AN ASBPA WHITE PAPER:

The state of understanding of the effects of beach nourishment activities on coastal biogeochemical processes and conditions

Science and Technology Committee, August 2019

By

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ABSTRACT

Sandy beaches are sites of significant exchange of matter and energy between water and sediment. This rapid exchange is attributed to the high permeability of sandy deposits and is one of the key ingredients in understanding how a given beach will respond to a nourishment event as a habitat for many important organisms. The response is driven by fundamental abiotically and biotically mediated chemical reactions that are profoundly affected by the ability of chemicals to accumulate or to be flushed out of a sandy column in the beach substrate. So while attention has correctly been paid to the effects of nourishment projects on infaunal communities and the upper levels of the food web, the chemical reactions connecting physics and geology on the one hand and ecology on the other are treated as a black box. We synthesize existing findings on biogeochemical processes at source areas and renourished beaches before, during, and after nourishment activities, and identify gaps in knowledge. Among other processes, we highlight how the exposure of reduced sediment to an oxic water column can initially increase oxygen demand, fuel microbial primary productivity, and drive the mobilization of potentially harmful contaminants. Restoration of oxic conditions in surficial sands can proceed rapidly through rapid exchange between sand and the oxygenated water column under the influence of physical forces, such as waves and currents, and high sand permeability. Based on our findings, we recommend foci for research, outreach, and broader impacts in this field as well as discuss coastal management needs for policy makers, planners, contractors, and the public to encourage information sharing.

ADDITIONAL KEYWORDS: Beach nourishment; biogeochemistry; sandy sediments; beach sediments; coastal processes.

Beaches are a unique geological feature that exists as a narrow strip of sand along the edge of land where it meets water. They are most prominent along ocean shorelines, where they are arguably the main direct interaction space of most humans with the ocean, whether it is for temporary recreation or permanent habitation. Their economic value can hardly be overstated. Houston (2018) estimated that U.S. beaches contributed $285 billion annually (in 2017 dollars) to the national economy. The billions of daily visitors to beaches every year (2.3 billion estimated in 2017) account for coastal states receiving 85% of annual tourism-related revenues in the U.S. (Houston 2018).

From an environmental standpoint, beaches provide significant services of benefit to coastal ecosystems and to human societies inhabiting them. They are biologically rich and diverse, as habitat for land-dwelling animals and birds, coastal waterbirds that use beaches both for nesting and feeding, a wide range of invertibrates including various aquatic worms and shellfish, and many species of fish and dolphins that often feed in shallow nearshore waters of the submerged portion of the beachface (McLachlan and Brown 2006). Beaches provide significant levels of storm protection in areas where they are naturally wide with healthy dunes or are properly maintained (Armstrong and Lazarus 2019). Sands on beaches can act as biofilters, constantly exchanging matter and energy with the water column under the force of waves, currents and tides (Boudreau *et al.* 2001), and processing large volumes of ground water being released into the near shore area on each tidal cycle (Robinson *et al.* 2007). Matter — both particulate and dissolved, from land and ocean — that would otherwise be harmful can be intercepted, immobilized and/or transformed, temporarily shielding the much more dynamic water column and fueling a productive food web that in its apex can sustain endangered shorebirds, among others (Rosov *et al.* 2016).

The beach restoration process

The economic importance of beaches has driven preservation efforts in places where beaches are eroding, most commonly through periodic nourishment/renourishment projects. The beach nourishment and renourishment processes and their effects are the focus of this paper. According to the ASBPA (2018) National Beach Nourishment Database, from the 1920s through May 2018, more than 818 miles of beaches were restored using in excess of 1.5 billion cubic yards of material. The total cost of these projects is estimated at $6.1 billion, underscoring on the one hand the economic importance of attractive beaches and on the other hand the underfunded and reactive nature of these projects, when considering their significant returns to the economy (Houston 2018).

A beach nourishment project is a coastal engineering project, designed for the unique conditions of the coastal

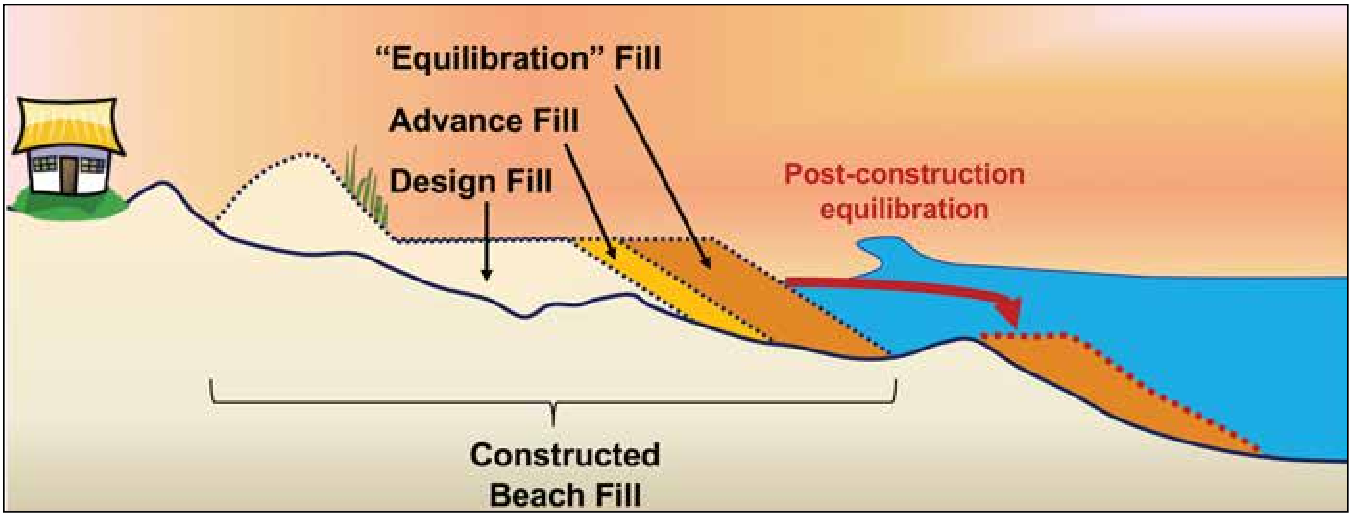


Figure 1. Beach profile illustrating the beach "fill" during a nourishment project (modified from Willson *et al.* 2017). The seaward segment of the fill, the "equilibration" fill, is expected to adjust to a flatter slope soon after the project to fill the closure depth of the beach, beyond which little change occurs (15-25 ft beneath the surface and seaward of where most natural littoral sand movement occurs). The advance fill accounts for long-term erosion, and when it fully erodes renourishment activities may commence.

