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Benthic video landers reveal impacts of dredged sediment deposition events on mobile epifauna are acute but transitory

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ABSTRACT

The "beneficial uses" of dredged sediment are increasingly being explored for habitat restoration and beach nourishment, but beneficial uses must be tempered by evaluating impacts to organisms. We studied a subtidal nearshore deposition site intended to aid beach nourishment where a "thin-layer" sediment deployment method was employed to minimize mounding and disperse sediment within a proscribed area. Baited benthic video landers (BVLs) in a Before-After Control-Impact (BACI) experimental design were used to test the acute effects (within one hour of deposition) of sediment deposition on dominant epifaunal Dungeness crab (*Cancer magister*) and dog whelk (*Nucella* spp). The effects of sediment deposition depths and the lateral surge (the turbidity front transiting the seafloor) were both considered. Observations revealed sedimentation levels were limited to <4 cm and burial likely posed no direct threat to epifauna. However, video and instrument measurements showed the lateral surge to impact the BVLs as a 1 to 3 m/s sediment-laden front. Crabs were significantly impacted, while gastropods were more resistant to dislodgment. However, the high velocity impact was relatively brief (2 to 7 min). Further, crabs returned to forage at BVLs after a mean lag of about 20 min post-impact. These results indicate an acute but ephemeral impact effect on crab, and support use of the thin-layer deposition method to minimize burial. Our novel use of BVLs in a BACI experimental design were an effective means of evaluating sediment impacts to targeted mobile epifaunal species, and video observations were informative for understanding lateral surge dynamics and the behavioral interactions of organisms.

1. Introduction

Sediment accumulation in rivers and estuaries is a chronic issue for managing shipping channels worldwide, and the disposal of dredged material is now a global infrastructure issue requiring adaptive management solutions (Brandon and Price, 2007; CDA 2012; Welch et al. 2016). In the United States alone nearly 162 million m^3 of sediment are annually dredged from navigational channels by the US Army Corps of Engineers (USCOP 2004). Advances in the management of dredged sediment include recognition of the potential to mitigate areas of environmental degradation to improve coastal resilience, ecosystem restoration, and climate change adaptation (Yozzo et al. 2004; Brandon and Price 2007; EPA, 2007). Such "beneficial uses" include upland brownfield and landfill projects (Maher et al. 2013), creation, restoration, and maintenance of wetland habitat (Shafer and Streever 2000; Bolam and Whomersley 2005; Baptist et al. 2019), and nourishment of eroding ocean beaches (Manning et al. 2007; Stive et al. 2013). In marine and estuarine zones of the US, beneficial use sediment placements usually occur in shallow subtidal or intertidal zones, and more rarely in deeper subtidal zones (Brandon and Price 2007).

Of course, such large scale habitat alterations risk major disruptions to existing benthic communities. In-water sediment deposition events can harm marine fauna by direct burial or mechanical effects of the sediment-laden plume as it impacts and transits the seafloor (Newell et al. 1998; Wilber et al. 2007), as well as through increased turbidity or toxic pollution levels (Essink 1999; Wilber and Clarke 2001; Katsiaras et al. 2015). Previous investigations of the effects of dredge spoil deposition on infaunal benthic community composition and species density have employed benthic grabs and cores, sediment profilers, or sediment surface photography (e.g. Valente 2006; Smit et al. 2008; Gray

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and Elliot, 2009). Mobile epifaunal communities are usually assessed using trawl collections inside and outside a disposal area after the disposal events have happened and comparing biomass and or community composition (e.g. Fields et al. 2019; Trannum et al. 2019). These studies indicate impacts and community recovery rates relative to reference or pre-impact conditions vary, with leading explanatory variables including sediment type (especially grain size and toxicity), deposition frequency and cumulative depth, and the nature of the pre-impact community (opportunistic/ephemeral versus stable/long lived).

While some infaunal communities are extinguished by sediment deposition events, in others organisms are adapted to sediment disturbance and are capable of reestablishing respiratory pathways or escaping from even relatively deep burial (10s of cm) (Maurer et al. 1981; Van Dolah et al. 1984; Bolam et al. 2006). Laboratory experiments have also been employed to test tolerance of both infauna and epifauna to burial scenarios (Maurer et al. 1981; Hinchey et al. 2006; Hendrick et al. 2016) and for short and long-term effects of suspended sediments and pollutant chemistry on survival (Maurer et al. 1981; Wilber and Clarke 2001). These laboratory experiments show that sessile epifauna (especially suspension feeders) often fare poorly even at shallow deposition depths (Maurer et al. 1981; Hinchey et al. 2006); while escape and survival rates for mobile species such as Dungeness crab appear to be related to the rate of deposition (Chang and Levings 1978) and access to oxygenated water (Vavrinec et al. 2007). Thus, in situ studies of sediment discharges and organism response must be conducted where existing oceanographic processes will affect deposition rates and the flow of oxygenated water in order to fully characterize the impacts of sediment deposition on mobile species.

In the Pacific Northwest of the USA (as elsewhere), reduced riverine sediment supply and increased wave heights (Gelfenbaum et al. 1999; Ruggiero et al. 1997, 2010) are among the leading causes of ocean beach erosion that has threatened coastal communities and infrastructure, including the ocean jetties stabilizing the mouth of the Columbia River (MCR). Beneficial sediment deposition in the nearshore zone has been proposed to mitigate for shoreline recession at the MCR (USACE, 2018). However, designated deposition areas are productive Dungeness crab (*Cancer magister* Dana) fishing grounds. Aside from being a keystone predator throughout its range (Pauley et al. 1986), Dungeness crab are the most lucrative single species fishery in Oregon and Washington states, with combined landings from 2014 to 2016 of 37,800 MT valued at 258 million USD (NOAA, 2017). This has prompted concerns over the impacts of deposition events on crab and other fauna (as well as on navigation interests) and spurred research to quantify possible deleterious effects (Greenwood et al. 2011).

Deposition events from hopper dredges commonly used in ocean disposal occur in three phases (Johnson and Fong 1995). The first, “convective descent”, is the release, mixing, and descent of a sediment-water plume through the water column. Second, “dynamic collapse” occurs as the plume encounters the seabed, where it spreads laterally and decelerates. If the dredge transits along the disposal transect, the dynamic collapse manifests as a lateral surge propagating along the seabed from the impact track. Third and finally, as the slurry loses momentum, the sediment is deposited and resorted by the hydrodynamic regime in a process known as “passive transport and diffusion”. These deposition events can be highly energetic. Modeling indicates velocities of the sediment-laden slurry at the seabed can reach 3–4 m/s (Pearson et al. 2006); however, the lateral deposition footprint at shallow nearshore sites may be limited to ~100 m from the ship track centerline, depending on sediment characteristics (e.g. Pearson et al. 2006; Moritz et al. 2014), and so may have a limited spatial extent. Observations of these sediment plume dynamics in field settings have been lacking.

To minimize some of the potential negative effects of sedimentation and the lateral surge on benthic fauna, the MCR beneficial sediment program employs a “thin-layer” dispersal technique to limit sediment mounding that could harm fauna and negatively impact wave amplification and navigation (USACE, 2015). In thin-layer disposal, sediment is gradually released while the vessel transits a pre-determined disposal track (Johnson and Fong 1995; USACE, 2015). Disposal tracks are arranged to distribute sediment widely within the permitted beneficial use site. Together, these procedures aim to reduce the sediment depth of individual disposal runs and also disperse the cumulative loads over an extended area.

Here we report experiments utilizing underwater video to measure the acute in situ effects of sediment deposition on mobile epifauna. We contrast effects on the Dungeness crab, a dominant epibenthic predator and important fishery resource (Pauley et al. 1986), to a medium-bodied gastropod, *Nucella* spp. (primarily a scavenger), which were the primary benthic invertebrates observed in our experiments. The experiments, conducted in August-October 2014–2016, utilized baited benthic video landers (BVLs) in a before-after control-impact (BACI) design that compared the impact of the sediment plume on organisms attracted to bait to a non-impact control treatment. “Acute effect” is defined as any disturbance (movement, displacement, burial, mortality) at impact treatments compared to control treatments within an hour of an impact event, and thus the individual experiments encompassed aspects of the dynamic collapse and passive transport and diffusion phases of deposition. The study had two main objectives: 1) Characterize the lateral surge and sediment dynamics, and 2) Ascertain acute effects of deposition on the Dungeness crab and dog whelk. We also comment briefly on observations of other organisms and their interactions.

2. Materials and methods

2.1. Study site and sediment disposal

Our primary research area was the South Jetty Site (SJS) located seaward of Clatsop Beach, Oregon, USA (Fig. 1), within the Clastop Plains subcell of the Columbia River Littoral Cell (Ruggiero et al. 2005). The 6.2 km^2 experimental beneficial use site was comprised of relatively level, sandy substrate located between 14 and 16 m depth. The sediment deposited at SJS is clean medium-fine sand (0.22 mm diameter with <3% silt and mud) dredged from the nearby Columbia River navigation channel (Moritz et al. 2003) and is of similar constitution to sediments at the disposal site ($D_{50} = 0.19$ mm with <3% silt and mud) (UASCE, 2007). Sediment deposition runs were conducted by the USACE ship *Essayons,* a multiple-door hopper dredge. Limited observations were also made at the Shallow Water Site (SWS) on the north side of the Columbia River channel.

