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Nearshore Drift-Cell Sediment Processes and Ecological Function for Forage Fish: Implications for Ecological Restoration of Impaired Pacific Northwest Marine Ecosystems

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David Parks[†], **Anne Shaffer**[‡*], **and Dwight Barry**[§]

[†]Washington Department of Natural Resources
311 McCarver Road
Port Angeles, Washington 98362, U.S.A.
david.parks@dnr.wa.gov

[‡]Coastal Watershed Institute
P.O. Box 2263
Port Angeles, Washington 98362, U.S.A.

[§]Western Washington University
Huxley Program on the Peninsula
Port Angeles, Washington 98362, U.S.A.

ABSTRACT

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Sediment processes of erosion, transport, and deposition play an important role in nearshore ecosystem function, including forming suitable habitats for forage fish spawning. Disruption of sediment processes is often assumed to result in impaired nearshore ecological function but is seldom assessed in the field. In this study we observed the sediment characteristics of intertidal beaches of three coastal drift cells with impaired and intact sediment processes and compared the functional metrics of forage fish (surf smelt, *Hypomesus pretiosus*, and sand lance, *Ammodytes hexapterus*) spawning and abundance to define linkages, if any, between sediment processes and nearshore ecological function. Key findings include: (1) beach sediment characteristics of the northern Washington nearshore are complex, with strong seasonal variation in habitat form and function both within and across geomorphic habitat types; (2) loss of sediment supply to the nearshore due to in-river damming and shoreline alterations results in significantly larger and more variable beach sediment at the drift-cell scale; (3) these differences in intertidal beach sediment characteristics have implications for habitat function as indicated by less forage fish spawning habitat and lower ecological function than intact drift cells; (4) feeder bluffs are important nearshore sediment sources for forage fish spawning beaches. Forage fish may spawn at the base of feeder bluffs if appropriate sediment is available during the spawning season; and (5) seasonal rate, total volume, and grain size of sediment delivery are important for habitat suitability for fish use. Feeder bluffs therefore should be managed more conservatively and understanding and protecting their role in nearshore habitat restoration practices is a high priority.

ADDITIONAL INDEX WORDS: *Elwha River dam removal, feeder bluff.*

INTRODUCTION

Nearshore marine habitats, including intertidal beaches, are critical components of Pacific Northwest marine ecosystems, providing nursery corridors for juvenile salmon and forage fish migration, feeding, and spawning (Penttila, 2007). The Pacific Northwest nearshore environment is delineated by the physical features of tidal influence and light limitation and extends from the area of tidal influence and tree line to 30 m below mean low low water (Shaffer *et al.*, 2008). Forage fish in turn are central components of large and complex marine food webs (Middaugh, Hemmer, and Penttila, 1987; Pikitch *et al.*, 2012). Surf smelt (*Hypomesus pretiosus*) and sand lance (*Ammodytes hexapterus*) are common forage fish of the nearshore waters of Puget Sound and the Strait of Juan de Fuca in Washington State, and are prey species of numerous marine birds, mammals, and predatory fish (Penttila, 2007) including federally listed Pacific salmon, illustrating the importance of forage fish for the conservation, restoration, and economic concerns of the Pacific Northwest (Fresh, 2006; Shaffer *et al.*, 2008).

Surf smelt and sand lance spawn on intertidal beaches that exhibit specific sediment grain-size distributions (Penttila, 2007; Quinn *et al.*, 2012). Surf smelt and sand lance use the upper intertidal areas of beaches of nearshore inland waters of northwestern Washington for spawning during summer and winter months. During spawning, eggs are attached to sand and gravel during high tide in less than 10 cm of water (Moulton and Penttila, 2000). Spawning takes place within the upper third of the tidal range, from approximately +1 m to the extreme high-water mark, and the eggs are then dispersed across the beach by tidal and wave activity (Moulton and

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* Corresponding author
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Penttila, 2000; Penttila, 2007). One of the critical factors of spawning habitat is grain size distribution of beach sediment. The preferred substrate size for surf smelt is a sand–gravel mix ranging from 1 to 7 mm in diameter, and a layer thickness from 1 to 10 cm (Penttila, 2007). Typical sand lance spawning substrate is smaller in diameter and can be characterized as fine sand, with the bulk of the material in the range of 0.2–0.4 mm (Penttila, 2007). Beaches at the distal ends of drift cells, where sandy spits, cuspate forelands, and other accretionary shore forms tend to occur, commonly support surf smelt and sand lance spawning habitat along Pacific Northwest beaches (Penttila, 2007).

Surf smelt and sand lance requirements for spawning are closely linked with the processes that supply sediments to beaches. Sediment composition of intertidal beaches is controlled by available wave energy, tidal range and current velocity, coastal bluff landsliding, fluvial delivery of sediment from rivers, and reworking of existing beach sediments by waves and tides (Johannessen and MacLennan, 2007). Beach habitats are typically located within coastal drift cells, *i.e.* sections of coastline that exhibit a sediment source, a zone of net directional sediment transport, and an area of sediment deposition.

There are two main sources of sediment supplying Pacific Northwest marine beaches: riverine-derived bed-load transport and mass wasting from bluffs. Sediments transported from rivers form delta deposits near their mouths and supply beaches with sand and gravel by bed-load transport during periods of high stream flow (Finlayson, 2006). Bluff erosion processes vary both temporally and spatially, with the main contributing factors being wave run-up and slope undercutting by beach erosion, precipitation, wind, and human-induced erosion (Johannessen and MacLennan, 2007). Sediments ranging in size from sand to boulders from eroding bluffs are transported alongshore within drift cells and deposited on beaches, replacing substrate washed away through wave action (Johannessen and MacLennan, 2007; Penttila, 2007). The central Strait of Juan de Fuca is a significant component of the Washington coast and exhibits some of the highest longshore sediment transport rates in Puget Sound (Finlayson, 2006; Galster, 1989; Schwartz, Wallace, and Jacobsen, 1989; Wallace, 1988) due to exposure to long fetch distances, propagation of large waves from Pacific Ocean swells, and oblique shoreline wave approach angles (Warrick *et al*., 2009).

Anthropogenic factors, such as in-river damming and diking, and shoreline armoring, have been documented to significantly disrupt the amount of sediment available for the maintenance of beaches, and cause an increase in beach sediment grain size, reduce beach width, and lead to beach scouring and erosion (Johannessen and MacLennan, 2007; Shipman 2008; Warrick *et al*., 2008, 2009) and can significantly disrupt ecological function in the nearshore for fish (Rice, 2006; Shaffer *et al*., 2009; Shipman *et al*. 2010).

Although nearshore habitats are critical to species such as forage fish, and are sensitive to anthropogenic factors, little work has been done to define the relationship between loss of sediment supply and habitat function at the drift-cell scale. Intertidal habitat and grain size requirements of surf smelt and sand lance could therefore be an excellent metric for defining the potential ecological response to disruption of physical processes at a drift-cell scale.

