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Beach Nourishment Impacts on Bacteriological Water Quality and Phytoplankton Bloom Dynamics

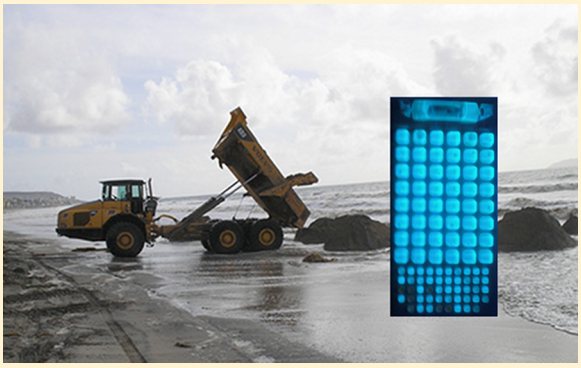
M. A. Rippy,*[,†] P. J. S. Franks,[†] F. Feddersen,[†] R. T. Guza,[†] and J. A. Warrick[‡]

[†]Scripps Institution of Oceanography, La Jolla, California 92093, United States

[‡]United States Geological Survey, Pacific Coastal and Marine Science Center, Santa Cruz, California 95060, United States

Supporting Information

ABSTRACT: A beach nourishment with approximately $^{1}/_{3}$ fine-grained sediment (fines; particle diameter <63 μm) by mass was performed at Southern California's Border Fields State Park (BFSP). The nourishment was found to briefly (<1 day) increase concentrations of surf-zone fecal indicator bacteria (FIB) above single-sample public health standards [104 most probable number (MPN)·(100 mL)$^{-1}$] but had no effect on phytoplankton. Contamination was constrained to the nourishment site: waters 300 m north or south of the nourishment were always below single-sample and geometric mean [≤35 MPN·(100 mL)$^{-1}$] standards. Nourishment fines were identified as a source of the fecal indicator *Enterococcus*; correlations between fines and enterococci were significant (p < 0.01), and generalized linear model analysis identified fines as the single best predictor of enterococci. Microcosm experiments and field sampling suggest that the short surf-zone residence times observed for enterococci (e-folding time 4 h) resulted from both rapid, postplacement FIB inactivation and mixing/transport by waves and alongshore currents. Nourishment fines were phosphate-rich/nitrogen-poor and were not correlated with surf-zone phytoplankton concentrations, which may have been nitrogen-limited.



INTRODUCTION

Beach nourishment, the placement of new sediment along a shoreline, is a frequently used "soft" engineering technique to combat coastal erosion and build beaches. With decreased sediment inputs to coastal systems[1] and the pending effects of sea-level rise,[2] beach nourishments may become more frequent, and opportunistic nourishments (including those where grain-size distributions do not match receiving sites), more common. While natural sources of coastal sediment typically have broad grain size distributions including a predominance of fine-grained sediment (fines; particle diameter <63 μm),[3] the sediment used for beach nourishments must be <20% fines unless the grain size distribution (i) matches that of the proposed placement site or (ii) meets contamination criteria and will have low negative impact on natural resources.[4] These regulations are intended to ensure that sediment placements do not deleteriously affect water quality, ecosystem function, circulation, or aquatic organisms. However, our understanding of the effects of fines on these processes is limited, making low-impact thresholds difficult to define.

Here we report the effects of a beach nourishment composed of >20% fines on concentrations of fecal indicator bacteria (water quality) and phytoplankton (aquatic organisms) at Border Fields State Park (BFSP) and nearby Imperial Beach, California. This study was one component of the Sediment Fate and Transport Study, which also monitored the dilution of fines in the outer surf zone and their effects on benthic and epibenthic fauna.[5] We incorporate observations from a separate field program, the Imperial Beach 2009 (IB09) study, which concurrently monitored near-shore waves, currents, temperature, phytoplankton, and fecal indicator bacteria (FIB) to the north of the nourishment site, at Imperial Beach.[6]

FIB are mostly nonpathogenic enteric bacteria found in human and animal waste[7−9] that are strongly correlated with infection and gastrointestinal illness.[10−12] Rapid growth/mortality rates make FIB ideal for monitoring short-term responses to episodic events like sediment placements.[13,14] Because FIB attachment to fine-grained sediment can exceed attachment to coarser particles,[9,15] fines may harbor elevated FIB loads, and nourishments with fines may increase health risk to beachgoers.[16,17]

Beach nourishments with fine-grained sediment may also reduce water quality by providing the nutrients necessary for the growth of nuisance phytoplankton species.[18−20] Concentrations of inorganic nutrients (especially phosphate) can be elevated in fine-grained sediment due to the attraction of cations (Ca^{2+} and Fe^{3+}) to negatively charged clay particles.[21] These cations reversibly bind nutrients, forming a reservoir of complex nutrient salts that are readily converted to bioavailable forms in seawater.[22]

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We use two methods to evaluate the association between fines and surf-zone phytoplankton or FIB concentrations: direct correlation and generalized linear model (GLM) analysis. GLM techniques were employed due to national and state interest in using predictive statistical approaches for monitoring beach water quality.[23,24] These approaches have been successful in freshwater systems[25] and are under evaluation for marine beaches.[23,26,27] We also estimate the residence time of nourishment-associated FIB in the surf zone and the relative contribution of mortality and physical dilution/mixing to residence time.

