1.000000
05N7 & 06S7	16	66.00000	0.103418	0.917632
05S7 & 06S7	15	59.00000	0.056796	0.954708
09N7 & 09S7	20	74.00000	1.157313	0.247145
12N7 & 12S7	16	59.00000	0.465379	0.641660
PrePost=Post Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000				
Pair of Variables	Valid	T	Z	p-value
02N7 & 02S7	14	0.00	3.295765	0.000982
05N7 & 05S7	17	3.000000	3.479351	0.000503
05N7 & 06S7	17	15.00000	2.911294	0.003600
05S7 & 06S7	16	45.00000	1.189302	0.234322
09N7 & 09S7	17	57.00000	0.923093	0.355959
12N7 & 12S7	18	1.000000	3.680005	0.000233

Table C2. Mann-Whitney U test of pre- and post-nourishment PSL-grain size by site.

PSL Grain Size							
Site	Pre		Post		Non-parametric M-W-U test		Site Type
	Average	N	Average	N	Z	P	Type
02N7	33.9	14	73.4	11	-4.13	0.00004	Drift
02S7	2.7	14	5.6	10	-2.98	0.00285	Nourish
05N7	52.2	16	68.1	13	-1.86	0.06236	Drift
05S7	53.9	15	55.1	13	0.23	0.81784	Nourish
06S7	49.3	12	51.1	13	-0.57	0.56792	Drift
09N7	40.7	16	61.2	12	-2.76	0.00574	Drift
09S7	45.7	16	63.4	13	-2.61	0.00907	Nourish
12N7	68.8	12	77.2	13	-0.84	0.39918	Drift
12S7	61.1	12	31.1	13	4.00	0.00006	Nourish
13N10	22.2	15	52.0	13	-3.22	0.00126	Drift
13N7	22.0	16	30.3	13	-0.72	0.46933	Drift
13S10	19.4	15	37.7	13	-1.89	0.05894	Drift
13S7	28.5	15	38.0	13	86.00	-0.50672	Drift
HP7			17.7	21			

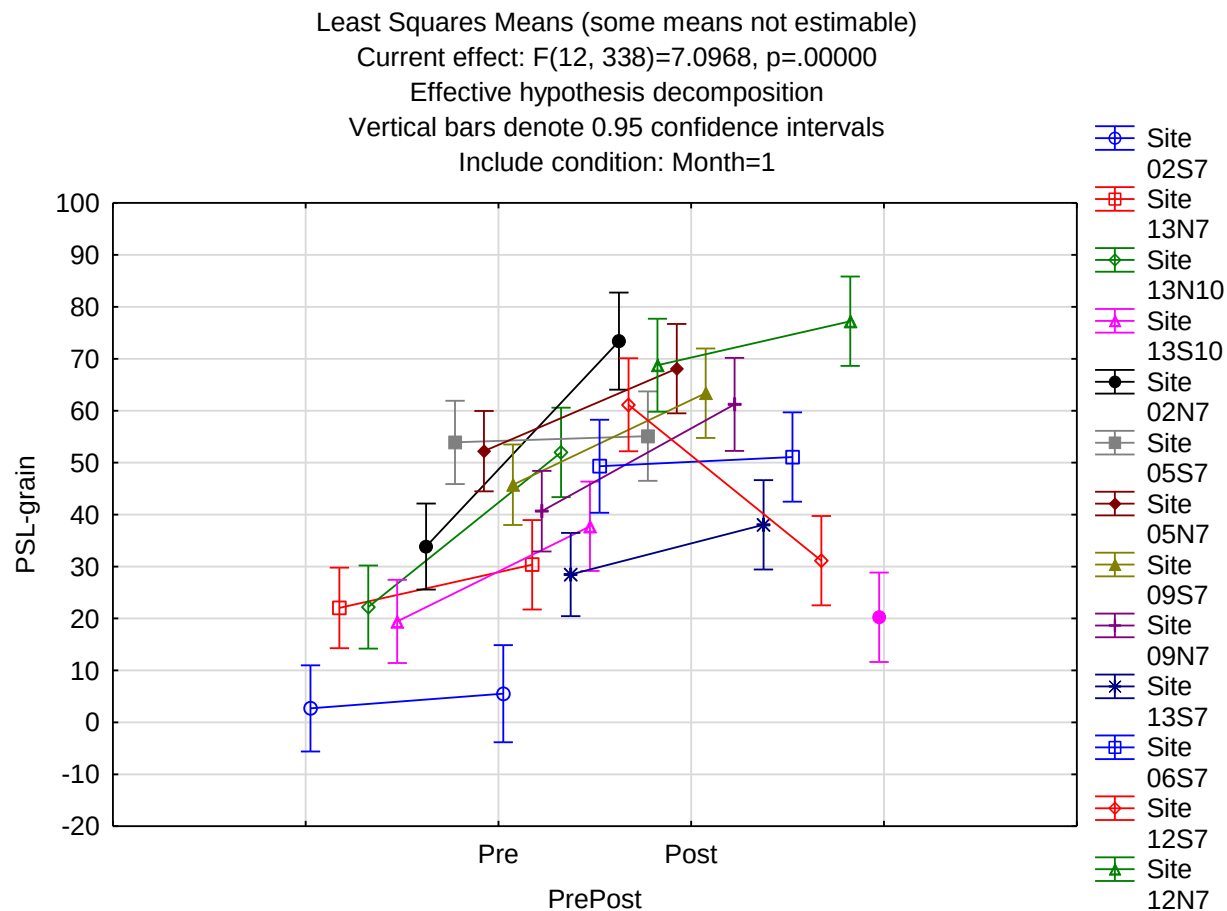


Fig. C23. Pre- and post-nourishment average PSL grain size by site. F-test is for sites.