stretch under consideration, and generally follows a set of key principles outlined elsewhere (U.S. Army Corps of Engineers 2007; Willson *et al.* 2017) and briefly summarized here. A "borrow source" of sand is selected, considering grain size distribution, composition and appearance, with the intent of making the source as practically similar to the native sand in composition (carbonate vs. quartz), grain size distribution, and color. This source can either be offshore, nearshore (inlet shoals or navigation channels), or upland sand mines. Of the 210 million cubic yards dredged dredged from U.S. navigation channels annually, 10 million cubic yards of sand are placed on adjacent sandy beaches (U.S. Army Corps of Engineers 2018). With the recognition of the value of beach sand and beach preservation, sand dredged from inlets is invariably and increasingly used to nourish beaches.

The preferred and generally most logistically economic method of nourishment, for delivering large volumes of sand in a short period of time, is to have pipelines transport a slurry of sand and water from source to deposition site. Trucks can be used in the case where the most viable and nearby source is upland. At the deposition location, bulldozers are used to redistribute the deposited sand to form a beach "fill" which typically includes a restored dune and berm (Figure 1). As shaping the beach slope underwater is economically impractical, beaches are typically constructed with a steep waterward slope and natural processes reshape that part of the beach. In longer time frames, the time needed for a beach to erode to a predetermined minimum design beach width is referred to as the renourishment interval, which determines when restoration activities should be repeated through a renourishment project.

The geotechnical investigation, which precedes the renourishment process, typically involves extensive bathymetric, seismic, sidescan, and magnetometer surveys, as well as vibracore samples. These surveys and samples allow for the identification of an uncontaminated borrow source of adequate sediment thickness, grain size, and composition that are similar to the native beach — all factors that are relevant to the physical performance of the nourished beach (Dean 2002).

Environmental considerations are also important in the process of borrow source identification. For example, the color of beach sand is regulated (e.g. Florida Administrative Code, Chapter 62B-41.007) due to potential impacts on sea turtle nesting with darker or lighter sand. Incubation temperatures of the sand, which are affected by sand color, determine the gender of hatchlings. Sand deposits may also be found in proximity to sea grass beds, offshore reefs, emergent shoals that are critical coastal waterbird habitat, or other environmentally sensitive resources. These are all considered during the permitting process so that projects as finally approved will eliminate or at least minimize environmental impacts, and sometimes require mitigation for impacts that are unavoidable.

State and federal permits are required for non-federal beach nourishment projects. For federal beach projects, the National Environmental Policy Act (NEPA) of 1970 requires federal agencies to assess the environmental effects of their proposed actions prior to making decisions. Consultations with the U.S. Fish and Wildlife Service and NOAA's National Marine Fisheries Service at a minimum are required for beach projects. Detailed Environmental Impact Statements that consider project implications for marine mammals, fish and essential fish habitat, infaunal invertebrates and the taxa that prey on them (U.S. Army Corps of Engineers 2015), coastal birds, and other environmental resources are the outcome of the NEPA process.

The geological characteristics of sand used in nourishment projects are also connected with animal communities by geochemical and microbiological properties and processes. This biogeochemical component has generally been treated as a black box during the nourishment process, and many of the key properties have not been characterized, identified, or monitored explicitly. As the Nearshore Processes Community (2015) pointed out, an interdisciplinary understanding of "how materials are biologically and chemically regulated in the nearshore" is necessary in order to properly evaluate coastal health and risks and to plan for

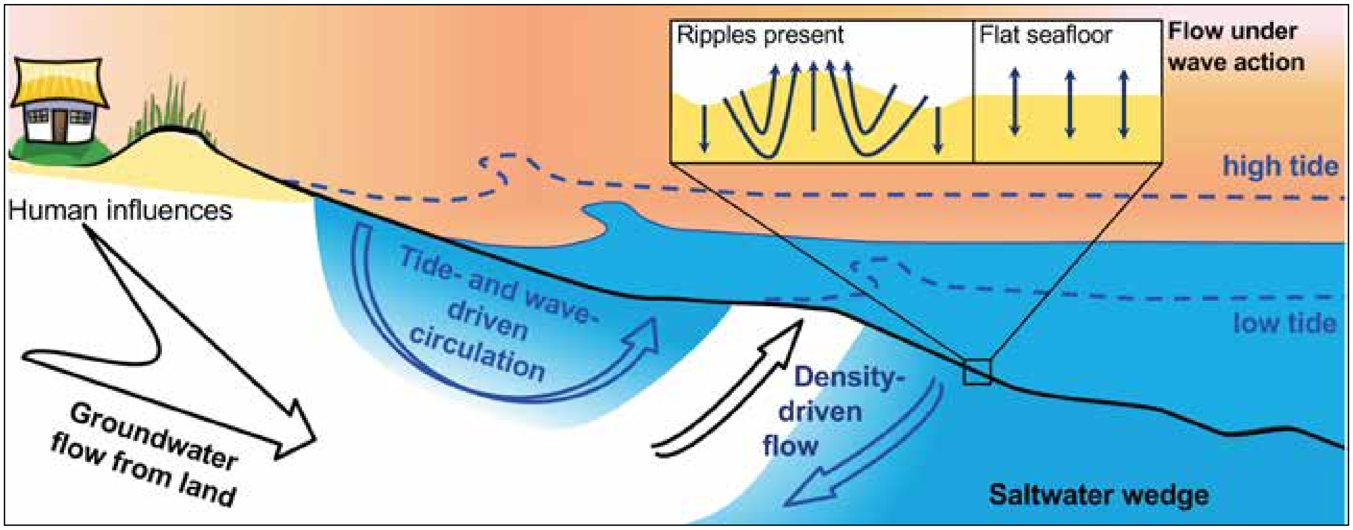


Figure 2. Features and associated processes controlling the exchange of matter across the sand-water boundary, based on the reviews in Huettel and Webster (2001), Robinson *et al.* (2007) and Santos *et al.* (2012a). Note that groundwater inputs are influenced by human activities such as fertilizer applications, sewage storage in septic tanks, etc., similar to surface water inputs through rivers and creeks.

improved coastal resilience in the future. Therefore, there is a need to address the gap in knowledge and understanding of biogeochemical changes that take place during beach nourishment projects, which in the past has not often been considered.