METHODS

Field Site Description. Border Field State Park (BFSP) in California is 2.4 km long, with its southern edge at the San Diego−Mexico border. This beach is backed by the Tijuana Estuary, which receives large volumes of sediment and water from the Tijuana River watershed (~4450 km^2 in both Mexico and California).[3,28−31] During the rainy season, watershed discharge to BFSP often contains elevated levels of FIB,[32,33] viruses,[32−34] heavy metals and other toxics,[35,36] and sediment.[3] These contaminants impact water quality at BFSP to the south, and adjacent Imperial Beach to the north, which in 2000−2001 was among the 10 most visited San Diego beaches and had the seventh highest closure cost.[32,37] The Goat Canyon retention basin (GCRB) was built in 2005 to reduce habitat loss from sediment discharge in the estuary.[31] GCRB traps more than 30 500 m^3 of sediment annually but is insufficient to capture the sediment loads during heavy rainfall.[5,31]

Beach Nourishment. In 2009, site HT (Figure 1) was nourished below the high tide line with 16 035 m^3 of sediment (9/21−9/25) and 10 725 m^3 of sediment (9/28−10/02; Figure 2A, blue bars). Nourishment material was dredged from GCRB and contained 26−46% fine-grained sediment (fines; grain size <63 μm). All material was sieved to remove trash and debris, screened for chemical and biological hazards, and trucked to the beach. Note that fines from GCRB may contain elevated levels of pollutants due to watershed contamination.[32−36,38] Thus, the relationships between GCRB fines and pollutants should not be extrapolated to other (particularly nonurbanized) sediment sources.[8]

Biological Monitoring Program. *Sample Collection.* From 9/21 to 10/13, concentrations of suspended fines, sands, FIB (*Enterococcus*), nutrients (phosphate, nitrate, nitrite, ammonia, and silicate), and extracted chlorophyll a (Chla), a proxy for phytoplankton, were monitored in surf-zone waters at BFSP and Imperial Beach (Figure 1). Though carbon:Chla ratios can vary by a factor of 5 or more, extracted chlorophyll is the most commonly used proxy for phytoplankton concentration. It is more robust than in situ fluorescence measurements, as it is not affected by the light history of the organisms, and it is more tractable than microscopic enumeration.

Water samples were collected between 0430 and 0530 (times reported in Pacific Daylight Savings Time, PDT) in knee-deep water. Samples were taken at eight alongshore stations spanning ~4.5 km from BFSP (BF, S1, HT, M, N1, N2, and TJR) to Imperial Beach (station F1). Daily samples, collected at three (HT, TJR, and F1) of eight stations, were analyzed for all constituents. The remaining five stations (BF, S1, M, N1, and N2) were sampled every other day for all variables except Chla. Tide height and phase (ebb vs flood and spring vs neap), water temperature, alongshore currents, and wave height were observed at F1 as part of the IB09 project. HT station was not instrumented due to health risk concerns associated with instrument maintenance in waters impacted by nourishment fines or tidal flushing from TJR.[32−36]

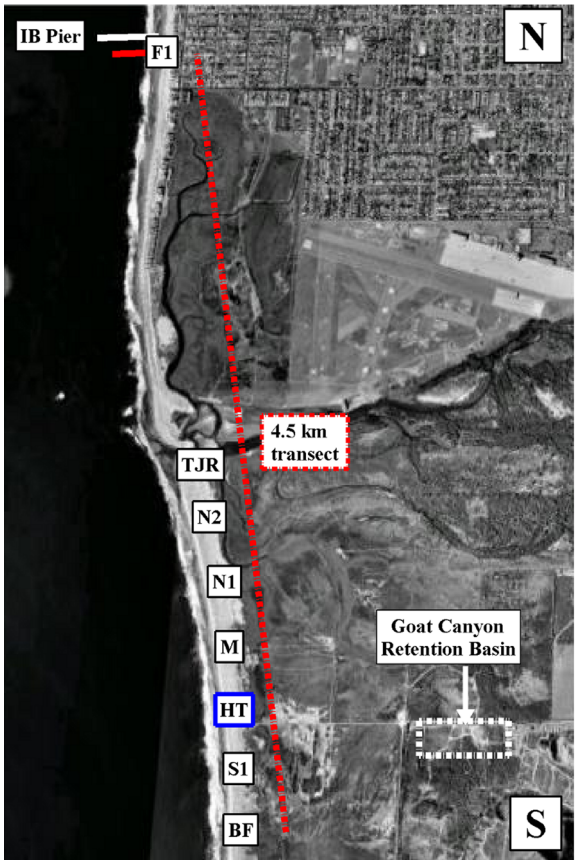

Figure 1. Map of sampling locations along a ~4.5 km transect spanning Border Fields State Park and Imperial Beach (stations BF−F1, labeled white boxes). F1 was located ~200 m south of the Imperial Beach pier (solid white line). *Enterococcus*, nitrate, nitrite, phosphate, ammonium, silicate, sand, and fine sediment concentrations were monitored at all stations. Chlorophyll concentrations were monitored at TJR, HT, and BF. Tides, alongshore current direction, waves, and temperature were measured at F1 and at five additional locations along a 130 m cross-shore transect seaward of F1 (solid red line). Sediments for the beach nourishment at HT (blue box) came from the Goat Canyon retention basin (white dashed box).