Table C3. Wilcoxon Matched Pairs test between paired Pre- and Post- nourishment average PSL-grain size for all sites.

Pair of Variables	Type=Drift Wilcoxon Matched Pairs Test (Spreadsheet1991) Marked tests are significant at $p < .05000$			
	Valid N	T	Z	p-value
Average Pre PSL-grain & Average Post PSL-grain – All Sites	13	12.00000	2.341169	0.019224
Average Pre PSL-grain & Average Post PSL-grain – Drift Sites	9	0.00	2.665570	0.007686
Average Pre PSL-grain & Average Post PSL-grain – Nourish Sites	4	4.000000	0.365148	0.715001

Table C4. ANOVA table of PSL-grain size for Pre- vs Post-nourishment and Treatment type. Note that 12S7 is excluded because it was not a typical beach nourishment site, but was part of Howarth Park restoration. Were it included in the analysis results would be more significant. Months are limited to those with expected PSL spawning. The PrePost*Treatment interaction effect from table is shown in Fig. C24.

Univariate Tests of Significance for PSL-grain (SnoCo-FF_Grain-data DRAFT 2020-02-03)					
Sigma-restricted parameterization					
Effective hypothesis decomposition					
Include condition: Month=1					
Exclude condition: Site="12S7"					
Effect	SS	Degr. of Freedom	MS	F	p
Intercept	452111.7	1	452111.7	799.2396	0.000000
PrePost	6600.2	1	6600.2	11.6678	0.000714
Treatment	5586.8	1	5586.8	9.8762	0.001823
PrePost*Treatment	3966.5	1	3966.5	7.0120	0.008479
Error	190067.6	336	565.7		

PrePost*Treatment; LS Means
Current effect: $F(1, 336)=7.0120$, $p=.00848$
Effective hypothesis decomposition
Vertical bars denote 0.95 confidence intervals
Include condition: Month=1
Exclude condition: Site="12S7"

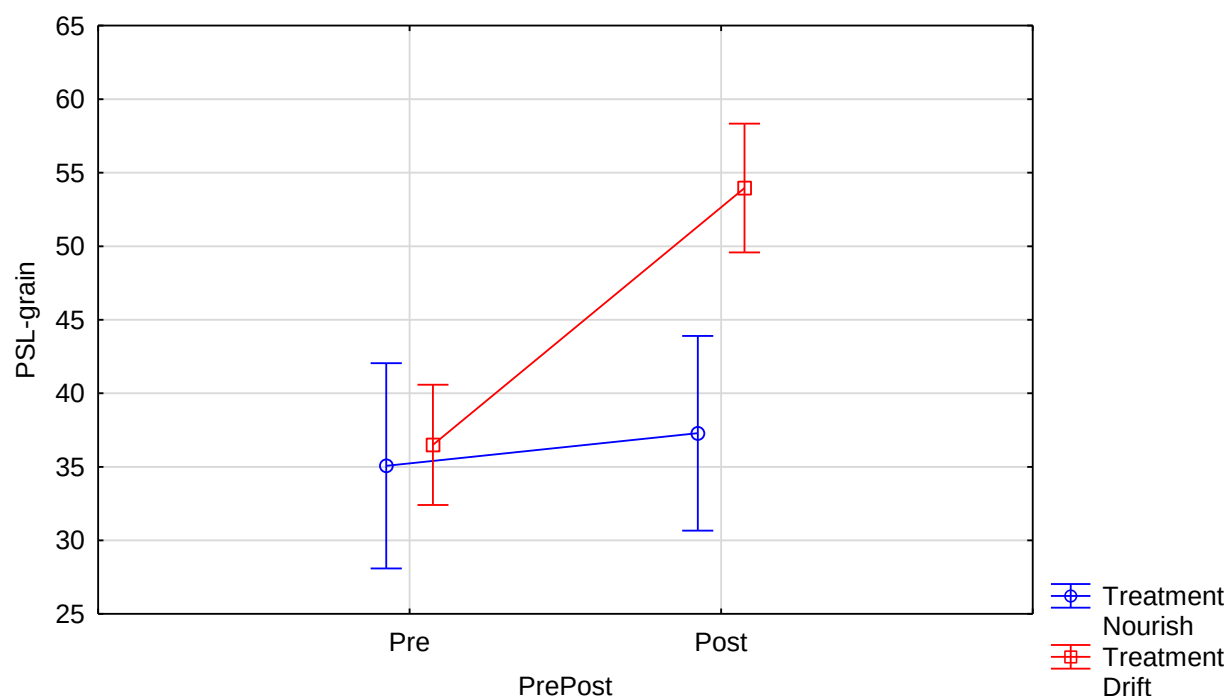


Fig. C24. Average PSL grain size pre- and post-nourishment by treatment type showing PrePost*Treatment interaction effect.

Results for Surf Smelt Substrate Size Favorability (suitability).