Goals of this white paper

This white paper aims to be the springboard for a community effort to understand and evaluate biogeochemical aspects of beach nourishment projects. As such, it has two major goals.

The first goal is a synthesis of currently available information on our understanding, or lack thereof, of biogeochemistry at (re-)nourished beaches throughout the erosion-enrichment cycle and at sand borrow areas (herein reffered to as source areas), whether offshore, nearshore, or upland.

The second goal is the compilation of a list of recommendations to stakeholders to help stir the community effort. A first set of recommendations and next steps are directed towards the nearshore/coastal processes research community. They indicate suggested research directions, with consideration to the provisions of the National Integrated Implementation Plan (USCRP 2016). The second set of recommendations is addressed to policy makers and other stakeholders, such as project sponsors, contractors, planners, and the public. It covers suggested steps in collecting and disseminating new knowledge on biogeochemical conditions and processes not currently considered during beach nourishment projects, and evaluating their impacts on practices and policy.

SAND BIOGEOCHEMISTRY: AN OVERVIEW

A brief but comprehensive review of what we know about sand and how it operates as a natural medium from an Earth-science perspective is necessary if we are to explore how the biogeochemistry of sand may be impacted by nourishment activities. We present such a review in this section, without an exhaustive evaluation of the subject nor of all the literature on the topic, but rather relying on syntheses and key publications. We focus on the coastal zone and the nearshore zone and highlight the key processes — with their relevant spatial and temporal scales — that will come to bear in our discussion later in this document. The reader is referred to the publications cited herein for more information.

Geological and physical considerations

Sandy shores and the nearby shelf are typically exposed to strong physical forces, such as waves, currents, and tides. These forces do not simply suspend particles from the sand surface and transport them in ways that alter shoreline and nearshore geomorphology. They also interact with and penetrate the underlying sand column, because of its high permeability, defined as the ability of a fluid to flow through a porous medium. While finer-grained sediments are also permeable, flow is so slow there that transport of dissolved constituents is controlled by the slower process of molecular diffusion. In sandy columns under the influence of moving water driven by a water elevation gradient, or "head" pressure, transport is dominated by actual water flow — or advective flow — between sand and the overlying water. This water flow is responsible for the exchange of water, particles, and solutes across the sand-water boundary, and takes place at various spatial scales, as shown in Figure 2.

The aforementioned physical forces that move water through sand substrates are practically always present, and only vary in their intensity. Therefore, sand permeability is the other major property that determines how much matter is exchanged between the water column and underlying sand. Permeability is estimated based on measurements of hydraulic conductivity, which unfortunately have not been made as frequently as measurements of grain-size statistics. Instead, several studies aimed at developing relationships between grain size statistics and permeability, concluded that (i) the greater the grain size, and (ii) the lower the variation in grain size (i.e. better sorted), the greater the permeability (Figure 3). Therefore, grain size and sorting exert control on the rate of exchange between sand and water through permeability. It should be highlighted that even a small amount of fine particles (that would barely change the mean or median grain size of a sand sample) can fill the pores between sand grains and detectably lower its permeability.