Sample Analyses. Water samples were analyzed for enterococci by use of Enterolert (IDEXX Laboratories Inc., Westbrook, ME) within 2 h of collection. Samples for Chla were filtered onto triplicate GF/F filters. Pigments were extracted with 90% acetone for 24 h in the freezer and quantified on a Turner Designs T700 fluorometer. The pheophytin signal was not removed. Water samples for nutrient analyses were frozen within 2 h of collection and shipped to MSI Analytical Laboratories. Concentrations of dissolved silicate, phosphate, nitrite, nitrate + nitrite, and ammonium were measured by flow injection analysis. Water samples for the analysis of fines and sand concentrations were refrigerated and shipped overnight to the USGS PCMSC Sediment Laboratory in Menlo Park, CA. Suspended sediment samples were wet-sieved into sand (>63 μm) and fine (<63 μm) fractions and then dried and weighed.

***Enterococcus* in Nourishment Sediments.** Three samples of nourishment material were collected between 0700 and 0730 on 9/25 and 10/1. To enumerate enterococci, 10 g of sediment/sample was suspended in 100 mL of ultrapure water

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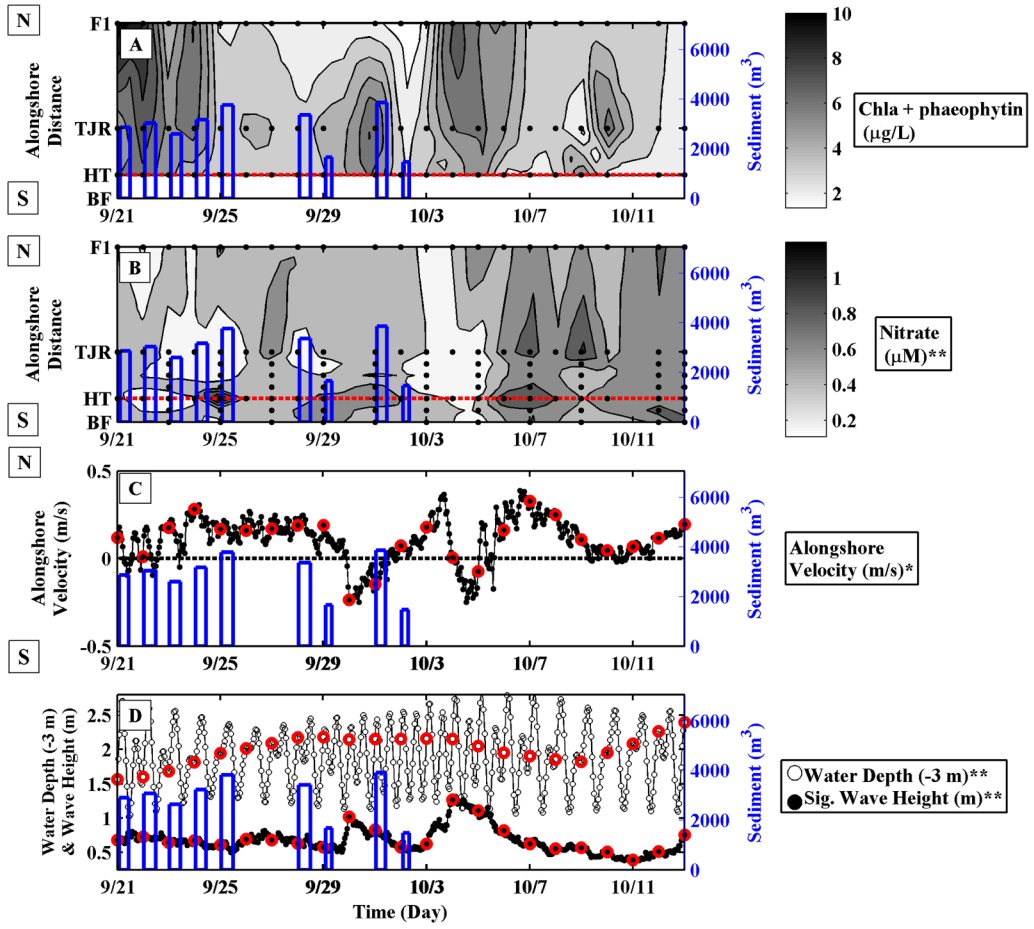

Figure 2. (A) Concentration vs time (*x*-axis) and alongshore sampling location (left *y*-axis) of chlorophyll a (Chl a, micrograms per liter). (B–D) All parameters significantly correlated with Chla at the (*) $p < 0.05$ or (**) $p < 0.01$ level: (B) nitrate (micromolar), and timeseries of (C) cross-shore averaged alongshore velocity (meters per second; positive is northward) and (D) adjusted water depth or significant wave height (meters). In panels A and B black dots mark data collection times and locations, and a red dotted line delineates the beach nourishment location (HT). In panels C and D, red circles mark parameter magnitudes for the collection times shown in panels A and B. Blue bars indicate the timing and volume (right *y*-axis) of individual nourishment events.

(Milli-Q; Millipore Corp., Billerica, MA), shaken by hand for 2 min to dislodge bacteria, and allowed to settle for 1 min. The supernatant was collected and analyzed for enterococci by use of Enterolert (IDEXX Laboratories Inc., Westbrook, ME). Additional biochemical analyses were performed to evaluate the accuracy of the Enterolert assay in sediments. For methodological details and discussion, see Supporting Information.