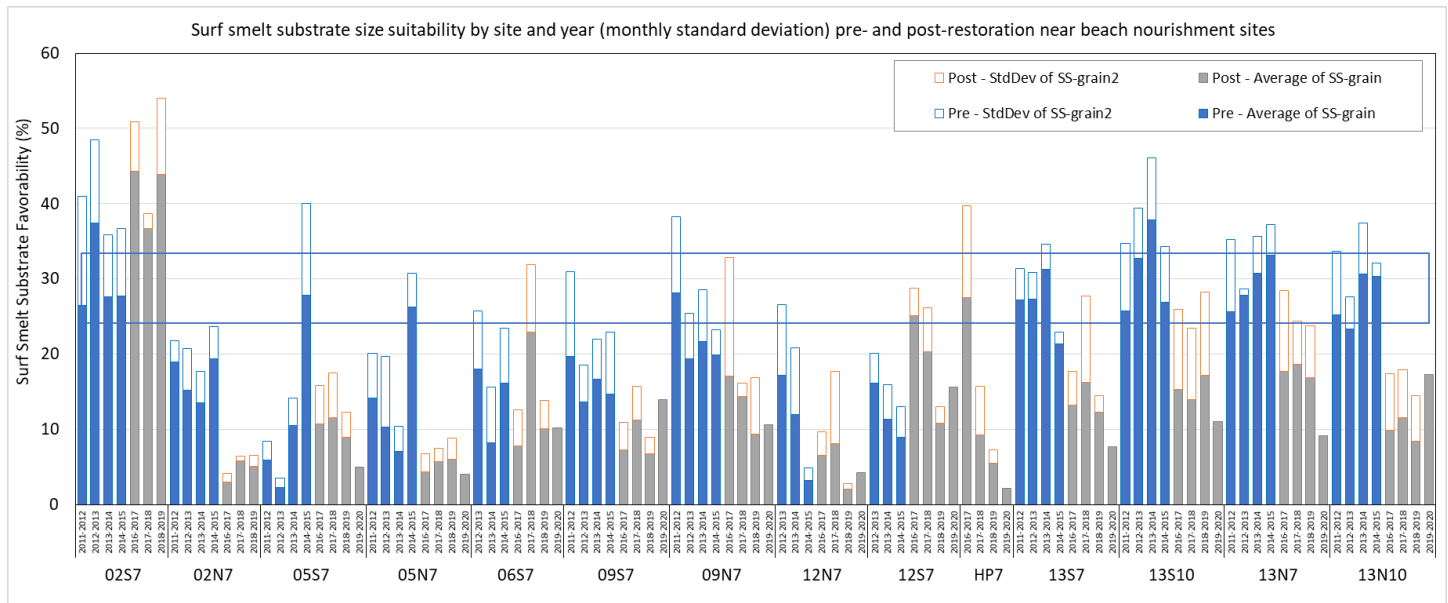


Fig. C25. Surf smelt annual average substrate size suitability pre- (blue bars) and post-nourishment (grey bars) by site (with standard deviation). A range of relatively higher suitability is bracketed between 25-33%, based on higher surf smelt spawning at Site 13.

Table C5. Non-parametric Mann-Whitney U test of pre- and post-nourishment SS substrate (grain) size favorability by individual site all months (Sept-Feb) spanning years 2011-2015 (Pre) and 2016-2019 (Post). Positive Z-values indicates decreasing suitability post-nourishment.

SS-Grain Size; Mann-Whitney U Test (w/ continuity correction) (SnoCo-FF_Grain-data DRAFT 2020-02-03) By variable PrePost Marked tests are significant at $p < .05000$ Include condition: Month=1 OR Month=2

Site	Rank Sum Pre	Rank Sum Post	U	Z	p-value	Z adjusted	p-value	Valid N Pre	Valid N Post
2N7	449.0	146.0	10.00	4.606188	0.000004	4.606188	0.000004	18	16
2S7	250.0	380.0	60.00	-3.02987	0.002447	-3.02987	0.002447	19	16
5N7	512.0	229.0	58.00	3.552085	0.000382	3.552085	0.000382	20	18
5S7	343.0	323.0	153.0	-0.253500	0.799882	-0.253500	0.799882	19	17
6S7	282.0	279.0	126.0	0.342208	0.732194	0.342208	0.732194	16	17
9N7	478.0	225.0	72.00	2.971420	0.002964	2.971420	0.002964	20	17
9S7	516.0	304.0	94.00	2.853784	0.004320	2.853784	0.004320	20	20
12N7	333.0	262.0	91.00	1.811422	0.070076	1.811422	0.070076	16	18
12S7	218.0	448.0	82.00	-2.46727	0.013615	-2.46727	0.013615	16	20
13N10	515.0	188.0	17.00	4.664382	0.000003	4.664382	0.000003	19	18
13N7	541.0	279.0	69.00	3.530037	0.000416	3.530037	0.000416	20	20
13S10	499.0	242.0	52.00	3.736928	0.000186	3.736928	0.000186	19	19
13S7	506.0	197.0	26.00	4.390901	0.000011	4.391161	0.000011	19	18
Drift	348000	19156.0	6115.0	8.535068	0.000000	8.535068	0.000000	167	161
Nourish	6414.0	7281.000	3095.0	0.889549	0.373709	0.889549	0.373709	74	91

Table C6. Wilcoxon matched pairs test of averaged pre- and post-nourishment SS substrate size suitability for all sites.