Another critical physical property of sand is surface area. Generally speaking,

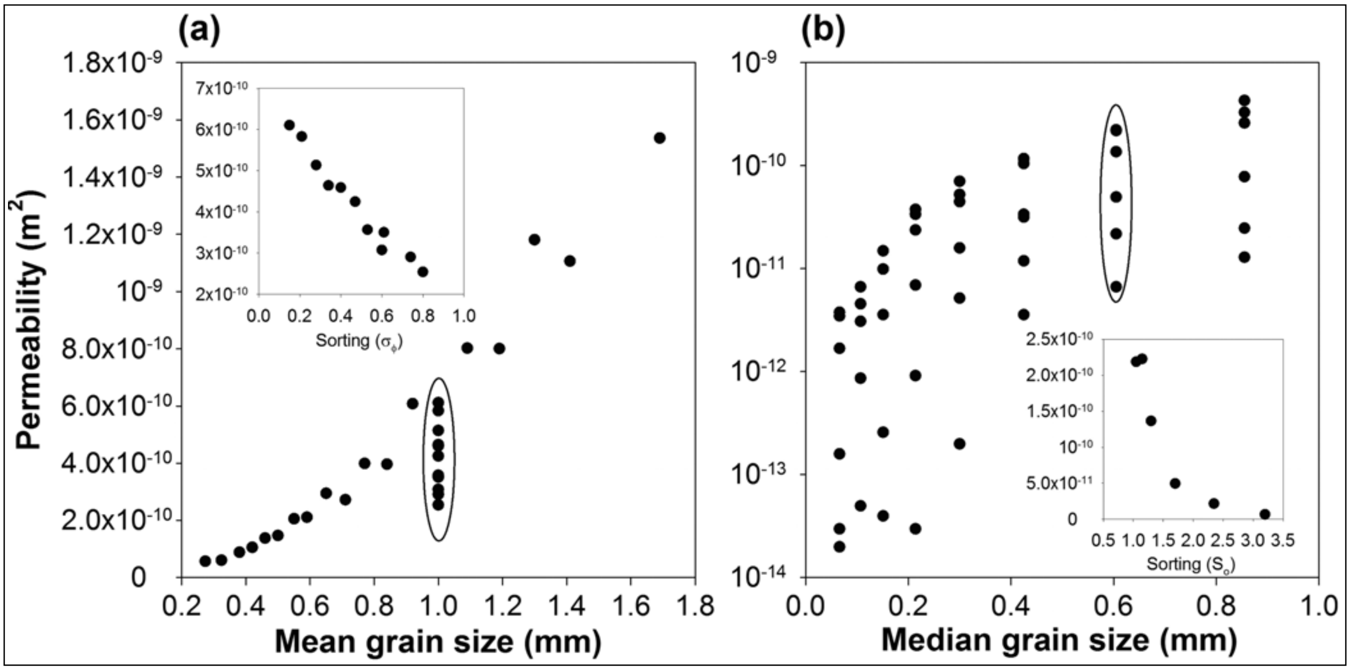


Figure 3. Relationships between grain size and permeability from two classic studies on this topic, (a) Krumbein and Monk (1943) and (b) Beard and Weyl (1973), showing a positive relationship between the two properties. The insets in both cases show the inverse relationship between sorting and permeability in a selected subset of samples (circled) of identical mean or median grain size.

smaller grains have higher surface area per unit of grain volume, therefore finer-grained sands have greater surface area per total unit volume of sand, even when considering the effects of grain sphericity and roundness (Rittenhouse 1943; Powers 1953). Surface area is not only affected by grain size, but also by mineralogical character (or provenance): biogenic carbonate sands are characterized by a variegated surface full of crevasses, pits, and other depressions, compared to the flat surfaces of weathered silicate grains, resulting in a much higher surface area in the former, all other things being equal (Figure 4).

Biogeochemical considerations

The interaction between sand permeability and the physical movement of water above it can have significant implications for the way sand operates as a natural filtration medium, through which water, dissolved constituents and suspended particles pass, are sequestered and modified (Boudreau *et al.* 2001; Rocha 2008). Hence the use of sand filters in a diverse range of engineering applications.

A dramatic manifestation of the role of accelerated exchange in sandy sediments is shown in Figure 5. Oxygen, which is abundant in the atmosphere and surface waters, penetrates orders of magnitude deeper in more permeable sediment. Oxygen is a master-variable and dictates the nature of biotic and abiotic processes that take place in any given setting. The deeper supply of oxygen in more permeable sedimentary columns implies greater availability for microbial aerobic respiration of organic matter, the highest energy-yielding form of respiration, and the oxidation of the chemical products of other suboxic or anaerobic processes (Jørgensen 2006).

Respiration is fueled by organic particles ultimately produced by photosynthesis in well-lit waters and injected into the sand column by the same interaction between sedimentary permeability and physical forcing of the water in which they are suspended. More permeable sand can filter particles at a higher rate, and those particles can, in turn, be respired at a faster rate (Figure 6), in part due to the enhanced supply of oxygen from the overlying water column. Accelerated filtration may also be the underlying reason behind the accumulation and survivability of microbial pathogens in beach sands (Boehm *et al.* 2002; Halliday and Gast 2011).

Respiration of organic matter in marine sediments can proceed aerobically (i.e. using oxygen as an oxidant) or anaerobically (using a suite of alternative oxidants). Common oxidants, in order of decreasing energy yield often referred to as the "redox" (reduction-oxidation) cascade, are nitrate (NO_3^-), oxidized manganese (Mn^{4+}), oxidized iron (Fe^{3+}), and sulfate (SO_4^{3-}), one of the major ions in seawater (Jørgensen 2006). The result is a vertical zonation of these chemicals and their reduced counterparts produced during respiration (Figure 7).

Oxygen (O_2) and sulfate (SO_4^{2-}) depletion zones demarcate oxic and anoxic regions (Figure 7a). Sulfate reduction produces various volatile sulfide compounds, including S^{2-} (shown above), HS^-, and H_2S, that are responsible for the "rotten egg" smell often noticed in excavated "borrow" material during placement at beach nourishment projects. Oxidized manganese and iron (Mn^{4+} and Fe^{3+}, respectively) undergo reduction in the suboxic zone (Figure 7b). Reduced iron, Fe^{2+}, reacts with sulfide to produce iron monosulfide, pyrite, and other Fe-S minerals (Figure 7b), that appear grey-black, in contrast with oxidized iron (Fe) minerals that appear yellow, orange, red or brown. The resulting characteristic transition from oxic to anoxic conditions is visible in a carbonate sand column incubated with oxygenated conditions at the top (Figure 7c). As is the case with many metals, the oxidized Mn and Fe compounds are very surface reactive and are typically found in the colloidal or particulate phase, while their reduced counterparts are dissolved, typically complexed with inorganic and/or organic ligands, and therefore more