Water Quality Assessment: Correlations and Predictive Statistical Models. Two methods were used to identify parameters related to enterococci or Chla at BFSP. First, direct correlations between all measured parameters were assessed. Because data distributions were non-normal, correlation was evaluated by use of Spearman's rank (ρ). The correlation significance was determined via bootstrap methods. Data were sampled with replacement 100 000 times, ρ was estimated for each new data set, and 95% bias-corrected bootstrap confidence intervals (CIs) were calculated. When ρ of 0 fell outside those 95% CIs, correlations were determined to be significant ($p \leq 0.05$).

Because alongshore velocity, wave height, and temperature tend to be coherent over kilometer scales, the measurements made at F1 should be representative of our entire study region.[39−41] However, some variability in physical parameters could exist, particularly for alongshore velocity, which can be sensitive to coastal discontinuities. Given that F1 was separated from HT by a river outlet and a bend in the coastline, correlations between FIB or Chla and alongshore velocity should be interpreted with care. Although direct correlations between all parameters were evaluated by use of Spearman's rank, the decision was made to omit those that were not alongshore-resolved, and could have varied, from GLM analysis (e.g., alongshore velocity, wave height, and temperature).

GLMs, multiple linear regression models that allow for response variables with non-normal distributions, were also used to identify significant predictors of enterococci or Chla. Chla measurements were modeled as a γ distribution with a log link.[42] Enterococci concentrations were modeled as present or absent by use of a binomial GLM with a logit link. Presence was defined as ≥10 most probable number (MPN)·(100 mL)$^{-1}$ and absence as <10 MPN·(100 mL)$^{-1}$ of seawater. GLM methodological details can be found in Supporting Information.

Surf-Zone Residence Time of *Enterococcus*. On 9/26, 9/27, 9/29, and 10/1, surf-zone concentrations of enterococci were monitored at HT every 30 min for 4 h. All monitoring was done either during or after sediment placements ≥1713 m^3. Concentrations of enterococci were averaged over each 4 h sampling event to smooth out short-term FIB variability from the overall decay signal.[43] Average FIB values were evaluated

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with respect to time since the last nourishment event (TSLNE); defined as the time lapsed (in hours) between the most recent sediment placement and the midpoint of a 4 h sampling event. If an entire sampling event occurred during a single sediment placement, TSLNE = 0. Least-squares curve fitting was used to estimate residence time from averaged FIB and TSLNE data. These residence times reflect bacterial loss from both physical transport and inactivation (mortality + loss via the induction of a viable but not culturable state). Microcosm experiments, discussed below, were used to quantify the inactivation component directly.

***Enterococcus* Inactivation.** *Microcosm Experiments.* Inactivation rates of nourishment-associated enterococci were evaluated on 10/1 by use of 22 250-mL seawater microcosms, mounted ∼1 m underwater on a floating platform (drifting *Enterococcus* mortality platform, DrEMP) (Figure S1, Supporting Information). The fused-silica microcosms allow the penetration of bactericidal UV wavelengths and the visible spectrum.[44,45] Half the microcosms were enclosed in black plastic, eliminating light penetration. We compared *Enterococcus* loss in covered and uncovered microcosms to assess the contribution of solar radiation to the inactivation of nourishment-associated enterococci. To quantify solar radiation, DrEMP was equipped with a PAR sensor (Alec Electronics MDS-MKV/L, 360−690 nm, JFE Advantech Co., Ltd.). Similar sensors were deployed postnourishment (10/3 and 10/30) to evaluate surf-zone solar penetration in the absence of the sediment plume.

Microcosm Sample Collection. On 10/1, sediment was placed at HT station between 0700 and 1700. At 0735, a 5 L surf-zone sample containing suspended nourishment sediments and seawater was collected, shaken, and distributed into DrEMP's microcosms. By 0755, DrEMP was moored offshore of HT, shoreward of breaking waves. The first microcosms (one light and one dark) were removed and placed on ice at 0800. Subsequent sample pairs were taken every 30 min for 5 h. All samples were analyzed for concentrations of enterococci within 6 h of collection, by use of IDEXX Enterolert.

RESULTS AND DISCUSSION

Physical Environment. The cross-shore-averaged alongshore current at Imperial Beach (F1) was predominantly northward (reflecting south swell conditions) and was southward only briefly (Figure 2C). Maximum southward and northward alongshore velocities were 0.25 and 0.39 ms^{-1}, respectively (Figure 2C). Two-thirds of the sediment placements performed during our study occurred when alongshore currents were northward, potentially transporting these sediments (and contaminants) toward Imperial Beach. Southward velocities on 10/1 and 10/5 coincided with peaks in significant wave height (Figure 2C,D). Average significant wave height at Imperial Beach was ∼0.7 m (Figure 2D).

Cross-shore-averaged water temperature exhibited strong daily fluctuations and overall decreasing temperatures. Averaged over all stations and times, water temperature was ∼18 °C (max 21 °C, min 16.2 °C). Most sediment placements occurred during the warmer half of the study, prior to 9/29 (Figure S2A, Supporting Information). Placements occurred both on neap and spring tides (Figure 2D).

Water Quality Assessment: *Enterococcus*. *Spatial−Temporal Patterns.* Surf-zone concentrations of *Enterococcus* ranged from 0 to 257 MPN·(100 mL)$^{-1}$, with all measurements >35 MPN·(100 mL)$^{-1}$ (the geometric mean standard for enterococci) observed at the nourishment site HT (Figure 3A). Water samples at nearby beach locations (300 m north or south of the nourishment) were always below this standard (Figure 3A). *Enterococcus* levels were elevated during the first half of the study (when sediment was being placed) and dropped to near-zero levels when placements ended (10/2; Figure 3A). Two discrete pulses of FIB were observed, a strong pulse (9/22−9/25), and a secondary, weaker pulse (9/29−10/1; Figure 3A).