At the MCR, individual deposition events average around 4200 m^3 with an expected footprint of approximately 1.8×10^5 m^2 and sediment depth up to 9 cm along the centerline (Moritz et al. 2014). Based on modeling and laboratory flume experiments, sediment deposition exceeding this depth could cause mortalities to benthic organisms such as the Dungeness crab (Chang and Levings 1978; Pearson et al. 2006; Vavrinec et al. 2007).

2.2. Benthic video landers

We built a series of BVLs to measure acute effects of sediment deposition on epifauna. These platforms were deployed immediately before disposal events and performed two functions: first, they measured sedimentation levels, and second, they recorded imagery showing the direct effects of sediment plumes on Dungeness crab and other organisms.

Each BVL had a base consisting of a 0.5 m^2 circular rim made from 15 mm stainless steel and slatted with a series of flat metal strips that prevent burial in the substrate (Fig. 2). Weights were attached to the rim of the base for stability. Welded to the base was a 110 cm central pole with four curved support ribs. The central pole held a downward looking video camera (GoPro Hero, models 2 or 3+) and an underwater light source (Intova IFL WA ZOOM). The downward viewing camera captured

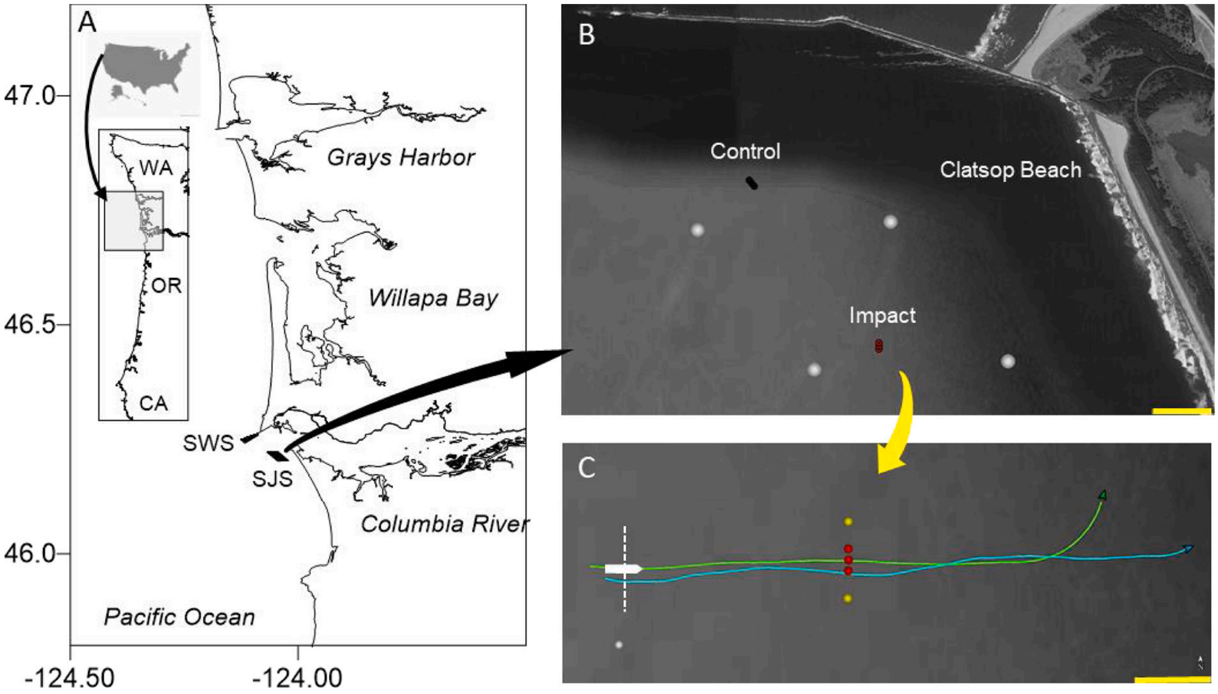

Fig. 1. Study region at the mouth of the Columbia River. (A) Locations of the South Jetty Site beneficial use area (SJS) and the Shallow Water Site (SWS). Insets provide a regional perspective of the Pacific Northwest of the USA. (B) SJS showing positions of Control and Impact BVL positions. White symbols designate borders of beneficial sediment deposition area relative to target beach nourishment site at Clatsop Beach. (C) Detail of Impact BVL orientation with near (red) and distant (yellow) units. Dredge vessel tracks for experiments 9 (blue) and 10 (green) are indicated. White bar: Scaled representation of dredge *Essayons* (102 × 21 m). White dashed line: expected footprint of sediment deposition (100 m). Yellow scale bar = 200 m.

images of the 0.5 m^2 base area and was used to estimate sediment cover from deposition events, and also to determine time series of faunal density. The underwater light source was used to evaluate the intensity of the sediment plume via observed particle velocities. A second, inwardly looking camera mounted on a support rib imaged sediment accumulation against a 200 mm staff gauge located on the bottom of the central pole, and also aided in behavioral observations. Each BVL was baited with diced northern anchovy (*Engraulis mordax* Girard) placed in a perforated plastic container secured to the base. Note that the baited BVLs were not intended for the purpose of organism population census. To compare epifauna densities among deposition and control sites, we conducted a concurrent study employing benthic video sled methodology (Fields 2016; Fields et al. 2019). The baited BLVs were designed explicitly to examine the response of Dungeness crab and other dominant epifauna to deposition events.

Video data from the GoPro cameras were recorded at a standard high definition resolution of 1920 × 1080 pixels at 30 frames/s on the “wide” field of view setting (1080p 30 wide). This setting provided the best balance between resolution, field of view, and battery life (~ 2.5 h with a standard battery at full charge). In 2016 we added extended battery packs to lengthen the post-impact observation period.

BVLs were deployed at Control and Impact sites during an experiment to test the null hypothesis of no acute effect of the lateral plume on crab density. At the Impact site, three BVLs were joined in a “daisy chain” configuration that allowed the dredge to release sediment directly over the BVLs without fouling mooring lines (Fig. 1C; Fig. 2D). There were 30 m between BVL units, thus assuring the Impact replicates would be within the sediment plume impact zone. During 2015 and 2016, additional individual BVLs were deployed as a continuation of the daisy chain line at the Impact site. These distant BVLs were deployed 100 m from centerline of the disposal track (70 m from the outer BVLs), and were used to gauge effects lateral from the targeted deposition track. At the Control site, three BVLs were deployed individually for each experiment.

During an experiment, BVLs were deployed at Control and Impact locations (separated by ~1.9 km), and the dredge *Essayons* then transited a pre-determined course over the Impact BVL daisy chain. Across experiments, the period between BVL deployment (T_0) and sediment impact (T_I) was between 25 and 44 min, depending on coordination with the dredge vessel, and allowed organisms attracted to the bait to accumulate at the BVLs. No sediment impact effects occurred at the Control site. BVLs were retrieved after ~2.5 h, when camera batteries were deemed to be exhausted.

2.3. Video analysis

We used the timing of the sediment plume at each impact BVL to define pre- and post-impact time periods. Pre-impact sequences ended once the sediment plume crossed the perimeter of the BVL base. Post-impact sequences began consecutively, ending either when the BVL was retrieved or more often when the camera battery was depleted. Between coordinating deployment of the cameras with the dredge vessel and variable battery life of the camera batteries, post-impact video sequences ranged from 9 to 75 min in 2014 and 2015 and up to 120 min in 2016 with extended battery packs. All video footage was sequenced and edited in Adobe Premiere Pro CC or CyberLink PowerDirector 13. See Fields (2016) for further details.

2.4. Observation of sediment levels

To assess potential for organism burial, we examined the upper and side video imagery from the Impact treatment immediately following dissipation of the sediment plume. With the upper camera we estimated the percent of the 0.5 m^2 base that was covered with sediment. Base units before deposition were generally sediment-free and newly deposited sediment was clearly discernable from pre-Impact levels from cover on the base slats. With the side camera we measured the depth of deposited sediment from the staff gauge.