Pair of Variables	Wilcoxon Matched Pairs Test (Spreadsheet3) Marked tests are significant at p <.05000			
	Valid N	T	Z	p-value
Avg SS-grain PRE & Avg SS-grain POST	13	14.00000	2.201398	0.027709

Wilcoxon Matched Pairs test for SS % substrate size favorability between paired Nourished and Drift sites by date (x-axis) pre- and post-nourishment. The example below shows for Sites 13N7 and 13N10 that pre-project there were no differences in SS grain size by date. Post-nourishment, both sites had depressed SS substrate favorability, but were now significantly different. Site 13N10 (higher elevation) had significantly lower SS substrate size favorability, likely due to a downdrift effect from finer sands in beach nourishment material. All other paired comparisons by date pre- and post-nourishment are included in Table C7 below.

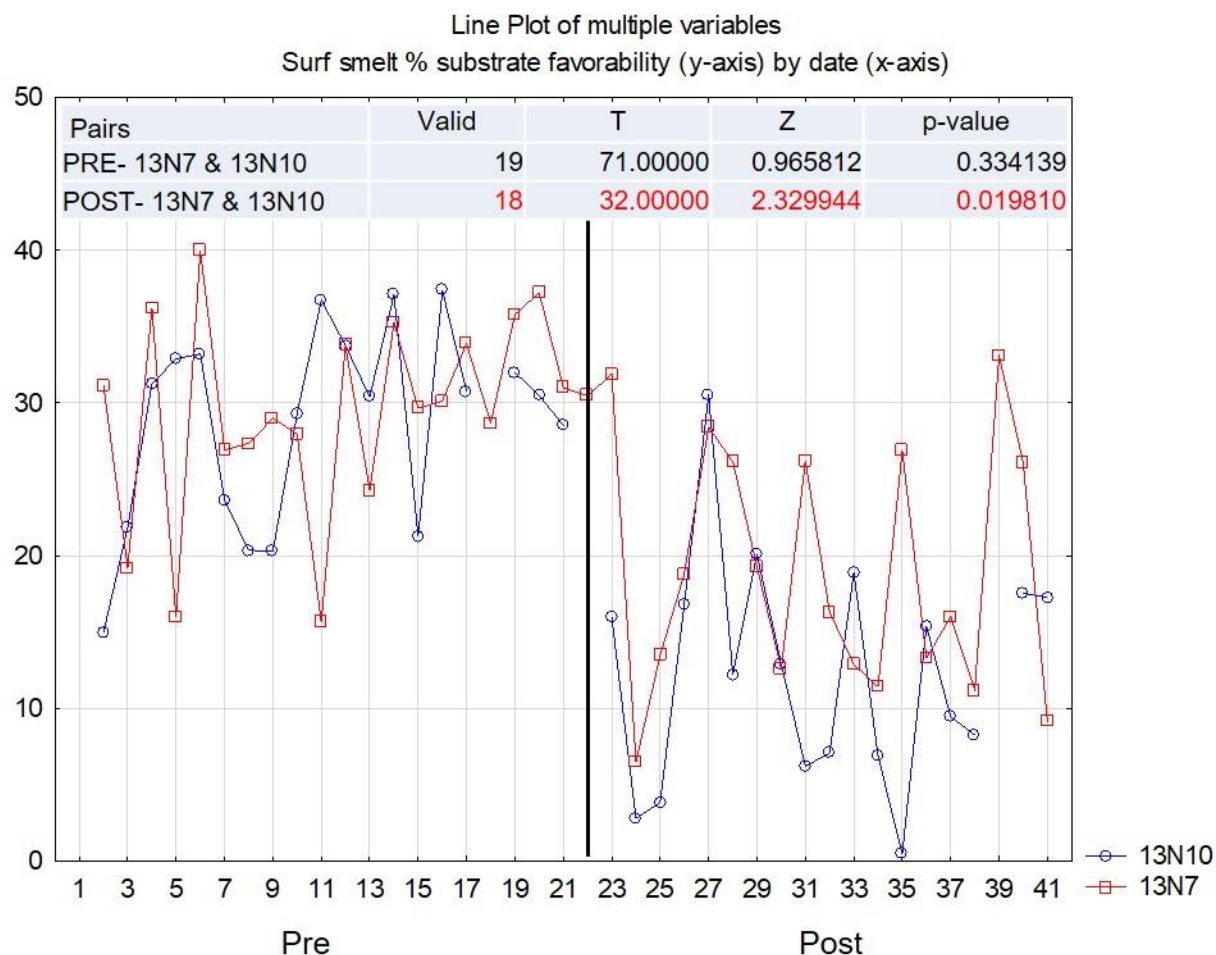


Fig. C26. Monthly (x-axis) SS grain size matched pair values for sites 13N7 and 13N10, demonstrating both decreasing overall substrate favorability and significant difference post-nourishment by site, where 13N10 is affected more.

Table C7. Wilcoxon matched pairs tests for paired nourish and downdrift sites. Results showing a significant post-restoration interaction effect are bolded.