The nearshore sediment processes of the central Strait of Juan de Fuca are integral in forming beach habitats, and in areas have been significantly impaired. In-river dams constructed on the Elwha River almost 100 years ago and subsequent shoreline armoring of feeder bluffs and spit have significantly reduced sediment supply to the Elwha littoral cell (Galster, 1989; U.S.A.C.E., 1971). The annual rate of sediment delivery from the river to the Elwha nearshore has been reduced to 2% of the historic rate (Draut, Logan, and Mastin, 2011; EIS, 1996; Shaffer *et al*., 2008; Warrick *et al*., 2009). The nearshore response to this reduction in sediment supply in the Elwha littoral cell has been net shoreline erosion of the Elwha Delta and Ediz Hook (Galster, 1989; Warrick *et al*., 2009). Removal of the Elwha and Glines Canyon dams began in September 2011. This national-scale restoration project will provide only a partial restoration of the predam nearshore sediment supply within the Elwha drift cell (Shaffer *et al*., 2008; Warrick *et al*., 2009) because shoreline armoring of coastal bluffs that historically supplied 70% of the sediment to the Elwha drift cell will remain in place after dam removal (Galster 1989; U.S.A.C.E, 1971). Ecological response to loss of sediment is becoming understood, and restoration of sediment processes is central to ecosystem restoration of the Elwha River (Duda, Warrick, and Magirl, 2011). However, response to the partial restoration of Elwha nearshore sediment supply due to dam removal is unknown, but important in defining additional restoration actions needed to achieve full ecosystem restoration (Shaffer *et al*., 2008, 2009, 2012).

In contrast to the reduced sediment supply in the Elwha littoral cell, the adjacent Dungeness drift cell, which has similar geomorphic features (*e.g*. coastal bluffs and spit) and relatively intact sediment supply processes, has exhibited net shore accretion of its spit feature over the last 130 years from bluff-derived sediment (Schwartz, Fabbri, and Wallace, 1987).

The goal of this study is to assess the intertidal sediment composition of beaches within drift cells with impaired and intact sediment processes, and define and compare the potential forage fish spawning habitat and use as a metric for ecosystem function in each. We characterize the beach sediment composition of impaired (Elwha) and intact (comparative) drift cells, and evaluate this information by geomorphic habitat type and ecological metrics of forage fish spawn density and published fish diversity indices to define linkages between habitat physical form and ecological function.

SAMPLING STRATEGY AND METHODS

To define the role sediment plays in providing forage fish spawning habitat on intertidal beaches, we chose a drift cell with an impaired sediment supply (*e.g*. Elwha drift cell) and adjacent drift cells with intact nearshore sediment processes (*e.g*. Dungeness and Crescent Bay drift cells) (Figure 1). Habitats within each of the drift cells were portioned into geomorphic habitat type (Shipman, 2008). Following the Elwha nearshore restoration strategy developed in 2005 (Shaffer *et al*., 2008), priority nearshore habitats within the Elwha (impaired) and Dungeness and Crescent (intact) drift cells

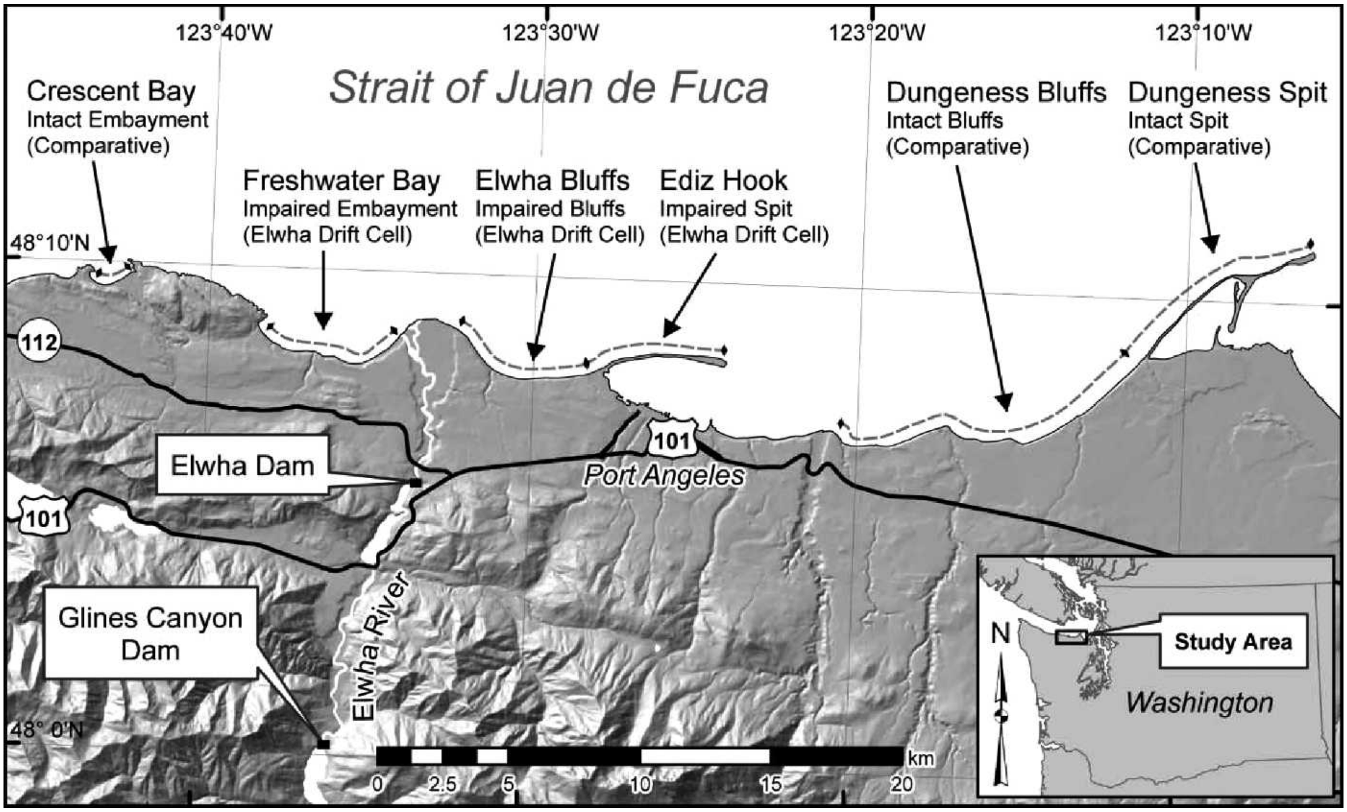

Figure 1. Sample locations for 2007 and 2008 surveys.

were categorized into the following geomorphic habitat types: embayments, spits, and bluffs (Figure 1). Physical habitat for forage fish was defined by sediment grain-size distribution of the upper 20 cm of the beach surface between +1 m and +2 m using the National Vertical Datum of 1988 (NAVD88) (Zilkoski, Richards, and Young, 1992). Habitat and ecological function were defined by forage fish spawning and by published fish abundance data (Shaffer *et al*., 2012).

Study Sites

The three drift cells evaluated for beach sediment grain-size distributions are adjacent to each other within the Central Strait of Juan de Fuca (Figure 1).

Crescent drift cell (intact): characterized as an embayment bounded by rocky headlands composed of marine sandstone and conglomerate with a 1–3-m veneer of glacial outwash (Figure 2A) (Schasse, 2003). The net sediment transport direction on beaches within Crescent Bay is westerly. Samples were collected from the eastern one-half of the Crescent Bay shoreline.