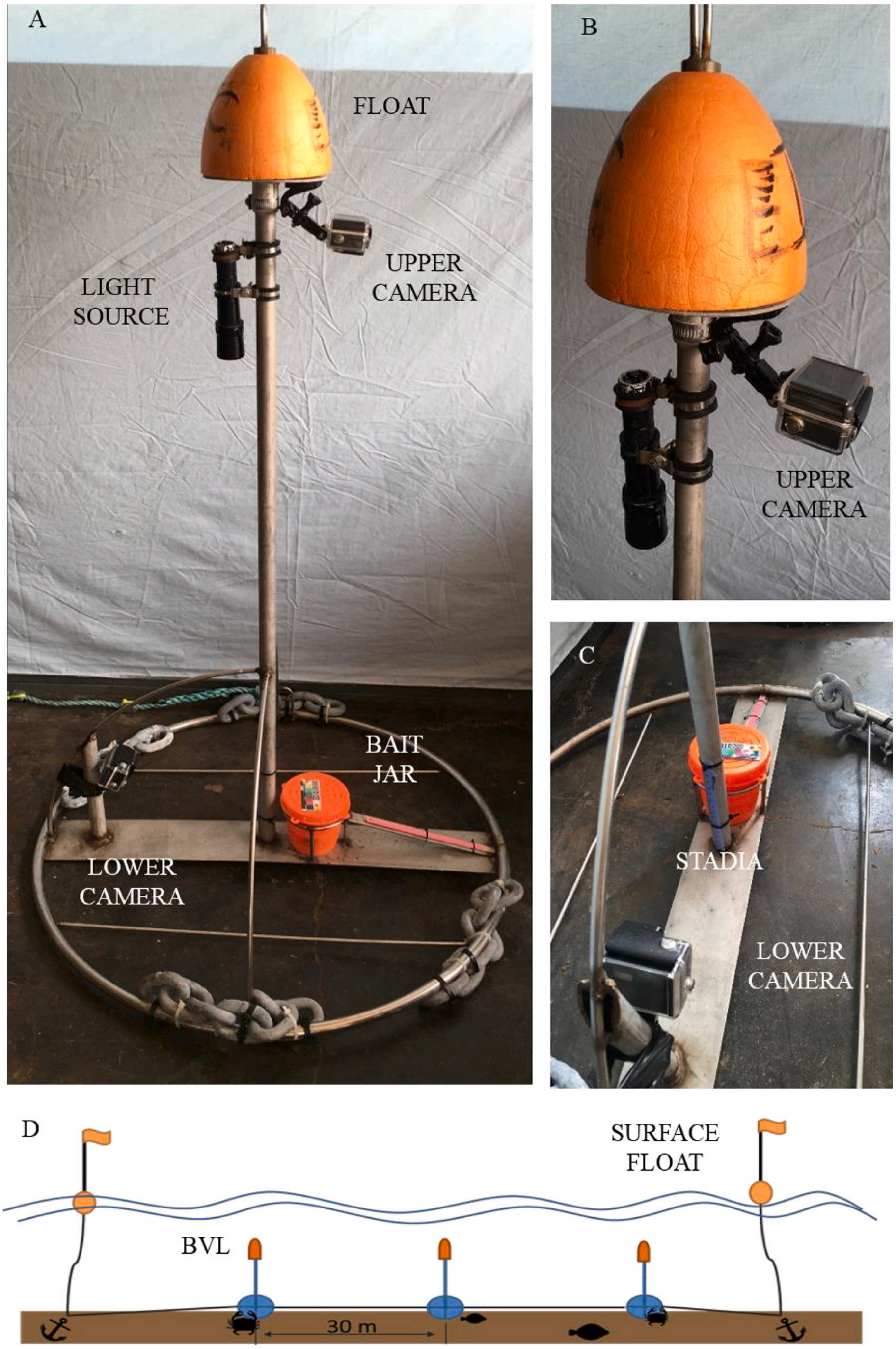

Fig. 2. Design of benthic video lander (BVL). Indicated are positions of upper and lower cameras, light source, sedimentation stadia, and bait jar. (A) Overview. (B) & (C) Details of upper and lower camera positions, respectively. (D) Schematic of the near/Impact BVL units joined as a "daisy chain".

2.5. *Organism density*

Each BVL video was scored at five minute intervals for organism density (D_T). We concentrated on Dungeness crab (*Cancer magister*) as the most abundant as well as ecologically and economically important epifauna. We secondarily evaluated impacts on dog whelk (*Nucella* spp) on a subset of deployments to consider the contrasting locomotor attributes of the two species. Organisms were enumerated only when observed contacting or within the 0.5 m^2 base of the BVL. Note that counts were not possible during impact events, when visibility was reduced to zero. These black-out periods proved to be less than seven minutes in duration and were typically ~three minutes in duration.

To test for impact effects, we standardized the density data in two ways. First, because maximum organism densities (D_{MAX}) between BVLs could vary (for crab, 2 to 20 ind / m^2) between and within experiments, we normalized densities (D_N) as proportion of D_{MAX}: ($D_N = D_T/D_{MAX}$). These data comprised the independent variable for statistical tests. Second, the time from deployment to the sediment deposition event (T_I) varied from 25 to 44 min among experiments (Table 1), and Control and Impact treatments were deployed up to 20 min apart. To standardize the time series of organism presence at Control and Impact treatments, we calculated the mean T_I among Impact replicates (which were within 5 min of each other), and applied that value to the Control time series, thus standardizing the organism accumulation period within an experiment.

To test for acute impact effects on organisms, we calculated the mean

Table 1
Summary of BVL experiments indicating number and status of replicates for each treatment group.

Exp	Location	Date	T_I	Near				Distant			
				Control		Impact		North		South	
				PRE	POST	PRE	POST	PRE	POST	PRE	POST
1	SJS	2014-09-04	38	3	2[a]	3	3	–	–	–	–
2	SJS	2014-09-12	70	3	3	3	3	–	–	–	–
3	SWS	2014-09-17	X	3	3	–	–	–	–	–	–
4	SJS	2014-09-18	40	3	3	3	1[a]	–	–	–	–
5	SJS	2014-10-03	X	3	–	–	–	–	–	–	–
6	SJS	2015-09-04	25	3	3	3	2[b]	1	1	1	NP
7	SJS	2015-09-18	28	3	3	3	3	0[c]	0[c]	1	NP
8	SJS	2015-09-26	28	3	3	2	1[b]	1	NP	1	1
9	SJS	2016-09-08	43	3	3	3	2[a]	1	1	1	1
10	SJS	2016-09-10	44	3	3	3	2[a]	1	1	0[c]	0[c]

There were three replicates for Control and Impact treatments (near) along the disposal track, but only one for north and south Distant BVLs. EXP, Experiment. T_I, Time (minutes) before impact with "X" indicating no deposition event occurred. (–) Not deployed. NP, No sediment plume reached the BVL.

[a] Short video sequence.

[b] Tipped by lateral surge.

[c] Equipment failure (bad deployment/camera knocked askew).

D_N over three time steps before and three time steps after T_I (the deposition event) for each BVL time series (i.e. three samples at 5-min intervals in the 15 min before and after T_I). In the same manner, we also computed the mean D_N for three time steps 40 to 55 min post-impact to evaluate if faunal densities had recovered from the deposition event. The sample scheme is detailed in Fig. 3. This process resulted in six treatment-time combinations for each experiment: Control-Pre, Control-Post 1, and Control-Post 2, and Impact-Pre, Impact-Post 1, and Impact-Post 2. We then ran a two-factor Analysis of Variance testing the significance of D_N by Treatment Group (Control versus Impact) × Time (Pre versus Post 1 versus Post 2). For the BACI test, a significant interaction term supports the hypothesis of an impact effect (Underwood 1991). A Tukey post-hoc test was used to distinguish significantly different groups. All statistical tests were conducted with Statistica v13 at $\alpha = 0.05$ on untransformed data.

To further explore the potential impacts of the sediment plume, we determined the time of first return (T_R) of crab during the post-impact period of the impact BVLs. We compared BVLs directly under the dredge track to those deployed distant to the main deposition track. Regression was used to examine the reliance of return time to length of video sequence.

2.6. Physical attributes of the lateral surge

In 2015, an instrument tripod was deployed at SJS to measure currents, waves, and turbidity during the sediment disposal season. On several occasions, transits of *Essayons* were close enough to the tripod for bottom currents and turbidity levels from the lateral surge to be measured. Here we concentrate on nearbed velocity and turbidity; further details of the instrument tripod configuration and results are in Golder (2016). Near bottom (0.54 m) current velocities (U) were measured with a 6000 kHz Nordek vector acoustic Doppler velicometer (ADV). Turbidity values (Nephelometric Turbidity Units, NTU) were measured with a pair of Campbell Scientific optical backscatter sensors (OBS) situated at 0.8 and 0.9 m above the bottom, respectively. Both instrument types recorded at 4 Hz during a 25 min "burst" period, resulting in 6000 measurements per burst. Data recorded on this time scale are required for observing the lateral surge. For seasonal time series, values from each 25 min burst were averaged (Golder 2016).

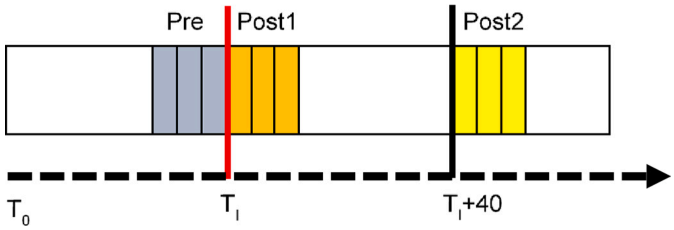

Fig. 3. Schematic of sampling design time sequence at the Impact treatment, indicating Pre-Impact, Post-Impact 1 and Post-Impact 2 treatments. T_0, deployment time. T_I, Sediment impact time. T_I + 40, 40 m after Impact time. Colored segments indicate timing (5 min intervals) of replicate density measurements for each treatment. Intervals were identical for the Control treatment within experiments, but T_I differed between experiments.