All Groups Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid months	T	Z	p-value
02N7	& 02S7	32	5.000000	4.843025	0.000001
05N7	& 05S7	36	298.0000	0.549870	0.582409
05N7	& 06S7	33	202.0000	1.402625	0.160730
05S7	& 06S7	31	203.0000	0.881845	0.377862
09N7	& 09S7	37	187.0000	2.481694	0.013076
12N7	& 12S7	34	169.0000	2.196902	0.028028
13S7	& 13N7	37	182.0000	2.557125	0.010555
13S7	& 13S10	36	173.0000	2.513692	0.011948
13N7	& 13N10	37	195.0000	2.361004	0.018226
13S10	& 13N10	36	168.0000	2.592245	0.009536
PrePost=Pre Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid	T	Z	p-value
02N7	& 02S7	18	5.000000	3.505804	0.000455
05N7	& 05S7	19	43.00000	2.092593	0.036386
05N7	& 06S7	16	53.00000	0.775632	0.437967
05S7	& 06S7	15	60.00000	0.00	1.000000
09N7	& 09S7	20	59.00000	1.717303	0.085925
12N7	& 12S7	16	60.00000	0.413670	0.679116
13S7	& 13N7	19	66.00000	1.167023	0.243202
13S7	& 13S10	18	34.00000	2.242843	0.024908
13N7	& 13N10	19	71.00000	0.965812	0.334139
13S10	& 13N10	18	53.00000	1.415387	0.156956
PrePost=Post Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid	T	Z	p-value
02N7	& 02S7	14	0.00	3.295765	0.000982
05N7	& 05S7	17	9.000000	3.195322	0.001397
05N7	& 06S7	17	20.00000	2.674603	0.007482
05S7	& 06S7	16	37.00000	1.602972	0.108942
09N7	& 09S7	17	36.00000	1.917193	0.055214
12N7	& 12S7	18	19.00000	2.896099	0.003779
13S7	& 13N7	18	28.00000	2.504145	0.012275

13S7	& 13S10	18	55.00000	1.328286	0.184085
13N7	& 13N10	18	32.00000	2.329944	0.019810
13S10	& 13N10	18	31.00000	2.373494	0.017621

Table C8. ANOVA table of SS-grain size for Pre- vs Post-nourishment and Treatment type. The PrePost*Treatment interaction effect from table is shown below in Fig. C27.

Effect	Univariate Tests of Significance for SS-grain (SnoCo-FF_Grain-data DRAFT 2020-02-03) Sigma-restricted parameterization Effective hypothesis decomposition Include condition: Month=1 OR Month=2				
	SS	Degr. of Freedom	MS	F	p
Intercept	138064.1	1	138064.1	1153.385	0.000000
PrePost	2805.7	1	2805.7	23.439	0.000002
Treatment	43.7	1	43.7	0.365	0.546212
PrePost* Treatment	2723.6	1	2723.6	22.753	0.000002
Error	58535.0	489	119.7		