Elwha drift cell (impaired): Includes Freshwater Bay, Elwha Bluffs, and Ediz Hook. Freshwater Bay is the embayment of the Elwha drift cell and is backed by 35-m-high bluffs composed of glacial till and outwash (Figure 2B) (Schasse, 2003). The Elwha River discharges into the east end of Freshwater Bay (Figure 1). The apparent net sediment transport direction on Freshwater Bay beaches is westerly (Miller, Warrick, and Morgan, 2011; Warrick *et al*., 2009). The Freshwater Bay site is located within 0.5 km of an eroding proglacial bluff located in the lower river, which has been identified as the most substantial modern source of sediment downstream of Elwha Dam (Draut, Logan, and Mastin, 2011).

The Elwha Bluffs site is located to the east of Freshwater Bay and is backed by 35-m-high bluffs composed of glacial till (Schasse, 2003) and is down drift (east) of the Elwha River mouth, which will be a significant source of sediment supply after dam removal (Figure 1). The upper one-half of the beach profile within the Elwha Bluffs site has been disturbed by the historic construction of a water-supply pipeline and associated rock revetment (Figure 2D). This revetment effectively limits the direct introduction of bluff sediment into the mid-foreshore portion of the beach from bluff landsliding (Figure 2D). Samples at the Elwha Bluff site were collected from the mid-foreshore just below the rock revetment. The net sediment transport direction at the Elwha Bluffs site is easterly (Galster, 1989).

The Ediz Hook site is located to the east of the Elwha Bluffs and is a natural spit that has been armored with rock revetments to control erosion (U.S.A.C.E., 1971). The upper one-half of the beach profile is disturbed by the presence of the rock revetment (Figure 2F). Samples at the Ediz Hook site were collected from the mid-foreshore just below the rock revetment. The net sediment transport direction at the Ediz Hook site is easterly (Galster, 1989).

Figure 2. Study site photographs. (A) Crescent Bay. (B) Freshwater Bay. (C) Dungeness Bluffs. (D) Elwha Bluffs. (E) Dungeness Spit. (F) Ediz Hook.

Dungeness drift cell (intact): Includes Dungeness Bluffs (Figure 2C) and Dungeness Spit (Figure 2E). The Dungeness drift cell is located to the east of the Elwha drift cell. The Dungeness Bluffs site is backed by 70-m bluffs composed of glacial outwash (Schasse, 2003). The net sediment transport direction at the Dungeness Bluffs site is easterly (Schwartz, Fabbri, and Wallace, 1987).

The Dungeness Spit site is the most easterly site and is composed of a natural sand and gravel spit. The net sediment transport direction at the Dungeness Spit site is easterly (Schwartz, Fabbri, and Wallace, 1987).

Forage Fish Spawn Sampling

Surf smelt and sand lance spawn sampling methods followed the protocols published by Moulton and Penttila (2000). Sites within the impaired and intact drift cells were partitioned by geomorphic habitat type of bluff, spit, and embayed habitats as detailed in Shaffer *et al*. (2008, 2012) (see Table 1). Beaches within each geomorphic habitat type were sampled using a modified stratified random technique in which the selected beach would be divided into a series of 120-m sections that were separated by 300 m. Within each 120-m-long sample section, regardless of substrate type, subsamples of the upper 20 cm of substrate from four 30-m-long subsection segments were collected with a hand scoop. This would constitute one sample. Each geomorphic habitat type site had a minimum of six samples. The bulk samples were sieved through 4-mm and 2-mm sieves, and the smaller fraction retained on the 0.5-mm sieve examined under a dissecting microscope for eggs. When found, up to 100 eggs for each sample were counted and identified for life-history stage.

Monthly sampling for surf smelt spawn occurred in July through September 2007 and 2008. Sand lance spawn sampling was conducted monthly from November 2007 through January 2008.

Sediment Characterization

Beach sediment grain-size distributions were estimated using photographic methods (Adams, 1979; Church, McLean, and Wolcott, 1987; Kellerhals and Bray, 1971; Wolman, 1954) and were compared with grain-size distributions derived from standard sieve techniques (ASTM, 2006) using linear regression of sample means. Sampling site selection followed protocols developed to document forage fish spawning published by Moulton and Penttila (2000). The sediment assessment portion of the study began during the November 2007–January 2008 sand lance spawning season, and continued through September 2008 surf smelt spawning season. Bulk sediment samples were collected following methods published by Moulton and Penttila (2000), air dried for a minimum of 24 hours, and then oven dried following ASTM (2006), procedures. The bulk samples were then processed through a square-hole sieve stack using aperture openings of 38.1 mm, 4.75 mm, 2.00 mm, 1.00 mm, 0.60 mm, 0.25 mm, and 0.125 mm. Each sample was shaken for a minimum of 15 minutes. The mass in grams of each size fraction retained on the respective sieve was weighed with an electronic balance and recorded. Sediment clasts larger than 38.1 mm were measured with an electronic caliper and weighed individually and recorded. Sieve data were analyzed with a computer program, Gradistat V. 5.0 (Blott and Pye, 2001), to calculate the particle size distribution for each sample.

Table 1. *Sample sites by geomorphic habitat type (GMHT).*[a]

Site	GMHT		
	Bluff	Spit	Embayment
Dungeness Bluffs	**X**		
Elwha Bluffs	*X*		
Dungeness Spit		**X**	
Ediz Hook		*X*	
Crescent Bay			**X**
Freshwater Bay			*X*

[a] Impaired (Elwha) drift-cell sites in italic, intact (comparative) sites in **bold**.

At each sample site, photographs were taken before and after spawn samples were collected using a digital camera mounted on a monopole suspended 1.2 m above the beach surface. Sediment photograph samples were then analyzed using grid-by-number point-count methods (Adams, 1979; Church, McLean, and Wolcott, 1987; Wolman, 1954). At each sample point, a 4×5 grid was superimposed on a digital photograph of the beach surface using Adobe Photoshop 7.1 software. The grid spacing was varied on the basis of the size of the largest particle in the field of view (Adams, 1979). At each grid intersection, a measurement of the sediment particle intermediate axis length in pixels was obtained. The intermediate axis length in pixels was converted into a length in millimeters using the ratio of pixels to millimeters observed in each photograph from a fixed scale. A minimum of 100 intermediate axis lengths was measured per each sample to obtain a frequency-by-number grain-size distribution for that sample. Multiple counts of intermediate axis lengths were then aggregated to obtain a frequency-by-number grain-size distribution for a site reach. Beach sediment grain-size statistics, including sample mean and standard deviation, were then calculated for each sampling month by geomorphic habitat type using methods developed by Bunte and Apt (2001).

We compared sample grain-size population means determined by photographic methods with those determined by standard sieve techniques for 79 samples using linear regression (Zar, 1984) for size classes between 0.125 mm and 38.1 mm (Figure 3). The calculated R^2 statistic of 0.9429 and standard error of 1.15475 using the least-squares method (Zar, 1984) for the regression indicated that the photographic techniques used to measure mean grain size were reasonably reliable when compared with standard sieve techniques for measuring mean grain-size diameter.