3. Results

Experiments were conducted from August to September in 2014–2016. During 2014, we deployed BVLs three times at SJS during sediment deposition events (Exp 1, 2, and 4) and one time during the recovery period when no deposition events occurred (Exp 5). We also made deployments at the Shallow Water Site for observation purposes when no direct impact event occurred (Exp 3). During 2015 we deployed BVLs at SJS an additional three times (Exp 6–8), and in 2016 we made two final experiments at SJS with extended battery packs to further investigate return of crabs after dredged sediment impact (Exp 9–10). Table 1 details the experiments and the number of BVL deployments with usable before and after data.

3.1. Sediment deposition dynamics

Videos revealed deposition events as rapidly moving sediment plumes that enveloped the BVLs (Figs. 4 and 5; Videos 1 and 2). Video data was obscured by high levels of suspended sediment during the deposition events. From particle trajectory analysis of an early experiment, Moritz et al. (2014) estimated this lateral surge to have horizontal current velocities of 2.4 to 3.0 m/s. Instrument measurements of three impact events in 2015 confirm velocities in this range, and reveal common attributes of surge magnitude and duration (Fig. 6). Foremost, as corroborated in the video, current velocities and turbidities dramatically increased within seconds of arrival of the front. In the examples shown, current velocities increase near instantly from background values of 0.05 to 0.15 m/s to maxima of 1.1 to 3.2 m/s. NTU values likewise spike several orders of magnitude from negligible background readings, on one occasion saturating the OBS sensor at 270 NTU (Fig. 6B). However, the impact period was relatively brief; based on image clarity from the downward-looking camera, the extent of the lateral surge did not exceed 7 min. Both ADV and OBS time series show decay of high velocity and turbidity values to background levels over a

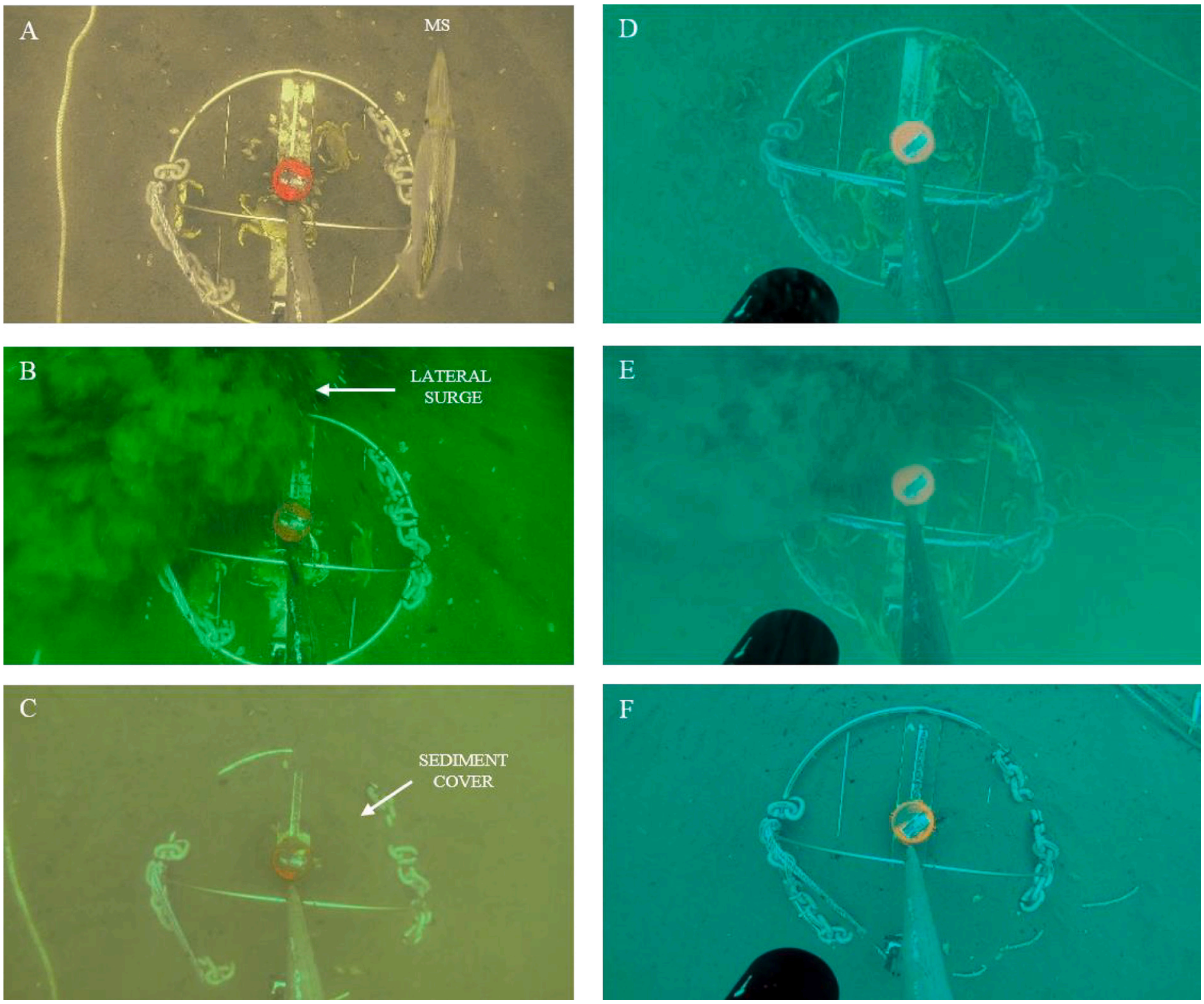

Fig. 4. Plan view examples of frame grab images illustrating before, during, and after impact of the lateral surge of a disposal event at BVLs. Images were 2 to 5 min apart in the video sequence. (A)-(C) Deployment on 2016-09-08. (D)-(F) Deployment on 2016-09-10. MS; the market squid *Doryteuthis opalescens*.

period of 1 to 2 min. Maximum values generally occurred during the initial 5 to 10 s of the impact. While turbidity quickly declined to ambient levels, enhanced oscillatory currents were sometimes observed post-surge, but with little associated sediment resuspension (to the height of the OBS units).

Sediment deposited on BVLs placed along the disposal track was relatively uniform in area and moderate in deposition depth. Mean percent sediment cover (± standard error, SE) deposited on the BVLs was 87% ± 14 (range 45 to 100%) (Table 2). Overall deposition levels averaged 1.1 cm ± 0.2 (range < 0.5 to 4 cm), and levels often did not register on the staff gauge. At the distant BVLs, ~100 m from the transect centerline, mean percent cover was only 22% ± 12 (range 0 to 60%), and on three occasions the impact plume failed to reach one of the paired distant BVLs. These observed deposition levels would not result in consequential burial of organisms.

3.2. Organism density during sediment plume impacts

The primary organisms quantified from BVL deployments were Dungeness crab, dog whelk, hermit crab (Paguridae) and several species of benthic fishes (see Fields 2016 for a full species list). However, only Dungeness crab and whelks were abundant enough for further analysis. Our observations indicate this was partially due to antagonistic behavior by crabs toward other organisms, excluding them from the BVL base area. Requirements for the BACI design were fulfilled for BVLs in all eight experiments conducted at the SJS with deposition for Dungeness crab. Whelks were not observed at all sites in the pre-impact periods in 2014 or 2015, and no whelk were enumerated in 2016, which reduced the number of replicates available for statistical analysis to 26 over six experiments.

For the Dungeness crab, results were consistent between experiments, and were significantly different among treatment groups (Fig. 7; Table 3). During the pre-impact period, mean proportional density of crab was similar between Control and Impact locations (Fig. 7), and densities tended to increase to an asymptote 20 to 30 min into the deployment. Fluctuations in the mean number occurred because crabs actively moved in and outside of the BVL base rather than accumulate as they would in a standard crab pot. When the lateral surge swept over the Impact site, all crabs were displaced (Figs. 4 and 5; Videos 1 and 2). Displacement occurred both by escape behavior, where crabs attempted to avoid the approaching sediment plume, and by entrainment, where crabs were engulfed and swept away by the plume. No crab remained at the BVLs post-impact, nor were crab buried in situ. Concurrently, mean normalized densities remained comparatively high at the Control site. Thus, we detected a significant effect of the lateral surge on Dungeness crab ($F(2, 106) = 38.42$, $P < 0.001$) as indicated by the significant interaction of treatment and time, specifically the “Pre” versus “Post 1” time points (Fig. 8; Tables 3 and 4).