Enterococcus concentrations measured at the Tijuana River [TJR; < 35 MPN·(100 mL)$^{-1}$] were low relative to concentrations measured at the nourishment site [HT; 35−257 MPN·(100 mL)$^{-1}$] and those reported at the river mouth following winter rains [2005−12 000 MPN·(100 mL)$^{-1}$].[32] This suggests that, during low-flow conditions, TJR is not a source of *Enterococcus* contamination to neighboring beaches.

Parameter Correlations. *Enterococcus* concentrations were significantly and positively correlated with fines (0.35), silicate (0.31), and phosphate (0.22) concentrations at BFSP ($p < 0.05$) (Figure 3; Table S1, Supporting Information). They were uncorrelated with tide height (0.03), tide phase (ebb/flood, −0.09, or spring/neap, −0.11), wave height (0.19), alongshore current direction (−0.12), or water temperature (−0.04; Table S1, Supporting Information), all of which have been associated with bacterial contamination at other California beaches.[46−50] This could indicate that measured physical dynamics (F1) are not representative of dynamics at southern stations. However, the majority of these parameters are coherent over large spatial scales, making it probable that the lack of correlation observed points to alternate drivers controlling FIB dynamics.

FIB and fines were both maximum at the beach nourishment site (HT), were elevated during the nourishment (first half of the study), and occurred in two pulses, the second of which was weaker (Figure 3A,B). This two-pulse pattern mimics the sediment placement schedule; the total volume of the first cluster of five placements was ∼40% larger than the second cluster (hence the stronger first FIB pulse), and no sediments were placed from 9/26 to 9/27, coincident with the gap between FIB pulses (Figure 3A,B). Surf-zone fines and *Enterococcus* concentrations are clearly linked to sediment resuspension from the beach nourishment.

From 9/21 to 9/25, spatial distributions of silicate and phosphate also tracked fines, suggesting that these nutrients (like enterococci) may have been associated with sediment resuspension from the beach nourishment (Figure 3C,D). However, elevated nutrient levels were observed after the nourishment when concentrations of FIB and fines were low, suggesting that surf-zone nutrient concentrations were not controlled by sediment resuspension alone (Figure 3C,D). Alternative controls are addressed in Supporting Information.

GLM Analyses of Enterococcus. GLM analysis indicates that fines were the single best parameter for predicting *Enterococcus* presence/absence at BFSP ($p < 0.01$) (Table S2, Supporting Information). The inclusion of additional parameters, even correlated ones such as silicate or phosphate, did not significantly improve model−data fits. This indicates that these parameters do not contain explanatory information for FIB beyond what is covered by fines. GLMs by design incorporate only variables that significantly increase model predictive power.

Goodness-of-fit for the best-fit model was calculated as percent deviance explained (% DE), where % DE is equivalent to R^2 for normally distributed data.[51] Over all stations the model performance was poor, with only 9.7% DE (Table S2, Supporting Information). However, the model performed well at the nourishment site HT (HT, 0 m, 45.0 % DE) and