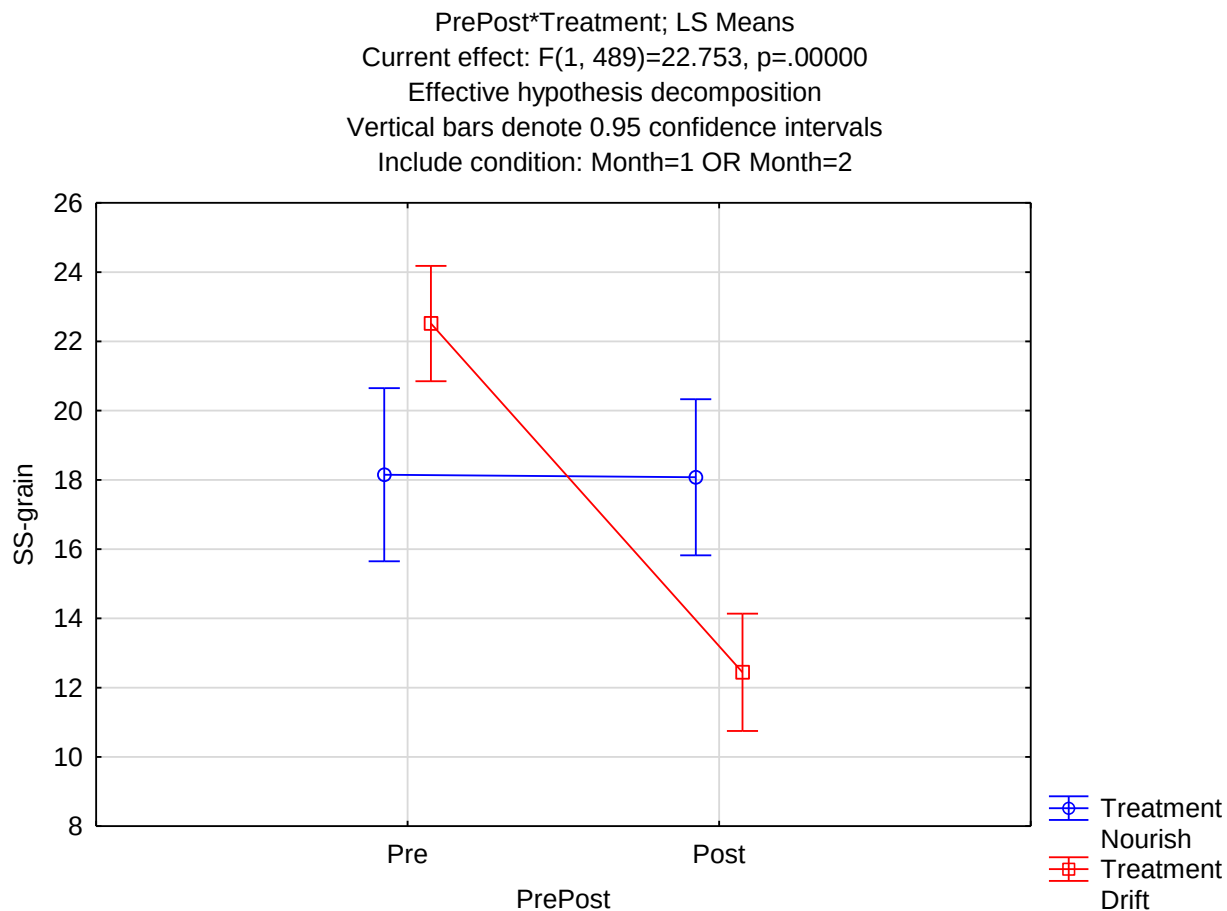


Fig. C27. Average SS grain size pre- and post-nourishment by treatment type showing PrePost*Treatment interaction effect.

Forage Fish Egg Count

PSL Wilcoxon Matched Pairs analyses between paired sites by date pre- and post-nourishment.

Figure C28 illustrates that for certain site pairs, locations downdrift from beach nourishment sites, egg count by matched sampling dates was significantly greater post-nourishment. Downdrift sites 5N7, 6N7, 9N7, and 12N7 matched to updrift nourishment sites all had greater egg count by date. However, among these sites, only Site 05N7 had significantly more favorable substrate size for PSL than Site 05S7. Usually, both sites making up a pair improved in PSL substrate size favorability between pre- and post-nourishment dates, so there was no difference by date for matched pairs.

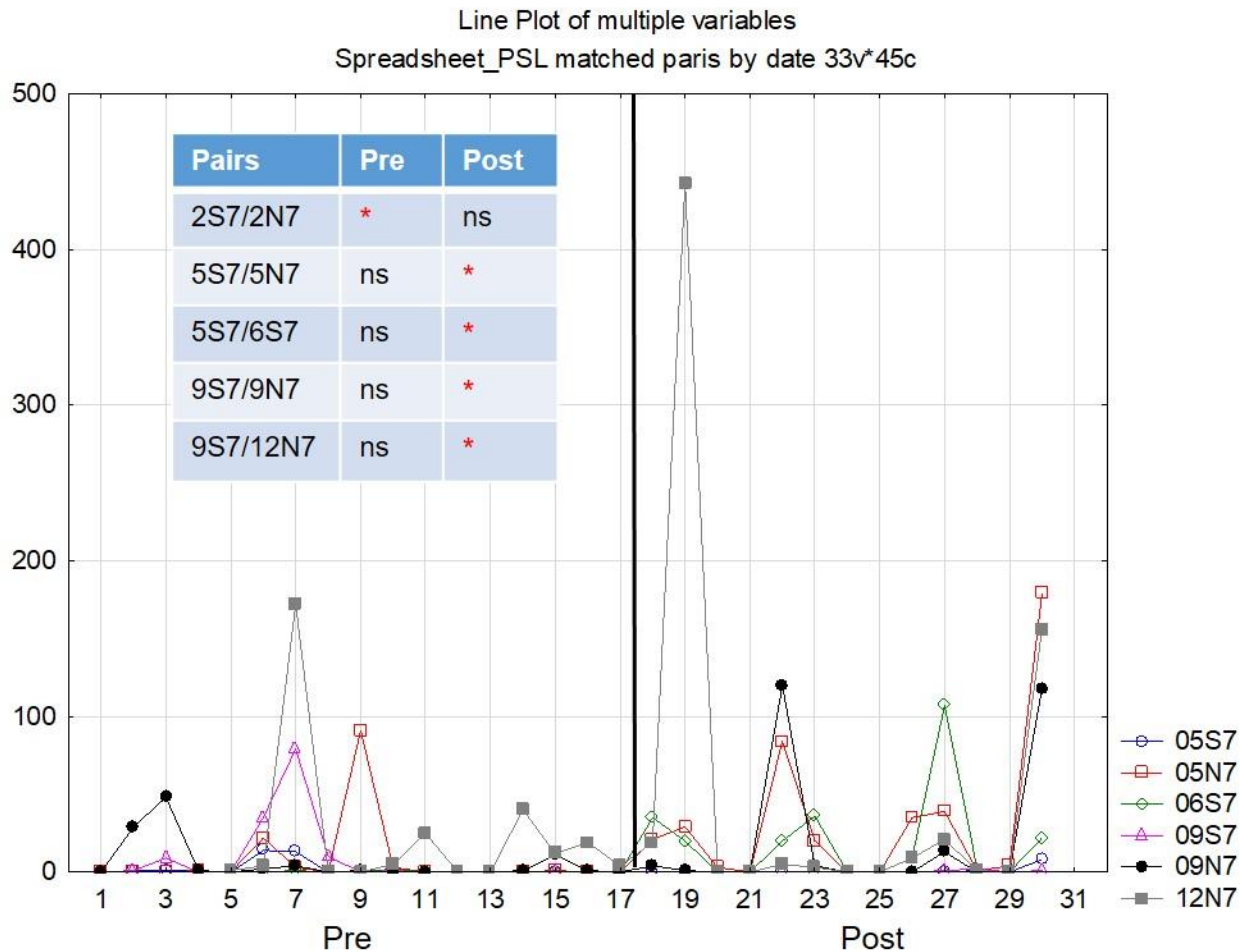


Fig. C28. Pre- and post-nourishment egg count by month for paired nourished and drift sites.