Three sediment texture classes ($\% < 1$ mm, $\% = 1$–7 mm, $\% >$ 7 mm) were evaluated for each sediment sample by geomorphic habitat type and drift cell to estimate the relative proportion of samples exhibiting grain sizes potentially suitable for surf smelt spawning habitat. Sediment data were then log transformed and analyzed to address the following null hypotheses: H_o: Mean beach sediment grain size is not statistically different between geomorphic habitat types of impaired (Elwha) and intact (Crescent and Dungeness) drift cells; H_o: Mean beach sediment grain size is not statistically different between

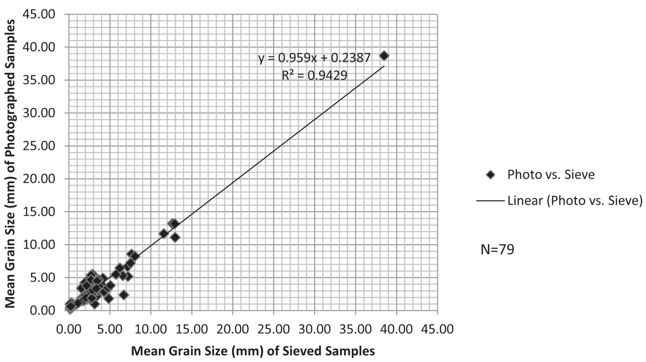

Figure 3. Linear regression of mean grain size (mm) of sieved and photographed sediment samples.

impaired (Elwha) and intact (Crescent and Dungeness) drift cells; Monte Carlo randomization t-tests (100,000 replications) were used to evaluate overall differences in study variable means between comparative and impaired drift cells, combined as well as separated by geomorphic habitat type, using RT4Win software (Edgington and Onghena, 2007; Huo, Onghena, and Edgington, 2006). Bonferroni corrections were used to control the type I error rate for these multiple comparisons. Plots were created using the base, plotrix, and vcd packages within the R system for statistical computing, Ver. 2.9.2, (R Development Core Team, 2009).

RESULTS

Surf Smelt Spawn

In 2007, 46 samples were collected and surf smelt eggs were found in 19 samples. Thirteen of these samples were taken from intact (comparative) Dungeness Bluffs (357 eggs), and impaired (Elwha); six samples collected from embayed Freshwater Bay had a total of 62 eggs), Table 2.

In 2008, of a total of 91 samples, only nine eggs were found: eight eggs were found in five samples along the intact (comparative) Dungeness Bluffs and one egg was detected in one sample from the impaired embayment site (Freshwater Bay).

Sand Lance Spawn

A total of 86 samples was collected between November 2007 and January 2008. No sand lance eggs were found in any of the samples.

Given the absence of observed sand lance eggs, we did not conduct statistical analysis on sediment grain size and sand lance spawn data.

Sediment Characterization

A total of 18,280 grain size measurements was collected from the all sampling sites between November 2007 and September 2008 (Table 3). Grain-size means and standard deviations by month by geomorphic habitat type are shown in Figure 4. Mean grain size of intact drift cell sites was smaller than impaired (Elwha) sites for all months except for the bluff site in September 2008. Grain-size means for the comparative sites ranged from 0.26 ± 0.24 mm to 5.08 ± 7.49 mm, whereas the mean grain size for the impaired (Elwha) sites ranged from 2.56 ± 3.68 mm to 16.62 ± 32.51 mm.

For spit sites, the comparative site (Dungeness Spit) exhibited little seasonal variability, whereas the impaired Ediz Hook site displayed the largest mean grain size and standard deviation in November 2007, followed by a general trend toward smaller mean grain size in August 2008. The mean grain size for the intact (Dungeness) spit was smaller than the impaired (Elwha) spit for all months sampled.

Bluff sites showed similar trends in grain size by season, with relatively small mean grain size in November 2007, increasing to largest mean grain size values in July 2008 for the comparative Dungeness Bluffs site, and August for the impaired Elwha Bluff sites. The mean grain size of the intact (Dungeness) bluff was smaller than the mean grain size of the Elwha Bluff for all months except September. Bluff sites had the highest proportion of 1–7-mm substrate range needed for surf smelt spawning.

Embayed sites showed similar trends in mean grain size to spit sites. The intact Crescent Bay site showed little seasonal variation, whereas the impaired site at Freshwater Bay had high seasonal variation, with the largest mean grain size in fall (November 2007) followed by the smallest mean grain size in summer (September 2008). The mean grain size for the comparative embayed site was smaller than the mean grain size of impaired site for all months. Embayments showed the highest proportion of 0.2–0.4-mm grain size, which is required for sand lance spawning. In particular, the comparative

Table 2. *Surf smelt spawn samples 2007–2008. Impaired drift cell sites are underlined.*[a]

Site	Linear Meters of Beach Sampled 2007	Total Eggs Found 2007	Linear Meters of Beach Sampled 2008	Total Eggs Found 2008
Spits				
Dungeness Spit	3963	0	3963	0
Ediz Hook	1981	0	1981	0
Bluffs				
Dungeness Bluffs	7315	357	4828	8
Elwha Bluffs	3962	0	3962	0
Embayments				
Crescent Bay	2743	0	2743	0
Freshwater Bay	914	62	914	1

[a] Impaired (Elwha) drift-cell sites in italic.

Table 3. *Number of sediment clasts measured by photographic analysis.*[a]

Site	November 2007	December 2007	January 2008	July 2008	August 2008	September 2008	# Grains
Spits							
Dungeness Spit	380	380	340	520	600	600	2820
Ediz Hook	300	260	420	660	700	400	2740
Bluffs							
Dungeness Bluffs	600	460	440	860	1020	760	4140
Elwha Bluffs	440	300	360	680	800	500	3080
Embayments							
Crescent Bay	380	600	480	440	580	400	2880
Freshwater Bay	380	380	420	400	540	500	2620
Total	2480	2380	2460	3560	4240	3160	18280

[a] Impaired (Elwha) drift-cell sites in italic.

embayed site (Crescent Bay) had the highest proportion of samples with grain sizes <1 mm relative to all other sites.

Statistical differences between mean grain sizes of geomorphic landforms of the intact and impaired sites were observed at $\alpha = 0.05$ during August for the bluff sites, during July and August for the spit sites, and July and September for the embayed sites (Table 4). No other statistical significance was found between geomorphic habitat types. When sediment data were combined to drift-cell scale and compared, the impaired (Elwha) drift cell had significantly larger mean grain size and significantly higher variability in grain size than the intact drift-cell sites (Figure 5).