Crabs were observed to return to the sediment-impacted BVLs (Fig. 7; Fig. 9); however, at the 40 min Post 2 time period, crab density remained

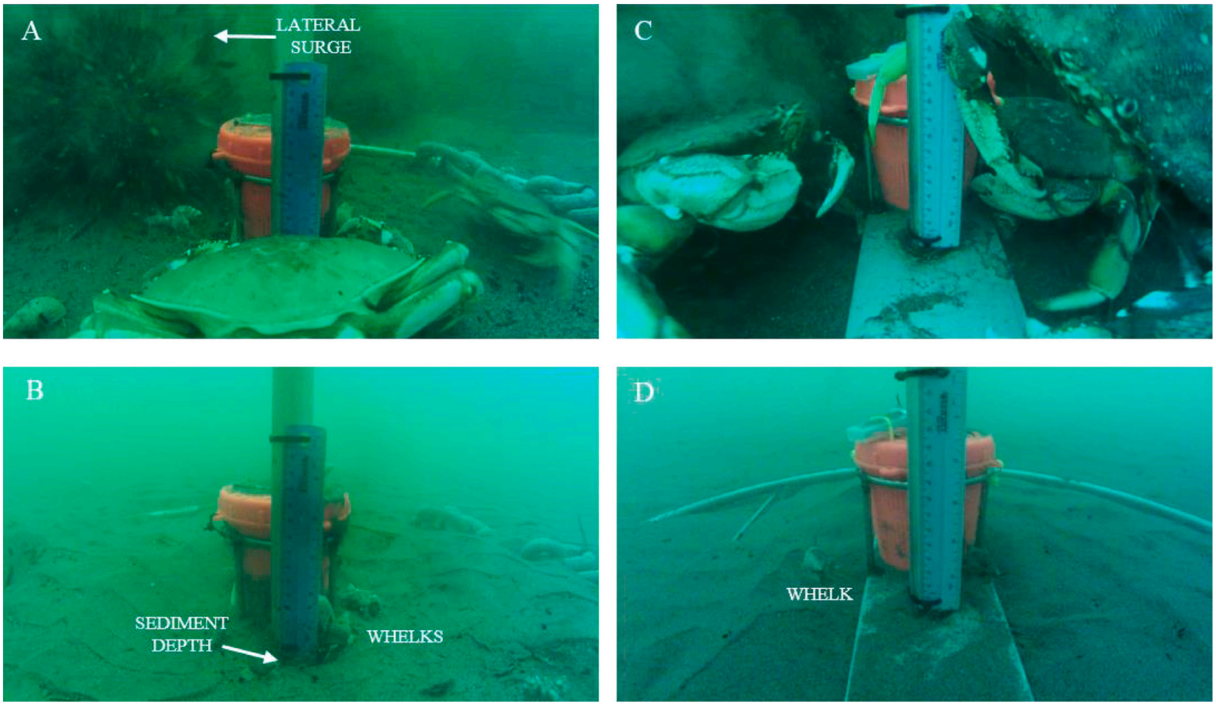

Fig. 5. Profile view examples of frame grab images illustrating during and after impact of the lateral surge at BVLs, indicating contrasting sedimentation levels. Note presence of whelks remaining on the newly deposited sediment surface while Dungeness crabs are dispersed. (A) & (B) Deployment on 2016-09-08. (C) & (D) Deployment on 2016-09-10.

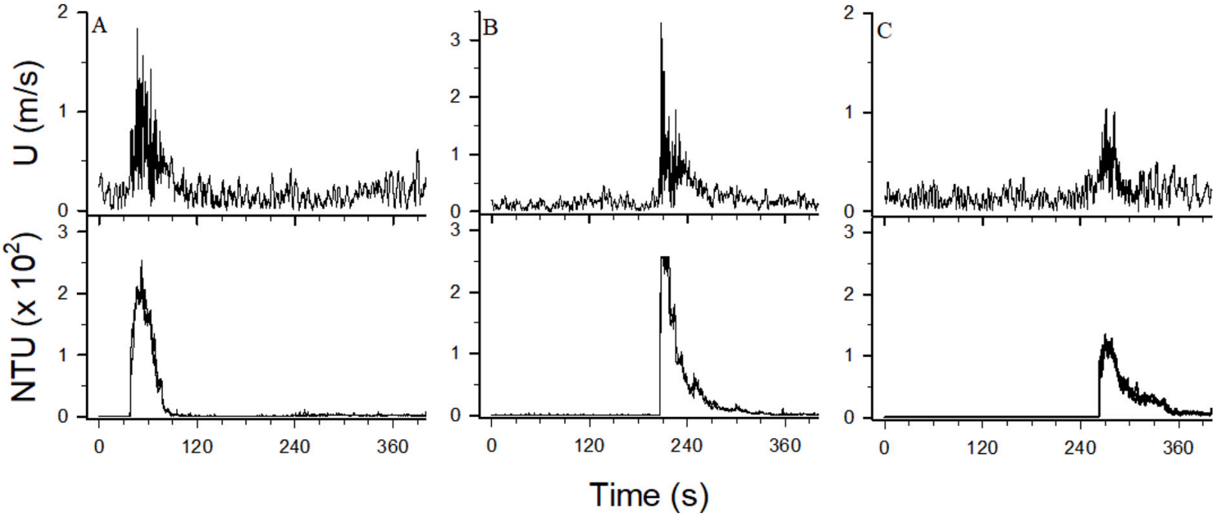

Fig. 6. Time series of velocity (U, m/s) and optical backscatter (NTU) from lateral surge impacts at an instrument mooring. Measurements (A)-(C) were made on 10–12 September 2015, respectively. Note ordinate axis scale change in B.

significantly lower than the Pre time period at the impact BVLs and did not differ from the Post 1 period (Table 4). The mean time for a crab to reoccupy a BVL was relatively variable (23.2 min ± 28 SD). Of the 17 trials with BVLs on the disposal track, six had no returns up to 90 min post-impact, but time to return was positively related to length of the video record ($r^2 = 0.43$), suggesting increased occupancy over time. If the no return values are neglected, the correlation increases to $r^2 = 0.49$. The distant BVLs generally experienced a diminished impact plume (Table 2), and all four of the trials when the lateral surge impacted distant BVLs had returns within 10 min. These data put boundaries on the detrimental effects of sediment deposition events and suggests a limited acute effect on crab foraging patterns.

Whelk were not as severely impacted by the lateral surge as were Dungeness crab. While video observation showed varied levels of dislodgement, inspection of the time series in Fig. 10 indicates overall densities were not consequentially affected by the impact event, and the interaction term of the BACI test was not significant (F(2, 66) = 0.51, $p = 0.601$; Table 5). The test thus failed to reject the lack of an acute Impact effect. Whelk densities tended to remain high at the BVL during the Post-Impact period, and were higher at the Post 2 time period at both Control and Impact sites than at the Pre or Post 1 time period (Fig. 11; $p = 0.007$). These data suggest whelk foraging at BVLs were not as strongly impacted by the disposal event as crab, and that whelk continued to accumulate at the BLV during the post impact period.

Table 2
Sedimentation on Impact BVLs.

Exp	Date	Sediment cover (%)					Sediment depth (cm)		
		Near			Distant		Near		
		North	Center	South	North	South	North	Center	South
1	2014-09-04	90	100	100	–	–	<0.5	<0.5	<0.5
2	2014-09-12	90	75	X	–	–	0.8	<0.5	X
4	2014-09-18	X	X	50	–	–	X	X	<0.5
6	2015-09-04	60	X	100	10	NS	1.5	X	1
7	2015-09-18	100	90	90	50	NS	4	<0.5	1
8	2015-09-26	45	X	X	NS	10	1	X	X
9	2016-09-08	100	100	100	60	X	1	3	1
10	2016-09-10	75	100	100	10	X	<0.5	X	1

Sediment cover is percent of 0.5 m^2 base with visible deposits measured with top camera. Sediment depth is amount of sediment (cm) deposited on measuring stadia determined from the side camera. Side cameras were not deployed on distant BVLs. X; deployment failed. (–); no distant treatment deployed. NS; no lateral surge observed.