Table C9. Wilcoxon matched pairs tests for paired nourish and downdrift sites. Downdrift sites are bolded. Results showing a significant post-restoration interaction effect are bolded.

All Groups Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables	Valid	T	Z	p-value	
02N7 & 02S7	8	0.00	2.520504	0.011719	
05N7 & 05S7	16	12.00000	2.895691	0.003784	
06S7 & 05S7	11	9.500000	2.089405	0.036672	
09N7 & 09S7	18	50.50000	1.524262	0.127444	
12N7 & 09S7	17	22.50000	2.556258	0.010581	

PrePost=Pre Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid	T	Z	p-value
02N7	& 02S7	5	0.00	2.022600	0.043115
05N7	& 05S7	7	10.00000	0.676123	0.498963
06S7	& 05S7	3	1.000000	1.069045	0.285050
09N7	& 09S7	11	29.00000	0.355643	0.722108
12N7	& 09S7	9	10.00000	1.480872	0.138642
PrePost=Post Wilcoxon Matched Pairs Test (Spreadsheet1); Marked tests are significant at p <.05000					
Pair of Variables		Valid	T	Z	p-value
02N7	& 02S7	3	0.00	1.603567	0.108810
05N7	& 05S7	9	0.00	2.665570	0.007686
06S7	& 05S7	8	0.00	2.520504	0.011719
09N7	& 09S7	7	2.000000	2.028370	0.042523
12N7	& 09S7	8	1.000000	2.380476	0.017291

Table C10. PSL ANOVA pre- and post-nourishment by treatment type. We excluded Site 12S7 because most PSL eggs were found at this site pre-project and it was uniquely affected by Howarth Park restoration, which changed the substrate size and caused disturbance at the site.

Effect	Univariate Tests of Significance for PSL (SnoCo-FF_Grain-data DRAFT 2020-02-03) Sigma-restricted parameterization Effective hypothesis decomposition Include condition: Month=1 Exclude condition: Site="12S7"				
	SS	Degr. of Freedom	MS	F	p
Intercept	15370.5	1	15370.52	14.01737	0.000211
PrePost	2328.5	1	2328.55	2.12355	0.145917
Treatment	2681.3	1	2681.32	2.44527	0.118753
PrePost* Treatment	1267.3	1	1267.28	1.15571	0.283072
Error	396945.3	362	1096.53		

PrePost*Treatment; LS Means
Current effect: $F(1, 362)=1.1557$, $p=.28307$
Effective hypothesis decomposition
Vertical bars denote 0.95 confidence intervals
Include condition: Month=1
Exclude condition: Site="12S7"

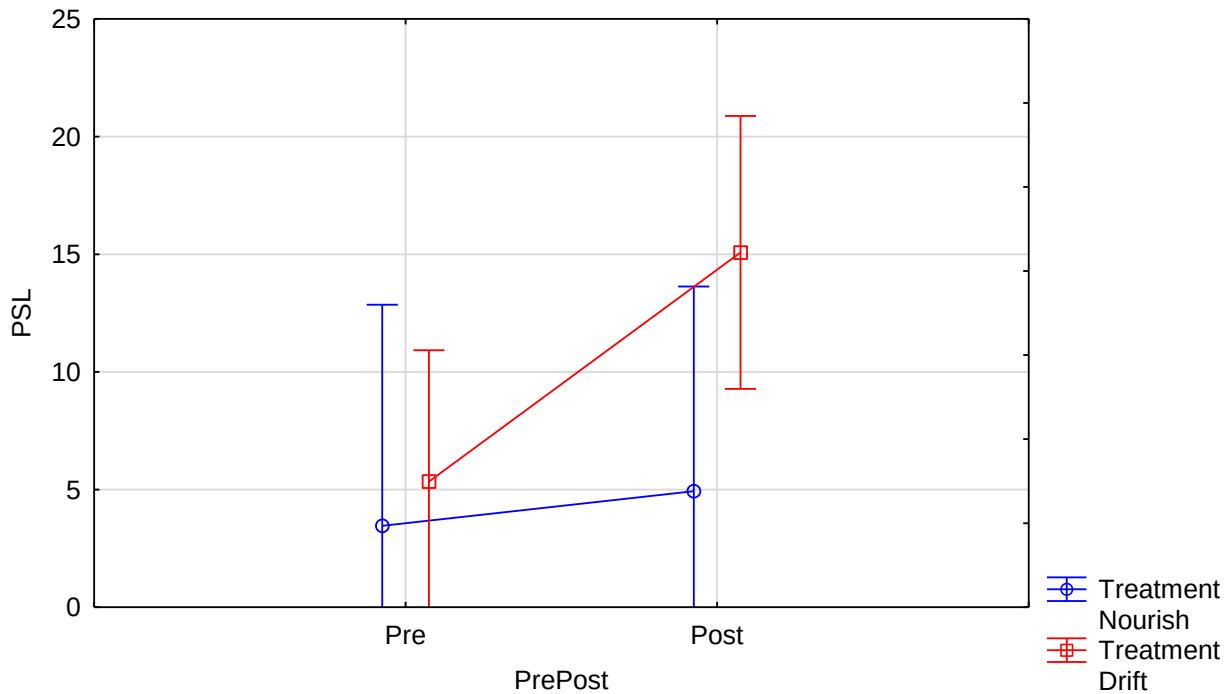


Fig. C29. Average PSL egg count pre- and post-nourishment by treatment type showing PrePost*Treatment interaction effect based on ANOVA Table C10.