When analyzed at the drift-cell scale, the intact drift cell had the higher percentage of samples with 1–7-mm grain size required for suitable potential surf smelt spawning. The impaired (Elwha) drift-cell grain size was significantly larger and more variable than the intact drift cell. Evaluation of the relative proportion of sediment samples with respect to three sediment size classes representing suitable surf smelt spawning substrate (1–7 mm) and unsuitable potential spawning

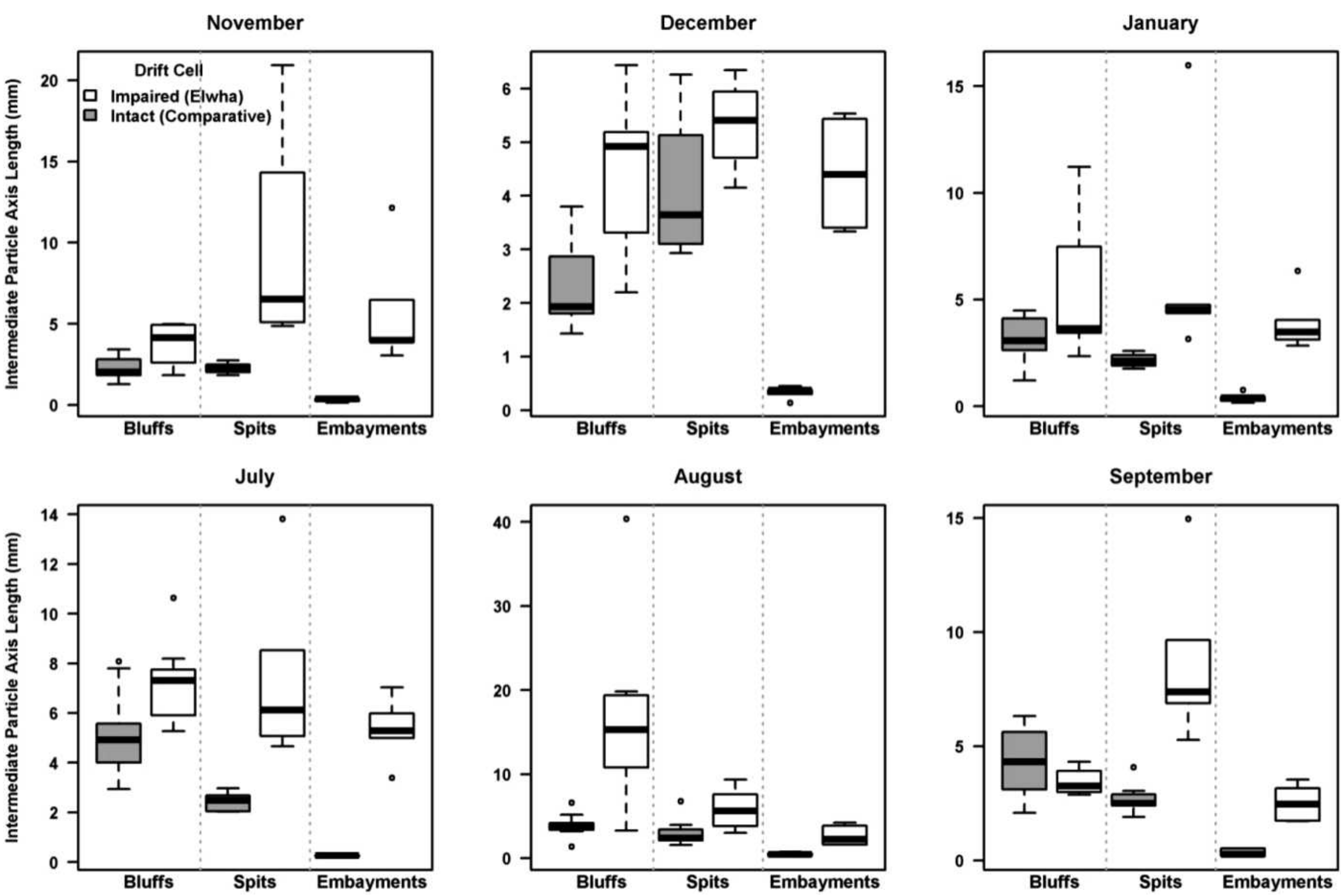

Figure 4. Monthly intact (comparative) and impaired (Elwha) mean grain sizes by geomorphic habitat type (GMHT).

Table 4. *Comparisons of mean intermediate particle axis length (mm) between intact (comparative) and impaired (Elwha) sites, by geomorphic habitat type (GMHT) and month.* p-*values are adjusted for multiple comparisons using the Bonferroni method. (*n *values are for intact (comparative) and impaired (Elwha), respectively*.

	GMHT								
	Bluffs			Embayments			Spits		
Month	*p*	*t*	*N*	*P*	*t*	*n*	*p*	*t*	*n*
January	1	1.443	5, 5	0.14	5.601	5, 5	0.57	1.638	4, 5
July	0.73	2.248	9, 7	0.07	8.465	5, 5	0.04*	3.512	6, 6
August	0.01*	3.556	10, 7	0.02*	4.622	6, 6	0.28	2.798	9, 8
September	1	1.225	9, 6	0.04*	6.394	5, 6	0.02*	4.269	7, 5
November	0.53	2.583	9, 4	0.29	2.963	4, 5	0.26	1.964	4, 4
December	0.93	2.38	5, 5	0.14	7.858	5, 4	1	1.382	4, 4

* Statistically different at $\alpha = 0.05$.
[a] Impaired (Elwha) drift-cell sites in italic.

substrate for surf smelt (<1 mm and >7 mm) (Figure 6) revealed that the impaired Elwha sites had a higher number of samples with grain sizes larger than 7 mm across all geomorphic habitat types. Conversely, the comparative sites showed a higher number of samples with grain sizes optimal for surf smelt spawning (1–7 mm) for all geomorphic habitat types compared with Elwha sites.

DISCUSSION

The results of this work indicate that the relationship between nearshore physical habitat structure and habitat function is complex. Specifically, the nearshore of this study, in both the drift cells, is highly variable with geomorphic habitat type and season. When data are combined to a drift-cell scale, however, trends in physical ecosystem response to reduced sediment inputs are apparent, statistically significant, and indicate, at an ecological scale, that beaches respond to sediment starvation by coarsening, resulting in a more variable sediment environment that is potentially unsuitable for surf smelt spawning habitat.

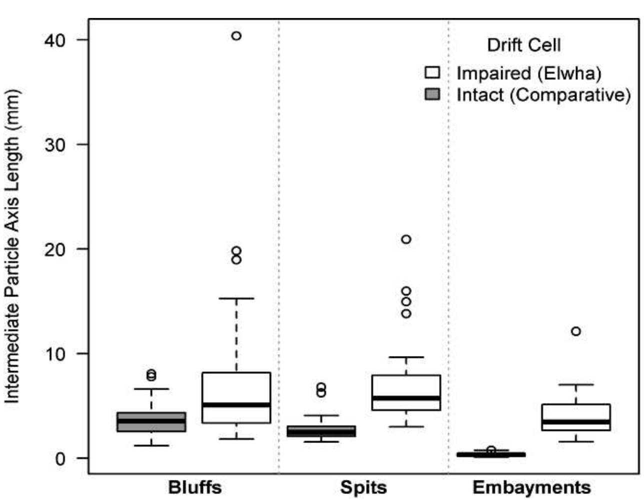

Figure 5. Combined particle size distributions by geomorphic habitat type for all sites for all months sampled.

Sediment delivery from feeder bluffs likely occurs at sufficient rates and with seasonal pulses in spring and fall (the surf smelt spawning season) to maintain the relatively high proportion of surf smelt-size grain-size material. We did find surf smelt spawning along the embayed site of the impaired drift-cell site down drift from, and immediately associated with, an active feeder bluff in the lower Elwha River (Draut, Logan, and Mastin, 2011; Miller, Warrick, and Morgan, 2011; Warrick *et al.*, 2009). This high rate of sediment delivery from bluffs likely maintains the grain size necessary for suitable surf smelt spawning substrate both along the intact bluff and impaired embayed site. The linkage of forage fish spawn sites to a feeder bluff in a lower river reveals a connection between fluvial and nearshore geomorphic habitat types that is often overlooked. We need to better understand riverine feeder bluff and shoreline nearshore relationships, including the role the future contributions of both fluvial, shoreline, and lower river feeder bluff sediment sources will play in Elwha nearshore function with restoration after dam removal.