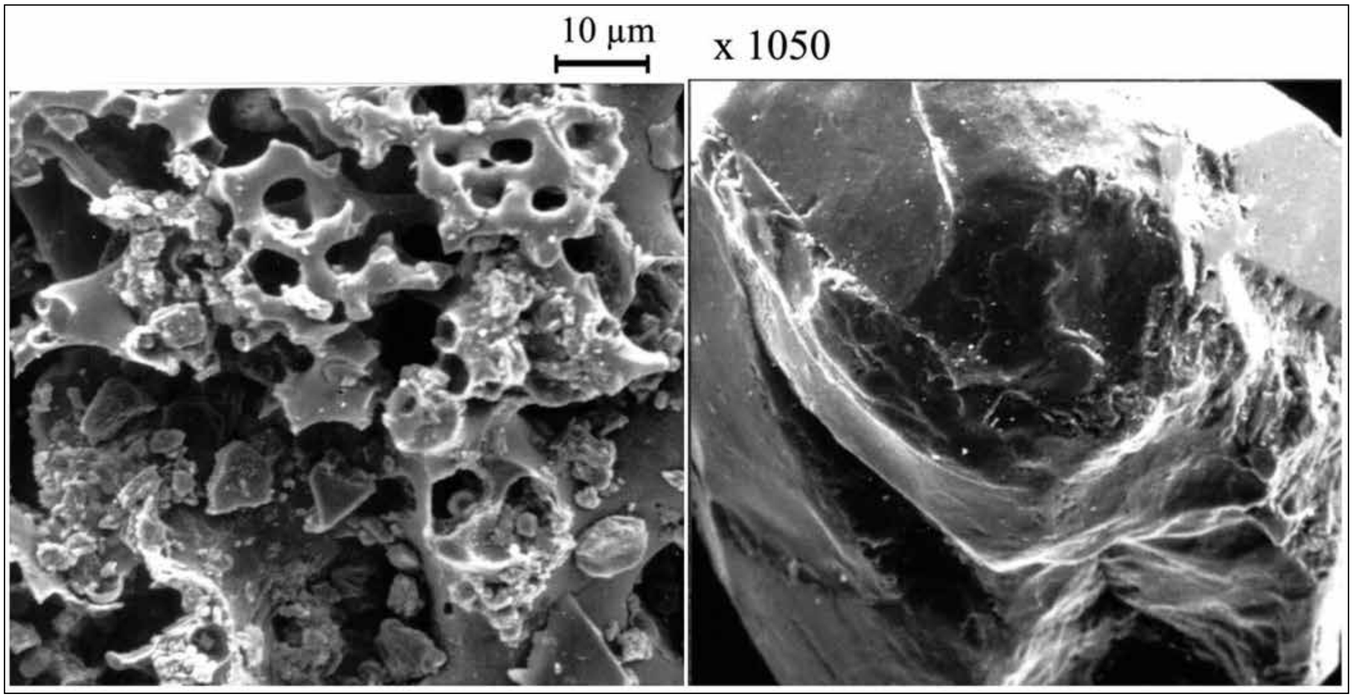


Figure 4. Electron scanning micrographs of carbonate (left) and silicate (right) sand grains from the Gulf of Aqaba, Red Sea (Rasheed *et al.* 2003). The surface area of the two sediment types used in this study was 0.41 $m^2 g^{-1}$ and 0.27 $m^2 g^{-1}$ for carbonate and silicate sand, respectively (reprinted with permission from the publishers).

mobile. This enhanced mobility under reduced conditions may have considerable implications if the reduced layer is suddenly exposed to a dynamically mixed and circulating water column, e.g. during dredging and subsequent sediment placement (see section 3).

Sand columns or, more precisely, the coarser fractions of sediments are often overlooked during heavy metal pollution studies because of the nominally lower surface area contribution by larger grains and the perceived paucity of their potential to carry adsorbed pollutants and impact their cycling. The result of this perception has been, for instance, the recommendation to use finer fractions in heavy metal analysis (e.g. Ackermann *et al.* 1983). Such practice has persisted even when significant concentrations of such pollutants were found in the coarser fractions, despite an inverse relationship between grain size and pollutant concentration (e.g. Lakhan *et al.* 2003). Recent investigations, e.g. by Otero *et al.* (2013), have documented that metal oxyhydroxide coatings on coarser grains increase this surface area, accounting for their significant contribution to heavy metal pollutant loads, and have called for inclusion of the sand fraction in heavy metal pollution studies.

The breakdown of organic matter results in the production of dissolved macronutrients, mainly ammonium (NH_4^+) and phosphate (PO_4^{3-}) that build up in sediments (Figure 7d). Dissolved macronutrients can also reach the sediment surface and the overlying water column, via molecular diffusion or, in the case of permeable sediments, accelerated exchange driven by physical transport of water. Groundwater that reaches the permeable coast and nearshore ocean (Figure 2) can also be enriched in reduced species and nutrients (Couturier *et al.* 2016; Reckhardt *et al.* 2015), which are either produced by the breakdown of organic material or are anthropogenic in origin. These nutrients can fuel primary productivity, with the potential for ecological and/or commercial implications, discussed following.

Biological considerations

The previous section implied the significant role microbial communities play in defining the biogeochemical function of permeable sediments. It is important to highlight two significant aspects of sand microbiology that are key contributors to this function.

The sedimentary microbial landscape is greatly affected by the surface area available for colonization. Therefore, finer and/or carbonate grains are likely to have higher surface areas for colonization than coarser and/or silicate grains, respectively (Figure 4). The consequences are multifold, but — most importantly — carbonate sands are characterized by higher respiration rates and may harbor suboxic or anoxic niches not likely in oxygenated porewaters or in the case of silicate sands of similar grain size distribution. Noteworthy examples include denitrification zones (Santos *et al.* 2012b) and sulfate reduction refuges (Sørensen *et al.* 2007). A higher surface area may also translate to increased carrying capacity for various pathogenic microbes and slower decline in abundances, as compared to water column decline rates (Zhang *et al.* 2015).

The second noteworthy aspect of sand microbiology relevant in this discussion is the high primary productivity performed by microphytobenthos, benthic microbial photosynthesizers. Microphytobenthic productivity on the shallow sandy continental shelf has been measured to be equal to the planktonic primary productivity of the whole water column overlying it (Jahnke *et al.* 2000). Even shallower coastal sands appear to be equally productive to an underappreciated degree (Hannides *et al.* 2014).