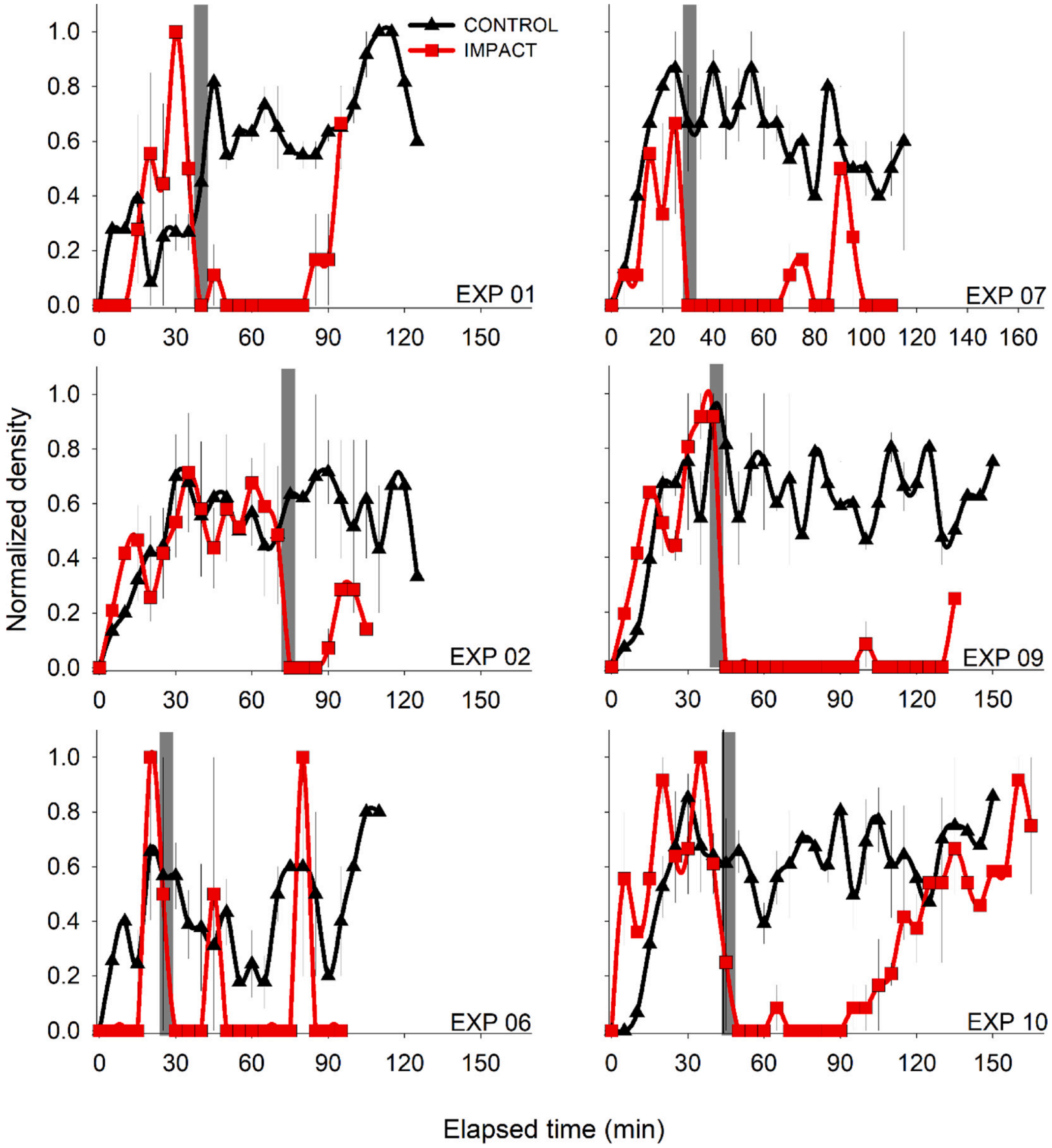

Fig. 7. Time series of mean (± standard error) normalized density of Dungeness crab per time interval ($n = 3$) at Control and Impact sites. Gray bar denotes timing of lateral surge and designates pre- and post-impact periods.

Table 3
BACI design: two-factor Analysis of Variance testing Dungeness crab normalized densities (D_N) among pre-and post-deposition time periods at control and impact sites.

Effect	SS	DF	MS	F	p
Intercept	17.49	1	17.49	481.11	**<0.001**
TRT	2.47	1	2.47	68.06	**<0.001**
TIME	1.86	2	0.93	25.56	**<0.001**
TRT*TIME	2.79	2	1.40	38.42	**<0.001**
Error	3.85	106	0.04		

Table 4
Probabilities from Tukey HSD Post Hoc tests to determine significantly different groups.

	TRT	CONTROL			IMPACT	
TRT	**TIME**	**PRE**	**POST1**	**POST2**	**PRE**	**POST1**
CONTROL	PRE					
	POST1	0.910				
	POST2	0.917	1.000			
IMPACT	PRE	0.201	0.779	0.832		
	POST1	<0.001	<0.001	<0.001	<0.001	
	POST2	<0.000	<0.001	<0.001	<0.001	0.995

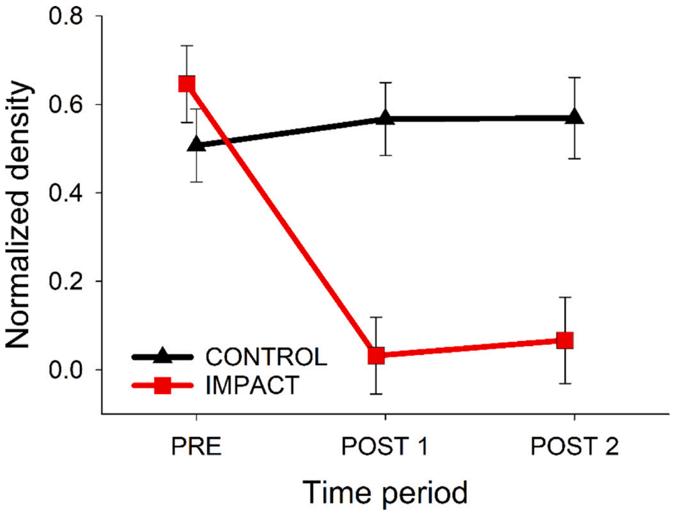

Fig. 8. Comparison of treatment effects for mean normalized density of Dungeness crab (± 95% Confidence Interval) in BACI design. Mean densities were determined just prior (Pre), just after (Post 1) and 40 min after (Post 2) arrival of the lateral surge at Control and Impact sites. The post-Impact treatments were significantly different from the others ($p < 0.001$). N ranged from 15 to 21.

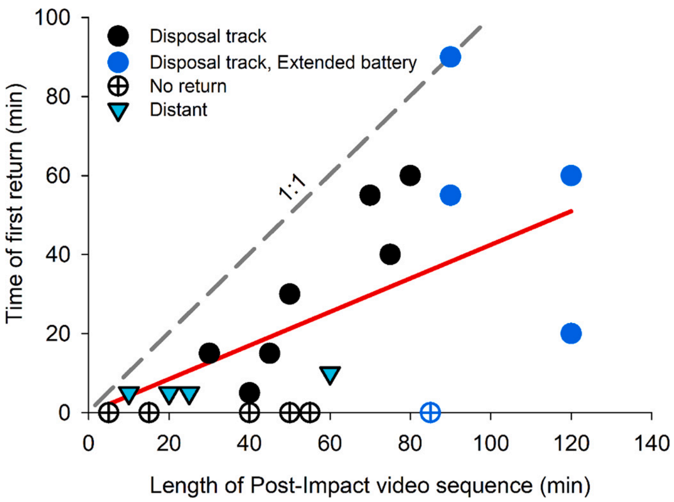

Fig. 9. Time of first return of Dungeness crab to BVLs following a sedimentation event by video length (= elapsed time).

3.3. *Qualitative observations of BVL deployments*

We conducted a BVL deployment (Exp 3) at the Shallow Water Site (SWS) in 2014, a high energy location on the Columbia River bar. This trial compared densities of crab and whelk at BVLs during a high wave period compared to more sheltered conditions at the SJS (Exp 5). Neither of these deployments included impacts from a sediment deposition event, and thus serve as observations rather than experiments. Fig. 12 illustrates that occupation of crabs at BVLs was similar at all three areas, increasing within 20–40 min to an asymptote. Whelk had similar abundance patterns at SJS but were uncommon at SWS (data not shown). Video observations of crab at SWS reveal the agility of crabs in oscillatory flow (Video 3). Surge from waves at the SWS resulted in 50–70 cm/s bottom currents accompanied by resuspension and transport of sand. Crabs were observed to resist dislocation by remaining near the substrate, but those dislodged by the more energetic bursts of water and sediment often returned to the BVL within a few seconds. Foraging crabs were also observed to ascend into the water column and travel several meters before dropping back to the substrate, and repeated sojourns could result in directional movement toward the BVL. Crabs did not bury to avoid high velocity near-bottom currents. These observations of motility in naturally energetic conditions contrast behaviors observed during the unidirectional force exerted by deposition events, and are discussed further below.

4. Discussion

We investigated the acute effects of sediment disposal on dominant mobile epifaunal organisms, as opposed to more commonly reported effects of cumulative impacts on sedentary infaunal organisms. Our use of BVLs in an experimental design was a novel approach to understand the effects of dredged material deposition events on mobile epifauna. The video imagery provided observations of the time series of forces directed on target organisms, and density data was extracted from the video sequences in a straightforward manner for use in hypothesis testing. Likewise, sediment deposition levels were determined immediately following the restoration of visibility and before hydrodynamic resorting of sediment could occur. These methods are reproducible at other sediment deposition sites of reasonable water clarity, as the most significant drawback to the method occurred during periods of high turbidity due to dense phytoplankton blooms.