The high variability of surf smelt egg density observed between 2007 and 2008 is consistent with other surf smelt spawn studies for the Strait of Juan de Fuca (Moriarty, Shaffer, and Penttila, 2002) and may be related to high interannual variability in surf conditions that potentially increases egg dispersal. High interannual variability of surf smelt egg density makes quantitative analysis of sediment data and forage fish spawning density difficult given the low and variable abundance of surf smelt spawn, and absence of any sand lance spawning. Some general observations are possible, including: (1) the intact drift-cell sites consistently displayed a higher proportion of grain size necessary for suitable surf smelt spawning habitat, and (2) for the 2 years of this study the intact drift-cell sites had significantly higher densities of surf smelt spawn than the impaired (Elwha) drift cell.

Whereas sediment processes are the basis for habitat function, other factors might also influence nearshore habitat use by fish. Areas with higher mean grain size and variability are also known to have higher wave energy (Gelfenbaum *et al.*, 2009). This higher wave energy may combine with the decreased rate of sediment supply due to in-river damming and shoreline armoring to cause a net decrease in suitable spawn substrate and other ecological metrics documented in

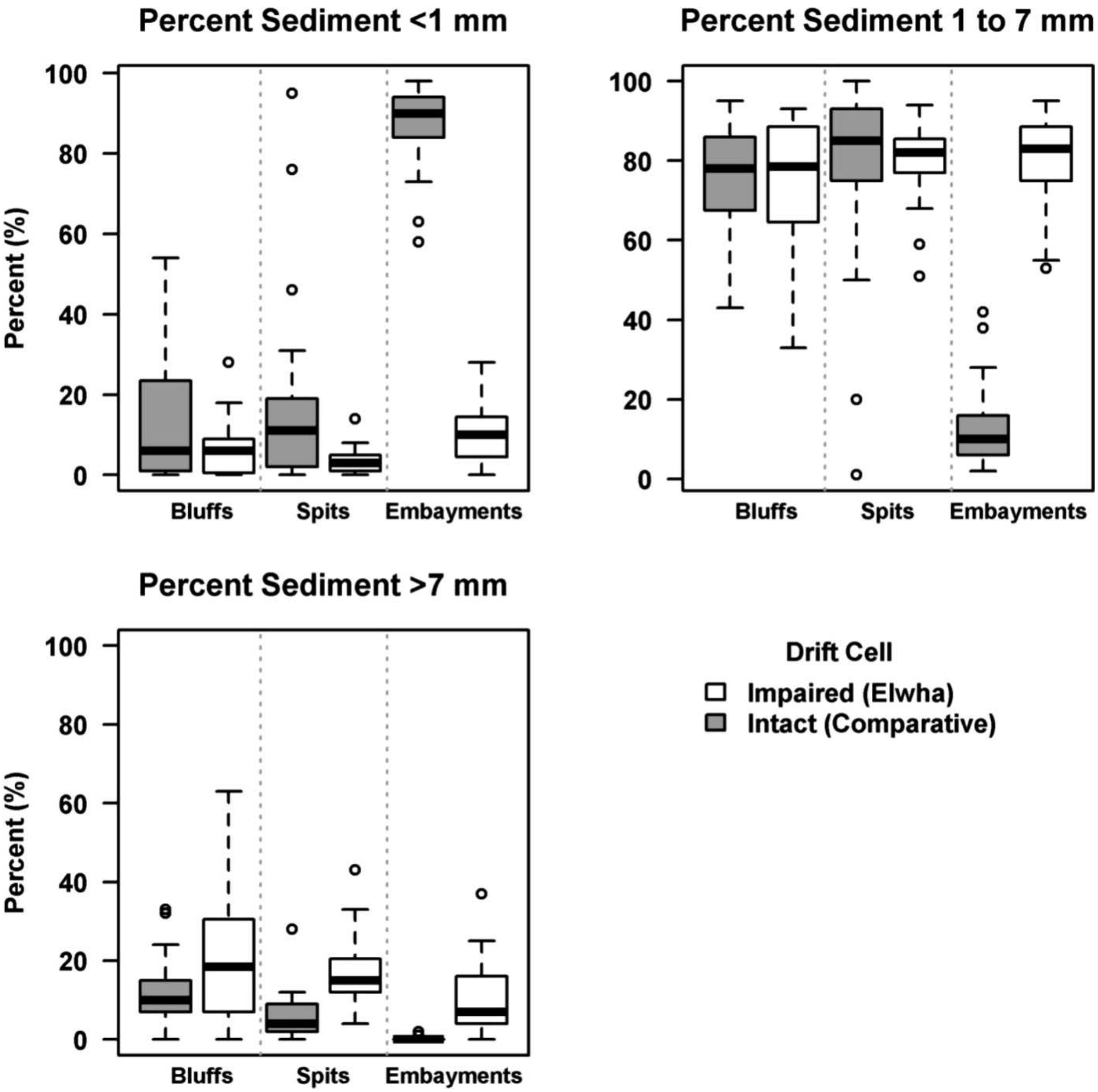

Figure 6. Sediment texture classes by geomorphic habitat types for impaired (Elwha) and intact (comparative) drift cells.

Shaffer *et al*. (2012) such as fish species richness and diversity and abundance of adult and juvenile surf smelt and sand lance. Long-term monitoring of smelt by seining indicates that surf smelt density plays a role in high interannual variability of egg spawn, and that interannual variability of surf smelt densities occur and may be related to sea surface temperature (Kaltenberg, Emmett, and Benoit-Bird, 2010). Therefore continued detailed multiyear assessment of fish use and concurrent micro-oceanographic and physical habitat characterization should be conducted to define in further detail the relative roles that interannual life histories and physical habitats play in affecting variability in habitat function.

We also must acknowledge the lack of replication at the drift-cell scale. We only sampled one impaired (Elwha) and two intact drift cells (Crescent and Dungeness).