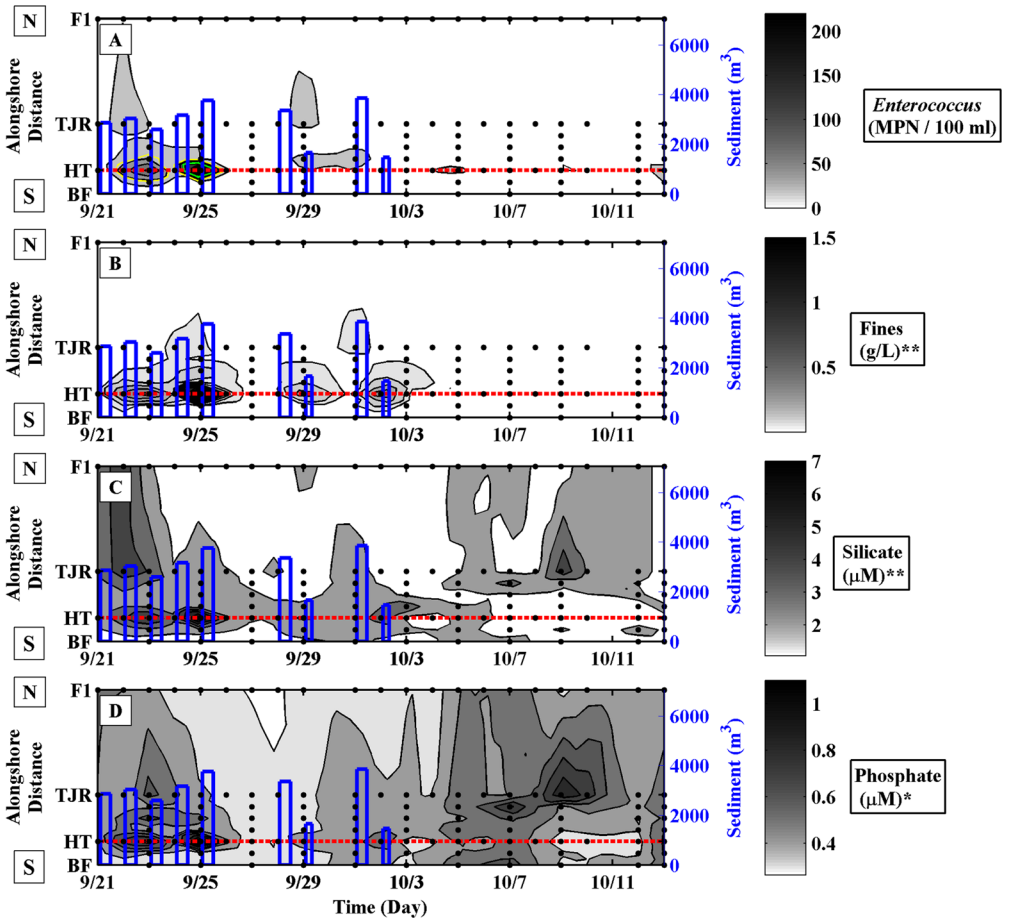

Figure 3. (A) Concentration (color units are log scale) vs time (x-axis) and alongshore sampling location (left y-axis) of Enterococcus [most probable number (MPN) per 100 mL]. (B–D) All parameters significantly correlated with *Enterococcus* at the (*) $p < 0.05$ or (**) $p < 0.01$ level: (B) fine sediment (grams per liter), (C) silicate (micromolar), and (D) phosphate (micromolar). The EPA single-sample standard (green) and geometric mean standard (yellow) for *Enterococcus* are noted in panel A. Black dots mark data collection times and locations for all parameters. The beach nourishment location (HT) and individual nourishment events are indicated as in Figure 2.

worsened with increasing distance from the nourishment (TJR, 1280 m, 4.2% DE; and F1, 4260 m, 1.9% DE) (Figure S3, Supporting Information). This pattern may reflect dissociation between enterococci and fines over time/distance, with FIB persistence increasingly controlled by processes other than transport (e.g., predation and solar inactivation). Alternatively, other FIB sources (bird feces, beach wrack,[46] or northward surf-zone transport of discharge from unsewered communities[32]) could have been present at BFSP, changing the correlation between FIB and fines at stations beyond HT. Multisource beaches may pose a challenge for GLM implementation, as signals from low-frequency or ephemeral FIB sources (however contaminated) are easily swamped by more dominant sources.

Water Quality Assessment: Phytoplankton/Chlorophyll a. *Spatial–Temporal Patterns in Chla.* Surf-zone Chla concentrations ranged from 2 to 10 μM. High-concentration Chla peaks were observed both during and after nourishment. Some peaks were localized at TJR (10/10; Figure 2A) and others co-occurred at several sites (9/22–24, 10/1, 10/5; Figure 2A). Alongshore-parallel bands of Chla are common in the nearshore and can be caused by vertical mixing of subsurface phytoplankton blooms via internal wave breaking,[52] alongshore transport/mixing of localized blooms by wind- and wave-driven currents,[53,54] and point/nonpoint source release of nutrients coupled with mixing and alongshore transport.[55,56]

Parameter Correlations. Chla concentrations were inversely correlated with surf-zone nitrate concentrations (−0.41) and tide height (−0.41) and positively correlated with wave height (0.43) ($p < 0.01$; Figure 2; Table S1, Supporting Information). Chla was also correlated with alongshore water velocity (−0.28): low Chla levels (2–4 μM) were observed during strong northward flows (>0.2 ms^{-1}) and high Chla levels (4–10 μM) during southward or weak northward (<0.2 ms^{-1}) flows ($p < 0.05$) (Figure 2; Table S1, Supporting Information). The inverse relationship detected between nitrate and Chla is consistent with phytoplankton uptake of nitrate in a given water mass.[57−59] Together, this inverse correlation with nitrate and the positive correlation between Chla and physical processes (alongshore current direction, wave, and tide height) suggest that phytoplankton patterns may have been driven by episodic alongshore transport of phytoplankton-rich/nutrient-poor waters. Note that transport on 10/1 and 10/5 may have been linked to elevated wave energy from the north that resulted in southward alongshore currents (Figure 2C,D).

Chla concentrations were uncorrelated with fines (0.24), tide phase (spring/neap, −0.02, or ebb/flood, 0.16), temperature (0.05), or any of the four additional inorganic nutrients measured (silicate, 0.25; phosphate, 0.13; nitrite, −0.06; and ammonium, −0.15; Table S1, Supporting Information). Phytoplankton growth may have been nitrogen-limited, as the surf-zone nitrogen to

phosphorus (N:P) ratio at BFSP was consistently <16, the Redfield ratio.[60−62] We conclude that fine-grained nourishment sediments did not stimulate local phytoplankton blooms, perhaps because the fines were phosphate-enriched and poor in nitrogen (nitrate, nitrite or ammonium) (Figure 3; Table S1, Supporting Information).

GLM Analyses of Chla. Two best-fit predictive models for Chla concentrations were identified. Both included nitrate and tide height, and one model included an additional nitrate/tide height (N:TH) interaction term (note that alongshore currents were excluded from these analyses) (Table S3, Supporting Information). The % DE for both best-fit Chla models over the entire sampling domain was ∼35% (Table S3, Supporting Information). Model performance was spatially variable, however, with lower model fits for northern stations (TJR and F1) than southern stations (HT) (at TJR and F1, avg ∼33.08% DE; at HT, avg 44.89% DE) (Figure S4, Supporting Information). This spatial variability was less extreme than observed for *Enterococcus* models and may reflect the separation of northern and southern alongshore stations by the river outlet/sand bar system (Figure 1). This separation could cause different phytoplankton dynamics alongshore that would not be captured by GLM methods because they assume spatially homogeneous correlations between parameters. The spatially variable GLM performance observed for both FIB and phytoplankton at BFSP suggests that, in practice, predictive statistical models may prove difficult to implement in isolation for dynamic systems like the surf zone.