As shown in the previous section, the fast respiration of organic matter in permeable sands is accompanied by the regeneration of dissolved inorganic and organic nutrients originally used in photosynthesis (Jørgensen 2006). Nutrient-rich groundwater that reaches the permeable coast and nearshore ocean (Figure 2)

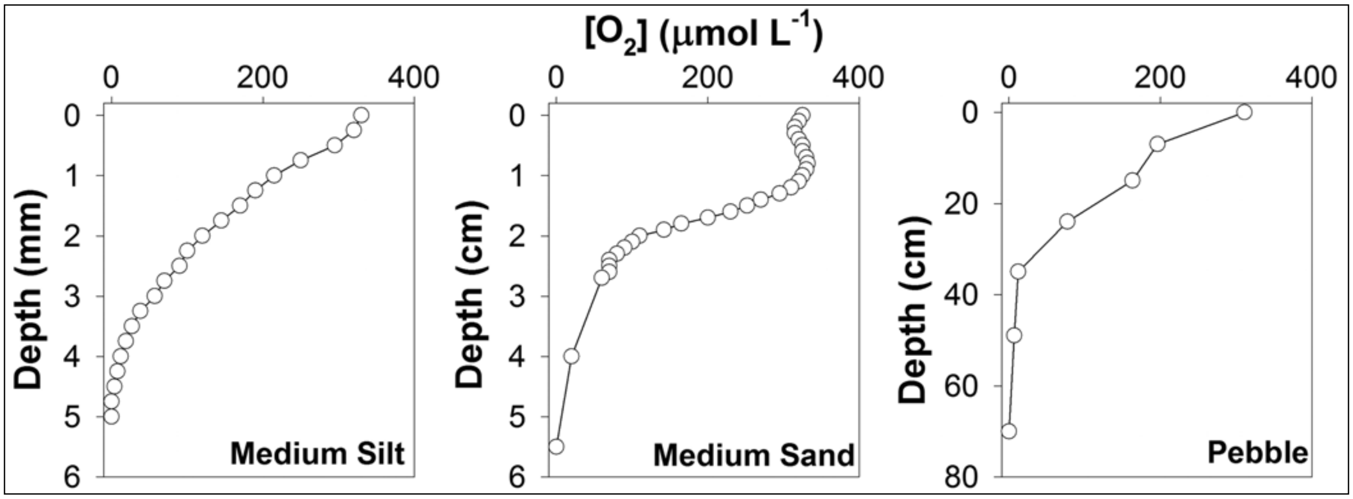


Figure 5. Profiles of porewater oxygen concentrations with depth in three sediment types, from finest to coarsest grain size (left to right; Udden-Wentworth scale) using data from Lohse *et al.* (1996) and Falter and Sansone (2000). Note the difference in depth scale.

can be transported from the sand column into the surface sediments and overlying water where the dissolved chemicals can be used anew by photosynthesizers (see Donis *et al.* 2017 and Schutte *et al.* 2018 for groundwater case studies).

The implication of microphytobenthic productivity on the food web could be significant. Even though the microbial and animal food webs tend to be described as mostly disconnected (e.g. McLachlan and Brown 2006), recent research (e.g. Schlacher *et al.* 2017) has demonstrated how microphytobenthic productivity fuels invertebrate populations that are incorporated in coastal food webs, with important ecological and commercial implications.

The length of the path groundwater follows through a sandy column before reaching the surface may be critical in determining the impact of nutrients dissolved in groundwater. Modification of groundwater by microbiota during this passage will affect the nutrient content of emerging groundwater. The presence of coastline nutrient pollution sources, such as seeping septic tanks of coastal establishments, combined with a shorter terminal sandy column path, as on an eroded beach (Figure 2), may act synergistically to create coastal pollution and eutrophication events where they would otherwise be alleviated (Mallin and McIver 2012; Meeroff *et al.* 2008; Paul *et al.* 2000).

BIOGEOCHEMICAL EFFECTS OF BEACH NOURISHMENT

Sand source areas

The biogeochemical effects of the dredging process on the source area center around the exposure of deep, chemically reduced sediment to the water column, with consequences that, beyond the immediate sedimentary environment, affect the overlying water column and the living communities in the area, as summarized in Figure 8. Following is a discussion on these consequences particularly as they are thought to apply to beach nourishment activities.

Pollutant mobilization

Pollutants, such as metals and organics, can be mobilized by the dredging process, whether in the dissolved or particulate phase. This problem is more probable in the case of urban harbor sands which might be used as source sand since they are likely to be more polluted than offshore deposits (e.g. Bigongiari *et al.* 2015), which is why contaminated harbors — due (but not limited to) the high density of boats, ablation of anti-fouling hull paint, higher potential for fuel spills, and preservatives used in construction of wooden harbor facilities — are highly regulated in the U.S. by Section 404 of the Clean Water Act (EPA 2019).

The deeper anoxic layers of sediment columns are characterized by conditions that favor dissolved metal compounds, as opposed to oxic or even suboxic layers where the same metals are immobilized in solid phases. The exposure of dissolved-metal-rich layers to the water column may result in the release and dispersal of metals long enough and far enough for their incorporation in the food web via bioaccumulation and eventually biomagnification. Oxidation by dissolved oxygen in the water column will remove oxidized metals to particles that, in turn, will settle and reenter the sediment column. The rate of oxidation and, therefore, the magnitude of the risk posed by mobilized metals is determined by the natural availability and replenishment of dissolved oxygen in the water column by exchange with the atmosphere. Consequently, the risk of this impact can be affected by the size and speed of the dredging operation and physical conditions that enhance gas exchange between the water column and atmosphere.

The dredging and sediment removal process also temporarily suspends potentially contaminated fine sediment into the water column. According to some studies, 75% of fines cannot be accounted for after deposition on the shore (Maglio *et al.* 2015; Ousley and Coor, 2015), but even the case of 5%-10% of unaccounted fines can result in substantial amounts when a million cubic yards of material or more are being transported. The unaccounted fines are likely to settle in the vicinity of the dredge and fill operation resulting in increased sedimentation of finer particles months after the dredging event and a finer sedimentary surface layer at the vicinity of a source site (Crowe *et al.* 2016; Nonnis *et al.* 2011). A finer-grained, less-permeable cap will delay or even prevent the restoration of redox conditions that are typical of sands, i.e. broad and deep oxic and suboxic zones underlying the water column (Figure 5). Fines must be retained much more efficiently if a nourishment operation's goal is to leave behind a permeable sand column with deep and broad oxic or suboxic redox zones.