Both our video observations and instrument measurements of near bed velocity and turbidity made by Golder (2016) yield a complimentary assessment of the dynamic collapse and the passive transport and diffusion phases of sediment deposition. Instruments measured sudden increases in velocity associated with the lateral surge (up to 3.2 m/s from ambient velocities <0.15 m/s), coinciding with a large increase in turbidity measured by optical backscatter (OBS). The corroborating video sequences show the approach of a turbidity front-like lateral surge and an immediate obscuring of video imagery by suspended sediments

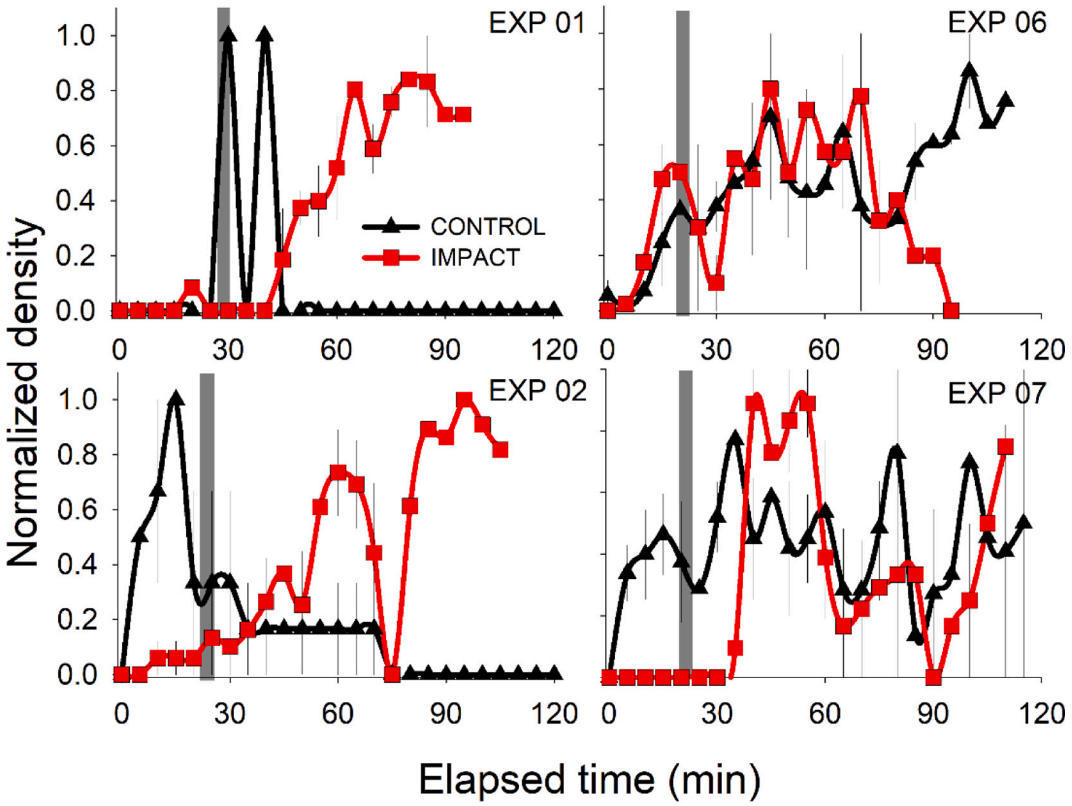

Fig. 10. Time series of mean (± standard error) normalized density of whelk per time interval (n = 3) at Impact and Control sites. Gray bar denotes timing of lateral surge.

Table 5
BACI design: two-factor Analysis of Variance testing whelk normalized densities (D_N) among pre-and post-deposition time periods at control and impact sites.

Effect	SS	DF	MS	F	p
Intercept	8.308	1	8.308	142.905	**<0.001**
TRT	0.001	1	0.001	0.016	**0.899**
TIME	0.626	2	0.313	5.380	**0.007**
TRT*TIME	0.060	2	0.030	0.514	**0.601**
Error	3.837	66	0.058		

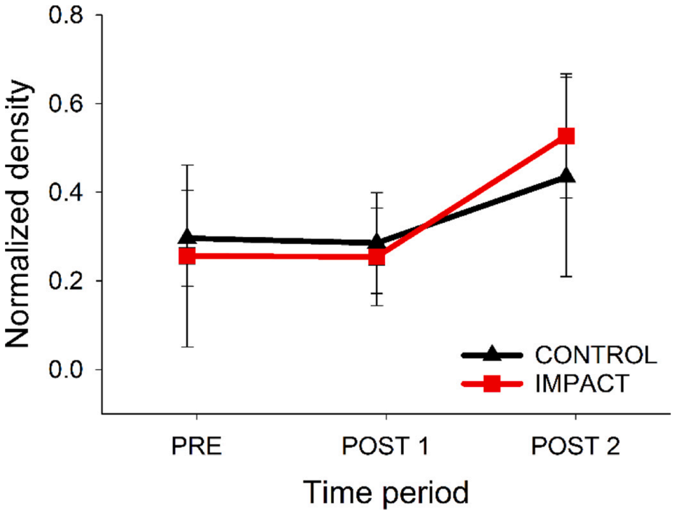

Fig. 11. Comparison of treatment effects for mean (± standard error) normalized density of whelk. Mean densities were determined just prior (Pre), just after (Post 1) and 40 min after (Post 2) arrival of the lateral surge at Control and Impact sites. No treatments were significant. N ranged from 10 to 13.

(Figs. 4 and 5; Videos 1 and 2). These observations characterize the lateral surge as an energetic front laden with sediment. However, equally striking was the rapid passing of the front during the passive transport and diffusion phase: at the instrument mooring, velocity returned to ambient levels within 2 min and OBS values within ~5 min. Similarly, high currents and turbidity levels diminished in our video imagery within 2 to 7 min. These results fit within predicted impacts based on model parameters of sediment grain size, water depth, and release rate presented by Pearson et al. (2006).

There was a varied response by organisms to impact events. Crabs attracted to bait at BVLs were often observed to sense the rapidly approaching sediment plume and enact an escape response involving abrupt "scuttling" into the water column. In most cases, the plume was observed to overwhelm the fleeing crabs, and in all cases crabs were displaced from the BVLs. Whelks and hermit crabs were impacted before they could meaningfully react, but were often not displaced from the BVL, and whelks continued to accumulate at BVLs during the post deposition period. Whelks are surface and shallow burrowing scavengers that would have little difficulty emerging from the shallow sediment layers when buried, and resistance to dislodgement was abetted by adhesion by the broad foot as well as a low profile presented to the surge. Fish and squid in and around the BVLs generally swam from the field of view without observations of them being engulfed, so we are unsure of their fate. These behavioral observations from the video recordings are insightful for elucidating impacts on epifauna.

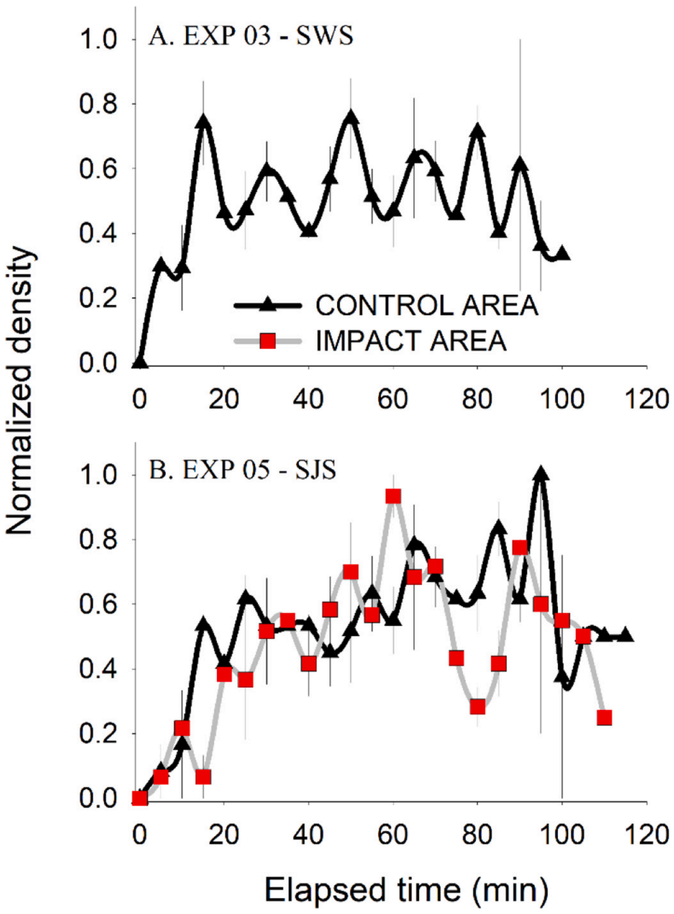

Fig. 12. Time series of mean (± standard error) normalized density at Impact and Control areas. (A) Dungeness crab on the Columbia River bar at the Shallow Water Site (SWS) on 2014-10-03. (B) Dungeness crab at the South Jetty Site (SJS) on 2014-09-17. The times series at (B) occurred in heavy swell. Neither of these deployments included impacts from sediment deposition events.