Sediment *Enterococcus* Source. Direct correlation and GLM analyses suggest that fine-grained nourishment sediments do not stimulate phytoplankton blooms but do elevate surf-zone FIB loads. This inference is consistent with the *Enterococcus* concentrations measured in nourishment sediments, which ranged from 117 to 51 486 MPN·(100 g)$^{-1}$ of sediment (Figure S5, Supporting Information). Maximum measured *Enterococcus* concentrations in nourishment sediments were higher than observed in sediments at other temperate beaches in California [8−7200 colony-forming units (CFU)·(100 g)$^{-1}$][16] but within levels reported for urban-impacted wetland sediments [2000−136 000 CFU (100 g)$^{-1}$].[8] Thus, Goat Canyon sediments are contaminated relative to California beach sands but are typical of urban estuarine material.

Sediment-associated *Enterococcus* concentrations varied between days and among placements in a day (Figure S5, Supporting Information). Patchy FIB distributions in nourishment sediments (in addition to variability associated with changing tides and waves) could have resulted in variable FIB loading at BFSP. This could have contributed to the low overall performance of our best-fit GLM for *Enterococcus*, as the relationship between the predictor (fines) and response variable (*Enterococcus*) was unstable.

Surf-Zone Residence Time: *Enterococcus*. Elevated *Enterococcus* concentrations were observed at station HT during the sediment placement on 10/1. The average FIB level, 141 MPN·(100 mL)$^{-1}$, exceeded the EPA single-sample standard for enterococci [104 MPN·(100 mL)$^{-1}$] (Figure 4). Temporal FIB decay was well described by an exponential:

$$C_t = C_0 e^{-k_s t} \quad (1)$$

where t is time, C_t is the concentration of *Enterococcus* at time t, C_0 is the starting concentration of *Enterococcus*, and k_s is the rate of *Enterococcus* loss from the study area, 0.24 h^{-1} (Figure 4). Surf-zone FIB concentrations decayed rapidly: below EPA single-sample standards in ∼1.3 h, below geometric mean standards (35 MPN·(100 mL)$^{-1}$] in ∼5.8 h, and barely detectable in 23 h [average 1 MPN·(100 mL)$^{-1}$] (Figure 4).

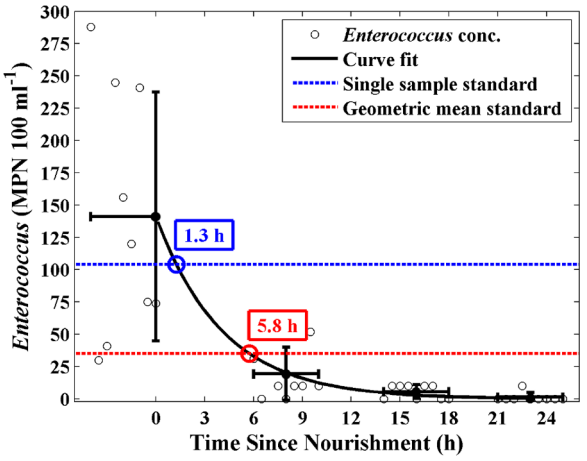

Figure 4. Four-hour average *Enterococcus* concentration [most probable number (MPN) per 100 mL] at HT (●) vs time since the last nourishment event (hours, *x*-axis). Horizontal spread bars indicate the 4-h time window over which FIB concentrations were averaged. Vertical spread bars are 1 standard deviation about the average FIB concentration. (○) Raw *Enterococcus* data. The first 4 h average is at t = 0 h (during a nourishment event). *Enterococcus* decay was exponential with decay rate k_s = 0.24 h^{-1} (eq 1; curve-fit marked by solid black line). *Enterococcus* concentrations fell below EPA single-sample (blue) and geometric (red) standards at 1.3 and 5.8 h, respectively.

The short residence time of surf-zone FIB suggests that the effects of nourishment sediments on local water quality are ephemeral, likely due to both advection of enterococci out of the system and biological inactivation.[63] If advection is the dominant source of removal, then the rapid FIB loss observed cannot be equated with ephemeral health risk because the pollutant plume may impact beaches north or south of the nourishment location. If inactivation is the dominant source of removal, however, then the health risk associated with Goat Canyon sediments may be short-term. The contribution of inactivation to surf-zone *Enterococcus* loss at BFSP is evaluated in the next section.

***Enterococcus* Inactivation: Microcosm Experiments.** Our microcosm experiments showed rapid inactivation of nourishment-associated *Enterococcus* during the first 0.5 h of sampling. Following these declines, *Enterococcus* concentrations were stable for 4.5 h (Figure 5a). This pattern is consistent with an asymptotic exponential model of the form

$$C_t = C_0 a + C_0\{1 - a\}e^{-k_s t} \quad (2)$$

where t is time, C_t is the concentration of *Enterococcus* at time t, C_0 is the starting concentration of *Enterococcus*, a is the fraction of *Enterococcus* that are resistant to inactivation, and k_s is the inactivation rate of the sensitive fraction. Simple exponential and biphasic models were also explored. The asymptotic exponential form in eq 2 was chosen because it provided the best model−data fits with the fewest free parameters (Table S4, Supporting Information).