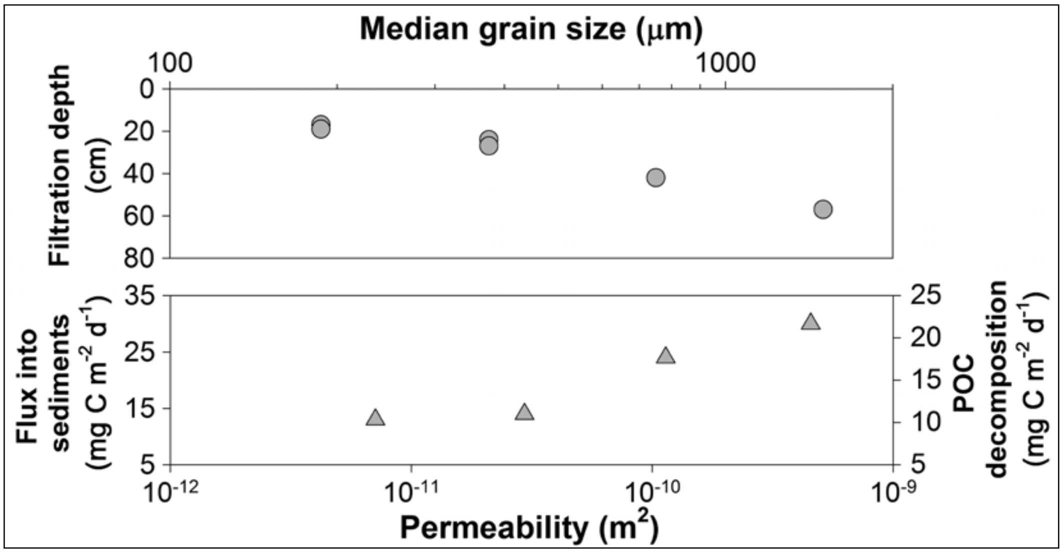


Figure 6. Experiments conducted by Huettel and Rusch (2000) exposed algal particles to sandy columns of varying permeability under stirring and monitored the depth to which algal particles were filtered (top) and the rate at which the contained carbon was supplied to and broken down within the sand columns (bottom) (replotted data from original publication).

Nutrient-fueled eutrophication

Dissolved nutrients that typically accumulate in the deep sedimentary layers will be released to the water column during and after a dredging event, similarly to dissolved metals. The enhanced nutrient pulses have the potential to boost primary productivity and, in the process, not only incorporate mobilized metals and other pollutants in the food web but also result in eutrophic conditions. The excess organic matter will fuel secondary productivity by upper levels of the food web but also the microbial communities in the water column or on sediments after settling. Increased respiratory activity will, in turn, lead to the consumption of electron acceptors, most importantly oxygen.

Elevated oxygen demand

Exposure of reduced sediments to the oxic water column and release of reduced metals and other chemicals will place a demand on oxygen, generally abundant in the shallow water column. An additional strain on oxygen reserves may result from excess organic matter produced during eutrophication. The cumulative effect of these oxygen sinks may be depressed oxygen concentrations perhaps falling to hypoxic levels, especially at greater depths where atmospheric oxygenation is less likely to impact water oxygen content. Hypoxia complicates the typical community structure, suppressing population abundances of sessile obligatory aerobes and potentially excluding mobile animals from the area. It may also delay the re-oxidation of the upper sedimentary column and restoration of redox conditions anticipated by the geophysical characteristics of the sediment present.

The recovery process

Permeable sandy columns are commonplace in physically dynamic, and therefore well-oxygenated, waters. The time needed for the re-establishment of near-saturation oxygen concentrations in the water column and sedimentary surface layers is expected to be rapid. Barring the placement of a thick layer of fines on the sediment column surface, newly oxidized surface sands will act as a cap to a reduced deeper column and reduced dissolved chemicals. Microbial reactivity and productivity on this surface layer will recover and lay the ground for recolonization by the baseline benthic fauna and the reestablishment of the food web.

THE (RE)NOURISHED BEACH

Freshly deposited beach fills differ from existing beach sands in numerous ways. The focus of numerous past monitoring efforts and subsequent reporting has been on qualitative characteristics of sand and impacts on infaunal communities reviewed elsewhere (Rosov *et al.* 2016). In this report, we focus on the biogeochemical implications of nourishment on restored beaches.

Physical characteristics, flushing rates and residence times

Despite design efforts to locate sand sources that most closely replicate the native material, it is impossible to find an exact match, and renourished sand will to some degree be of different grain size distribution and permeability than sand previously present on an eroded beach. If coarser sand is used, larger particles may be more stable than the native beach was, and therefore persist for longer periods of time in the vicinity of nourishment (e.g. Peterson *et al.* 2014), because of slower resuspension and transport, resulting in long-term physical consequences. For instance, a coarser sand column is also likely to be more permeable (Figure 3) and, consequently, more intensely flushed. Higher flushing rates may result in a higher supply of oxygen from the water column, a deeper oxic layer and a broader oxic-anoxic gradient (Figure 5). A more oxygenated sand column, accompanied by higher organic particle removal and decomposition rates (Figure 6), may serve as a better biofilter of particulate and dissolved constituents alike. However, the use of coarser sands for beach nourishment may result in a degraded habitat for important infaunal taxa (Peterson *et al.* 2014), which is also typically the case where finer-sand beaches are nourished with similar, low-permeability sand (Colosio *et al.* 2007). Therefore, biogeochemical and ecological consequences may diverge in such a scenario.