However, if at the same time we only include sites with beach nourishment (2S, 5S, 9S) and downdrift locations (2N, 5N, 6S, 9N, 12N), then results appear to be marginally significant and are suggestive of a downdrift benefit from the smaller scale nourishment. Site 12 and 13 as well as Howarth Park (HP7) are excluded due to their unique treatment.

Table C11. PSL ANOVA pre- and post-nourishment by treatment type. We excluded Site 12S7, HP7, and Site 13, to isolate effects from only smaller beach nourishment applications. These sites were uniquely affected by Howarth Park restoration, which was based on a unique design, larger scale, different substrate size, and other treatments and caused disturbance at the site.

Effect	Univariate Tests of Significance for PSL (Spreadsheet9_(Recovered)) Sigma-restricted parameterization Effective hypothesis decomposition Include condition: Month=1 Exclude condition: SiteAll=13 OR Site="12S7" OR Site="HP7"				
	SS	Degr. of Freedom	MS	F	p
Intercept	16074.9	1	16074.93	11.45417	0.000840
PrePost	2133.1	1	2133.12	1.51995	0.218896
Treatment	9773.5	1	9773.52	6.96410	0.008890
PrePost* Treatment	4833.5	1	4833.52	3.44411	0.064768
Error	319978.3	228	1403.41		

PrePost*Treatment; LS Means
 Current effect: $F(1, 228)=3.4441$, $p=.06477$
 Effective hypothesis decomposition
 Vertical bars denote 0.95 confidence intervals
 Include condition: Month=1
 Exclude condition: SiteAll=13 OR Site="12S7" OR Site="HP7"

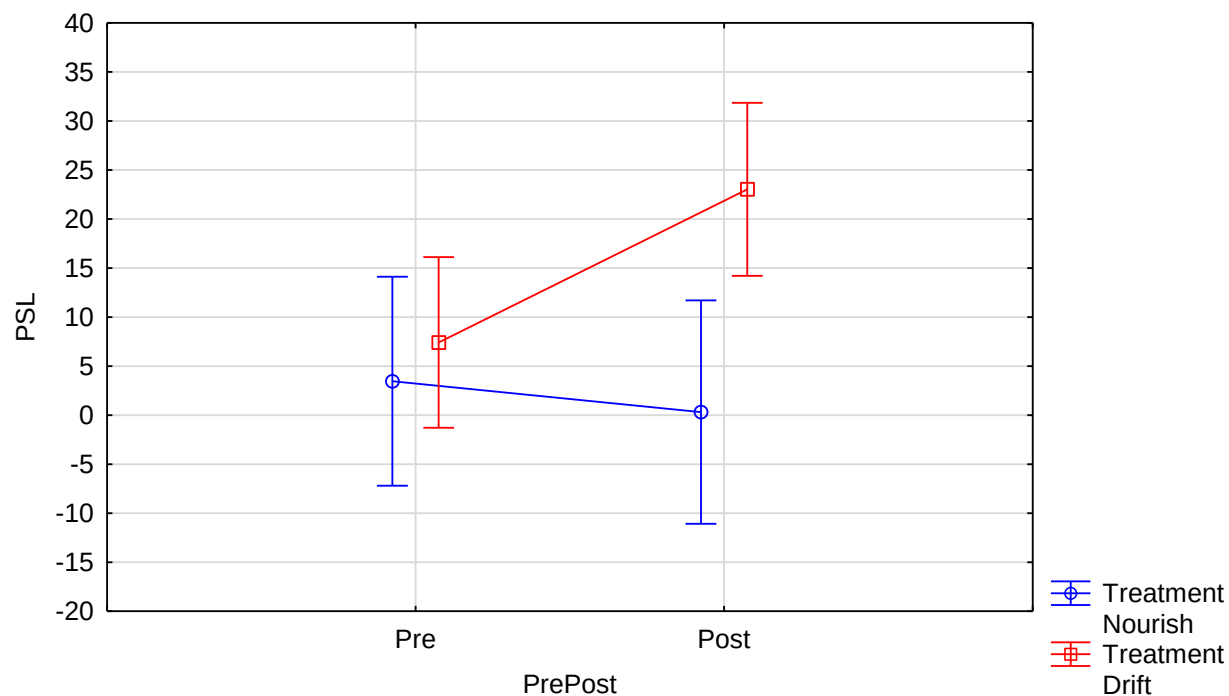


Fig. C30. Average PSL egg count pre- and post-nourishment by treatment type showing PrePost*Treatment interaction effect based on ANOVA Table C11.