Negative effects of disposal events include increased turbidity, burial, and mechanical effects of the lateral surge. While turbidity increased dramatically during deposition events, the effects were transitory. At the MCR, Moritz et al., (2014) calculated the bulk sediment density (sediment plus seawater) of the descending plume at contact with the seabed to be 1.3×10^3 kg/m^3, which at typical seawater density yields a dense suspended sediment concentration of 2.8×10^2 kg/m^3. In comparison, Peddicord and McFarland (1976), in laboratory suspended sediment challenge experiments, found a concentration of 9.2 kg/m^3 induced an incipient mortality to 30–40 mm Dungeness crab. These challenge tests used fine grained sediments (mud derived from an industrialized harbor thus possibly toxic) and had a duration of 8 d, and so were substantially different from short term impacts from sand depositions observed during our in situ experiments. A meta-analysis conducted by Wilber and Clarke (2001) concluded few detrimental effects on crustaceans would be expected at the suspended sediment concentrations and relatively short time intervals caused by dredging operations. In agreement, our results and that of Golder (2016) indicate the high settling velocity of fine sand sediments at the MCR sites and the overall dispersive nature of the wave climate at these nearshore sites led to ephemeral turbidity effects from dredge deposits.

We ascertained the potential for organism burial by measuring sediment deposited on the BVLs immediately after passage of the lateral surge. Post-Impact video from both upper and lower cameras revealed sediment deposition levels were moderate (maximum of 4 cm). Previous laboratory experiments examined the survival of crabs as functions of burial depth and time, the primary concern being the maximum depth a crab could reestablish respiratory currents to the overlaying water or from which they could extricate themselves (Peddicord and McFarland 1976; Chang and Levings 1978; Vavrinec et al. 2007). Results indicate burial up to about 10 cm was not detrimental for most crab sizes tested if they were unconstrained by experimental conditions. The sediment accumulation levels at BVLs thus were below depths of concern documented by previous authors, and supports use of thin-layer disposal technique.

The force of the lateral surge is another matter to consider. With an estimated bulk density of 1.3×10^3 kg/m^3 and a representative surge velocity of 1.0 m/s (Fig. 6), the instantaneous bulk mass flux (bulk density × velocity) of the slurry impacting crabs would be 1.3×10^3 kg/m^2/s. Over a 180 s impact event, more than 2.2×10^5 kg of sediment would pass the BVL. These bulk fluxes, driven mostly by water movement, rival those estimated from submarine turbidity currents, albeit at a much smaller spatial extent (Xu et al., 2010; Hughes Clarke 2016; Azpiroz-Zabala et al., 2017). In comparison, sediment fluxes from breaking waves in nearshore environments are generally less than 5 kg/m^2/s (Houser and Greenwood 2005; Osborne and Greenwood 1992), although fluxes may be considerably higher in large storms. The instrument placed by Golder (2016) recorded near-bed conditions for several days during two storms in 2015 when maximum currents averaged 0.60 to 0.70 m/s and OBS values averaged less than 15 NTU. These values are far less than those measured for the lateral surge. Thus one should expect a disruptive effect of these sediment disposal events on the position and behavior of mobile epifauna. Nevertheless, the Dungeness crab was found resilient to simulated dredge deposition conditions by Vavrinec et al. (2007), who used flume experiments to examine crab responses to a discharge of sediment-laden water, and who concluded behavioral responses by crab could minimize burial risk at velocities up to 3.2 m/s. Other studies of acoustically tagged Dungeness crab likewise indicate high survival and mobility after sediment deposition events (Roegner and Fields 2015).

As a measure of post-impact effects, crabs returned to BVLs after a mean lag of about 20 min following disposal, although battery power of the cameras was not always of sufficient duration to observe crabs returning. Other than the whelks and hermit crabs that withstood the lateral surge, Dungeness crabs were generally the first organism to reoccupy BVLs, suggesting crabs continue foraging relatively soon after a single deposition event. Together, field observations of sediment deposition levels, the force of the lateral surge, and crab behavior agree with laboratory and modeling results and lend support to the hypothesis there are acute effects of disposal events on epifaunal crab distributions, but that recovery from single impact events is rapid.

Also important for determining the severity of sediment deposition impacts is consideration of organism life-history characteristics, such as size/age (timing of larval settlement and growth) and reproductive status (molting, mating, egg-bearing). For crustaceans, juveniles, recently molted individuals, and gravid females potentially have increased susceptibility to the effects of burial and forces associated with the lateral surge. The Dungeness crab in our study were predominately large intermolt individuals (100–170 mm carapace width) that were generally resistant to disposal events, and the late August – September time window permitted for disposal at SJS is mostly outside the larval recruitment period (peaking in April-June; Roegner et al. 2007) or the molting season (females in spring and males from July-August; Cleaver 1949; Stone and O'Clair 2001). However, new recruits <30 mm were sometime found in both video and crab pot samples, and we also observed one pair of crabs in conjugal embrace at a BVL moments before an impact event, so at least some disruption of small crabs and of mating and injury to thin-shelled female crabs may occur at the SJS. Additionally, little is known of the distribution of ovigerous females during the late fall brooding period; more data are needed to identify and conserve these habitats. Thus, the size and reproductive state of crabs and other organisms in relation to the timing of sediment deposition events should be considered to ameliorate negative effects on sensitive stages (Manning et al. 2007). Factoring in the biology of potentially affected organisms varies across regions, and underscores the need for regional sediment management plans.

Our research with the BVLs prompts several recommendations for further research and development. Extending the camera battery life would allow a more complete evaluation of post-Impact reoccupation, which was a limitation in our study. Another improvement would be to quantify the forces and sediment fluxes imparted by the lateral surge on individual BVL units. This could be accomplished with coupled velocimeter and sediment-calibrated OBS sensors (as presented in the mooring data). Sediment fluxes from various BVLs would enable determining variation in the lateral extent of the deposition event, important when considering the overall or cumulative effect at a site, and would also be useful when comparing sites, for example where finer grained sediments that pose higher risk to epifauna are deposited (Valente 2006; Smit et al. 2008; Katsiaras et al. 2015). Finally, behavioral observations made possible from video data, while not quantified in the present project, offered unique insights on species interactions that affect density data. A more nuanced investigation of competitive interactions, especially antagonistic behaviors, would help calibrate species densities at BVLs (e.g. crabs versus whelk in our study).

Repurposing dredged sediments for “beneficial use” projects has been increasing at USA coastal sites (e.g. Yozzo et al., 2004; EPA 2007; Parson and Swafford 2012; Maher et al. 2013) as well as internationally (e.g. Bolam et al. 2006; Stive et al. 2013; Baptist et al. 2019). Our test site in the PNW of the USA, characterized by well sorted sandy sediments in an energetic tidal and wave-energy regime (Ruggiero et al. 2005), may be considered near one endpoint of a continuum opposed by lower energy, fine sediment environments (e.g. Gulf Coast USA habitats). Benthic infauna inhabiting energetic nearshore sites are adapted to disturbances by waves (Hinchey et al. 2006; Gray and Elliott, 2009), and as Video 3 demonstrates, we observed epifaunal crabs to maneuver with dexterity in oscillatory flow strong enough for sediment resuspension. Populations of organisms inhabiting sandy substrates also generally recover comparatively faster from disturbance than those at mud or silt substrates (Maurer et al. 1981; Roberts and Forrest 1999; Dernie et al. 2003), and energetic sites are naturally dispersive and so minimize negative water quality impacts such as heightened turbidity during deposition events (Smith and Rule 2001; Newell et al. 1998). The similarity in sediment grain size and composition and lack of toxicity between dredged and receiving areas (USACE, 2007) are additional factors limiting negative effects of sediment deposition on the benthos (Newell et al. 1998). These conditions at MCR contrast the many coastal areas in the world dominated by fine sediments and low energy hydrographic regimes, for which our methods could lend insight.

Nevertheless, sediment deposition events from dredging activities have few natural analogs at nearshore sites, except perhaps turbidity currents in subtidal river discharge channels (Hughes Clarke 2016). Surge from storm events, both locally and remotely forced, generally build in intensity, allowing organisms to take precautionary actions such as burial or dispersal to deeper water. In contrast, the abrupt, forceful, and unanticipated impact of dredged sediment disposal plumes allows little opportunity for such behavioral adaptions, and we correspondingly observed crabs to be surprised and overwhelmed by the rapidly approaching lateral surge. Yet with the thin-layer disposal technique utilized at our study site, the short duration of individual sedimentation events and limited deposition depths do not appear capable of inflicting acute harm to crabs or other organisms. What remains unclear is the experience of individual organisms entrained in the lateral plume (including possible mechanical damage), as is whether the effects of multiple deposition events (cumulative impacts) have detrimental effects on epifauna. While chronic effects are under investigation (Roegner and Fields 2015), data to date suggests thin-layer disposal and the practice of staggering deposition tracks throughout the designated disposal area are warranted for reducing potential cumulative impacts on epifauna. Results of this study indicate the methods described provide a standardized capability for assessing sediment deposition impacts to mobile epifauna.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jembe.2021.151526.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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