Results of this study exhibit trends observed in ecological metrics observed in other studies. A companion study assessing fish abundance documented significantly higher postlarval surf

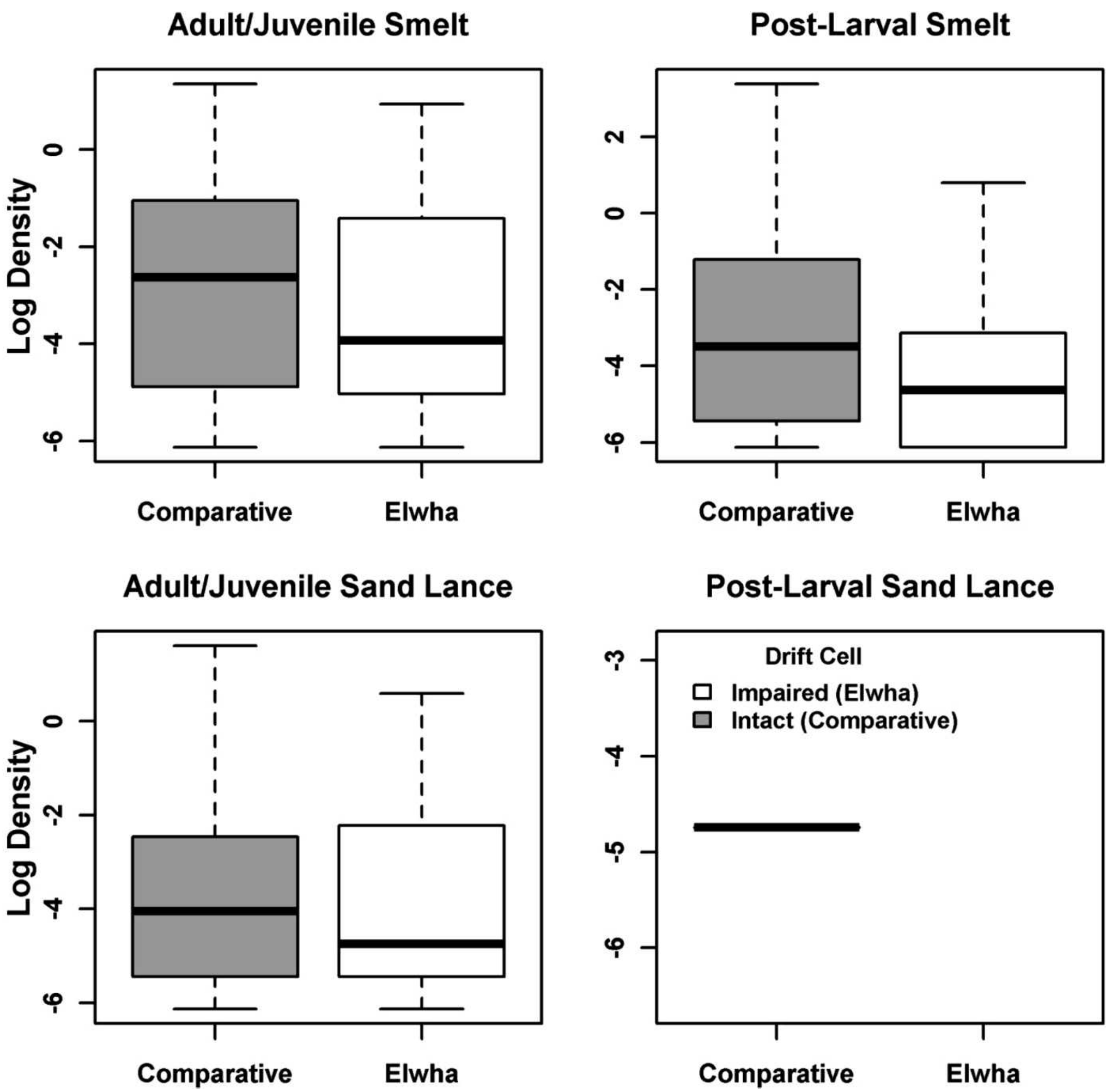

Figure 7. Density of smelt by impaired (Elwha) and intact (comparative) drift cell. Data published in Shaffer *et al*. (2012) and provided here with permission of authors.

smelt density along the intact (Dungeness) drift-cell feeder bluff that was also a surf smelt spawning beach (Figure 7). Shaffer *et al*. (2012) also documented significantly higher ecological diversity and species richness along the intact drift cell (Figures 8 and 9). The combination of sediment composition differences between the drift cells observed in this study and others' observations lead us to therefore reject our null hypotheses and conclude that disruption of sediment delivery across a drift cell results in significantly higher variability in sediment size distributions and significantly lower functional habitat for forage fish spawning. We further hypothesize that not only volume of material, but rate, timing, and composition of sediment delivery to nearshore habitats are all critical elements of feeder bluff contribution to nearshore ecological function.

Applying our results to future restoration actions, we theorize that when nearshore sediment processes are partially restored via the restoration of fluvial sediment sources, there

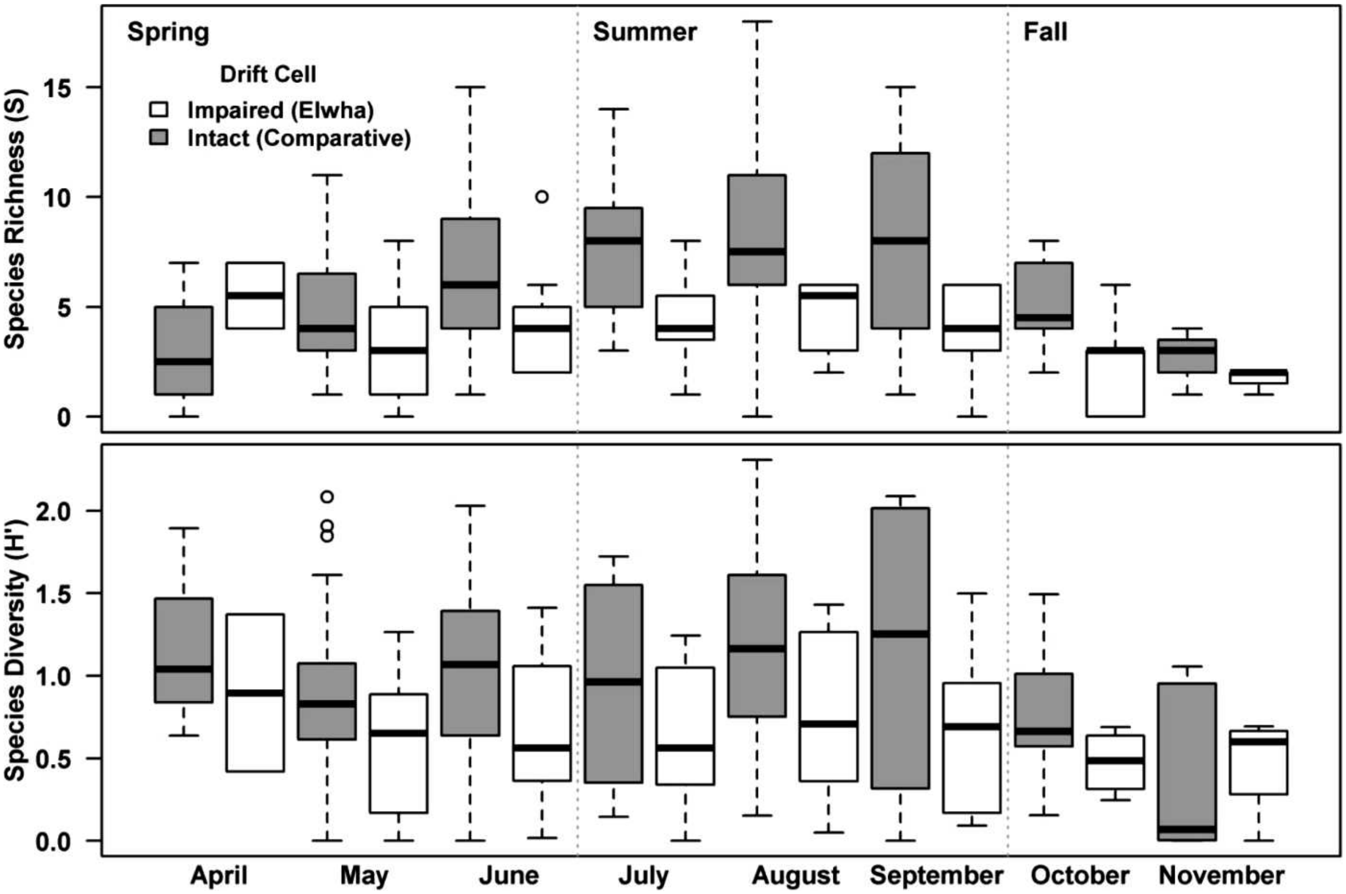

Figure 8. Fish species richness and diversity by drift cell. Data published in Shaffer *et al*. (2012) and provided here with permission of authors.