Approximately 60% of nourishment-associated enterococci exhibited rapid seawater inactivation in both dark and light microcosm treatments (k_s = 3.1 and 4.8 h^{-1}, respectively); the remainder were resistant to inactivation (Figure 5A).

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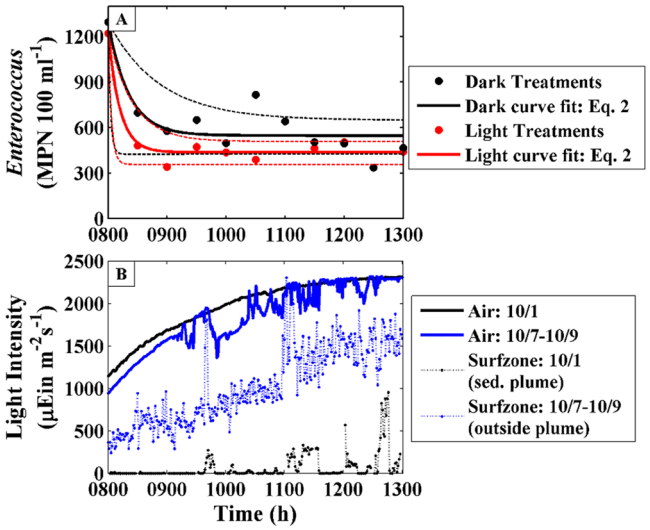

Figure 5. (A) *Enterococcus* concentration [most probable number (MPN) per 100 mL] vs time (hours, *x*-axis) in dark (black) and light (red) microcosm treatments on 10/1. *Enterococcus* inactivation was modeled as an asymptotic exponential (eq 2; Table S4, Supporting Information). Model parameters were estimated in R by use of maximum likelihood statistics and the statistical routine *nls*. *Enterococcus* inactivation was not significantly different in light and dark treatments (e.g., overlapping 95% confidence intervals, dashed lines). (B) Solar insolation levels (μEin·m^{2}·s^{-1}) vs time (hours) from 0800 to 1300. Insolation within the sediment plume during microcosm treatments (10/1; black dashed line) is compared to average surf-zone insolation levels when the plume is absent (blue dashed line) for days with similar light intensities (black, light intensity 10/1; blue, average intensity on alternate days). Note the reduced insolation levels on 10/1 within the plume.

The sensitive and resistant FIB fractions observed may have consisted of different *Enterococcus* species (or species groups) with distinct seawater inactivation rates.[64,65] Alternatively, the sensitive fraction may have been composed of previously damaged and/or stressed cells, explaining its rapid decay relative to the resistant fraction.

The inactivation rates of our sensitive fraction exceeded reported ranges (0.001−1.0 h^{-1}),[13,63,65] possibly reflecting enhanced sensitivity of sediment-associated enterococci to environmental variables such as salinity, temperature, and pH.[66] Solar radiation was probably not a major contributor, however, as FIB inactivation in dark microcosm treatments was not significantly different than light treatments ($p < 0.05$) (Figure 5A). This finding may reflect the shading of experimental microcosms by the sediment plume. Surf-zone solar insolation levels within the plume were low on average (67.54 μEin·m^{-2}·s^{-1}) despite it being a sunny day (avg insolation in air, 1842.99 μEin·m^{-2}·s^{-1}) (Figure 5B). On days with similar light intensities (but no sediment plume), average surf-zone insolation was over an order of magnitude higher (1031.75 μEin·m^{-2}·s^{-1}) (Figure 5B). This suggests that, in addition to being a source of enterococci to the surf zone, nourishment sediments may provide FIB with solar protection, eliminating a dominant source of FIB mortality.[13,67,68]

The rapid decay of sensitive FIB, leaving behind a resistant community, suggests that initial rates of surf-zone FIB loss may be faster than implied by the simple exponential fit in our residence-time analyses (~3.95 vs 0.24 h^{-1}) (Figures 4 and 5A). This discrepancy may be due to the low temporal resolution of our residence-time field sampling, which masked changes in inactivation rates. Further comparison of these two methods shows that while *Enterococcus* concentrations stabilized in our microcosms (Figure 5A), they continued to decline in the surf zone (Figure 4), pointing to physical transport and dilution as a source of loss.

Taken together, our residence-time and microcosm studies suggest that both inactivation and dilution/advection contribute to surf-zone FIB loss at BFSP. Specifically, sensitive FIB (~60% of the population) appear to be inactivated within 1 h, with subsequent losses driven by physical forcing. This suggests that the majority of nourishment-associated FIB will be inactivated before they can be transported to other beaches. However, we cannot rule out the possibility that nourishment fines could impact long-term surf zone water quality beyond the ~1 month duration of our study. Beach wrack and sands can harbor FIB, with persistent strains exhibiting environmental regrowth.[8,14,17] This could result in recontamination of the surf zone later in the year by processes like storm-associated sediment resuspension.[17] Longer term studies are called for to evaluate this possibility. Furthermore, because FIB are mostly indicators, not pathogens, future studies assessing beach nourishment health risk should be expanded to include screening for human pathogens and quantification of pathogen survivorship in the nearshore.

■ ASSOCIATED CONTENT

Supporting Information

Additional text, five figures, and five tables. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: mrippy@ucsd.edu; Phone: (831)-419-5285.

Notes

The authors declare no competing financial interest.

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