could be an increase in potential spawning habitat for both sand lance and surf smelt proportional to the amount of additional appropriate-size material provided by the restoration. A majority (93%) of feeder bluffs and spit within the impaired Elwha drift cell are armored, and will remain so after dam removal (City of Port Angeles, 2011). Impacts to nearshore function will continue as documented for shoreline armoring of higher-energy beaches along other regions of Puget Sound and the world (Johannessen and MacLennan, 2007; Pilkey and Wright, 1988; Pilkey *et al*., 1998, 2011; Young, 2012). We surmise that sediment accumulation will likely be at best partial. In armored areas deposition will likely be limited to the toes of armored sections of shoreline and persist for an unknown duration. Deposition will likely be greatest along unarmored beaches that are the most proximal to the river. Full Elwha nearshore restoration will therefore be limited due to remaining shoreline armoring. Additional efforts should therefore be made to optimize shoreline restoration to take advantage of the in-river sediment restoration. These efforts could include softening the armored shoreline by removing existing armoring, or promoting sediment accretion by placement of large woody debris structures. Finally, the impaired drift-cell sediment characterization indicates the critical importance of protecting the intact sediment delivery processes, including those of the comparative drift-cell areas of this study. Without protective measures at the drift-cell scale we risk impairing ecosystem function. Once impaired, ecosystem function is extremely expensive and difficult to restore.

CONCLUSIONS

We conclude that disruption of sediment processes plays an important and direct role in both sediment size and nearshore habitat function at both local and drift-cell scales. When sediment processes are disrupted and sediment delivery is reduced, beach substrate sizes are more variable and coarse, and less habitable for forage fish spawning across the drift cell than in unimpaired drift cells not associated with reduced sediment supply. Further, the role feeder bluffs play in nearshore habitat is complex, with the sediment composition, volume, and seasonal rate of sediment delivery important for nearshore ecological function and restoration.

The current dam removals in the Elwha River will at best provide a partial restoration of nearshore sediment processes. Additional restoration actions of acquisition, shoreline modification to remove armoring, and further study are warranted for complete restoration of the nearshore. The creation of preser-

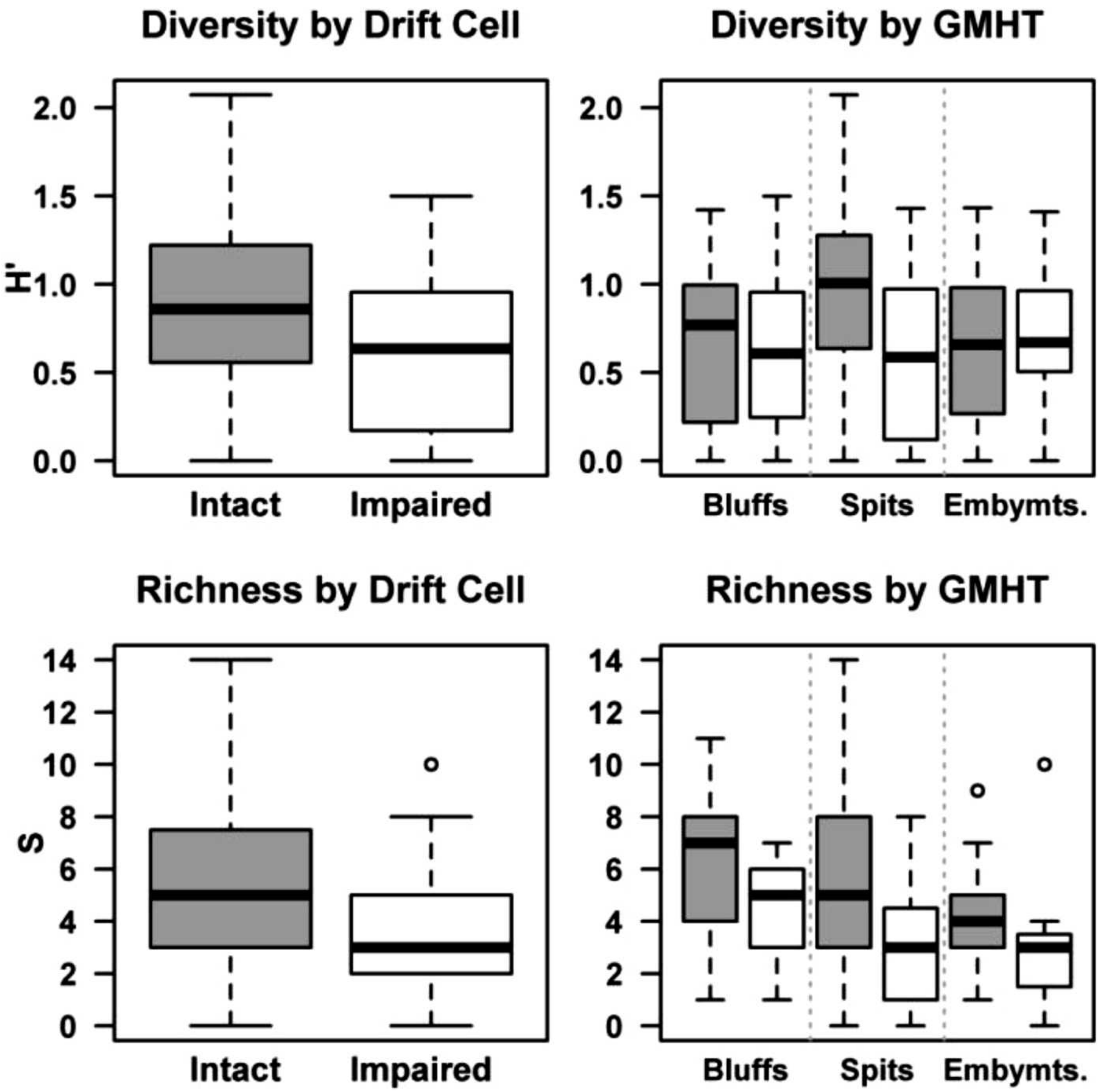

Figure 9. Diversity and richness by drift cell and geomorphic habitat type. Data published in Shaffer *et al*. (2012) and provided here with permission of authors.

vation areas and conservation easements to protect the last functioning remnants of the Elwha drift cell (for example the feeder bluff in the lower river of the Elwha and embayed Elwha shoreline) as well as the entire intact comparative drift cell are therefore a high priority. Soft armoring alternatives and restoration of armored areas of the Elwha drift cell are suggested, but may be a lower priority than preservation due to cost and likelihood of success.

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