An additional important consequence of a renourished beach is a longer path for above-ground or under-ground water flows from land to ocean (Figure 2). This longer travel path extends the time over which chemical exchange can take place between sediment and water and may result in enhanced modification of land-derived materials. Previous studies have documented the transport of septic leachate to drainage water bodies and, in turn, to the nearby beaches (Mallin and McIver 2012; Meeroff *et al.* 2008). In this case, surface runoff is unlikely to be significantly curbed by a mere broadening of the beach face. Underground flows of septic leachate must also be investigated since the rates of transport may be faster

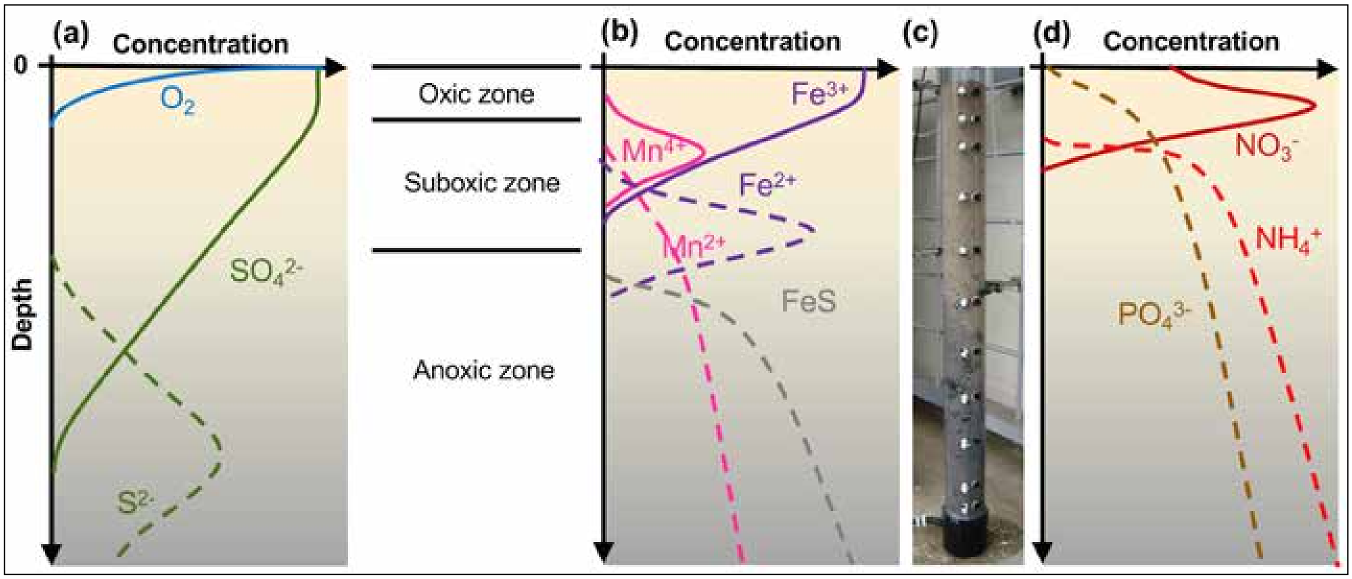


Figure 7. Variation in the sedimentary concentrations of reactants (straight lines) involved in organic matter respiration and respiration products (dashed lines) with depth from the sediment surface (after Jørgensen 1983; Photo in 7c: A. Hannides). The depth and concentration scales depend on the type of sediment present.

than the geophysical framework would predict (Paul *et al.* 2000).

Cementation (i.e. binding of sand grains in impermeable aggregations) is a potential problem that may arise in the case of high calcium carbonate content in placed sand (Speybroeck *et al.* 2006). If sufficiently concentrated, the newly dissolved high-magnesium calcite and aragonite will reprecipitate to form cemented layers that will impede water and air flow through a nourished beach.

Mineralogical characteristics and microbial habitat

Mineralogical composition, and specifically the contribution of calcium carbonate, has important consequences for microbial activity. Given a similar grain-size distribution, sand of higher calcium carbonate content will have a higher surface area per unit volume of total space (Figure 4), and therefore more potential habitat for microbes, including both human-derived and natural pathogens. Analysis and comparison of pathogen loading in beach sands across latitudes and settings has focused for good reason on pathogen sources and other pressures (e.g. Halliday and Gast 2011). The fate of those pathogens and the environmental conditions that may affect it are less well known. Ruiz *et al.* (2009) identified sun radiation exposure and sand grain transport as factors counteracting pathogen loading. The examination of deposited sand as a microbial habitat, starting from straightforward indicators such as carbonate content, may be a useful approach to identifying properties of source material that may affect its behavior as a pathogen host and a bioreactor across the renourished beach face.

Redox cycling and pollutant immobilization

Source sand consists mostly (by proportion) of deeper, and therefore hypoxic or anoxic, sedimentary layers. The typical gray color of freshly deposited sand (Figure 9a) mined from greater depths in the sedimentary column is evidence of the chemically reduced environment from which this sand has been retrieved and specifically of elevated concentrations of iron-sulfur compounds. Generally speaking, reduced conditions are favorable for chemical species of metal pollutants that can be easily mobilized from the solid phase to the dissolved phase, while oxidation of these reduced chemicals by exposure to the atmosphere and well-oxygenated surf-zone or swash-zone water will immobilize them back into the solid phase.

Another potential consequence of the oxidation of iron-sulfur compounds is a color change to lighter-colored beach sand (relate to Figure 7c). Regulatory agencies occasionally request that source sand be exposed to ambient light for two weeks to determine the eventual color of the the sand if approved and placed on the beach as sand fill. The driving mechanism behind the anticipated color change is presumed to be bleaching by natural UV light. Oxidation of the darker Fe-S minerals by oxygen may be equally responsible for the color change.

The placement process is accompanied by suspension of fines in the water column (Manning *et al.* 2014). Fines have a large surface area (relative to volume) onto which pollutants may be adsorbed, therefore their suspension constitutes another pollutant distribution mechanism. A sufficiently permeable sand column, in conjunction with physical forcing from waves, currents and tides, will not only promote rapid oxygenation but also accelerated filtration of fines into the sand column, and sequester and immobilize any metal pollutants.

Another common practice during sand placement is tilling that aims to reduce sand compaction. While this practice originally aims in achieving compaction suitable for sea turtle nesting, from a biogeochemical perspective, a benefit of this practice is to enhance the exposure of reduced compounds within the sand column to oxygenated media (atmosphere or swash-zone water) and accelerate their oxidation.

The parameterization of the combined effects of sand permeabilities, physical forcing rates, chemical speciation kinetics, and practices during the placement process, will allow a better understanding of the extent of the challenge of reduced-sand placement and the conditions that may exacerbate it.

Nutrient sequestration

Nutrient concentrations in renourished sands are most likely to be elevated since they also accumulate in

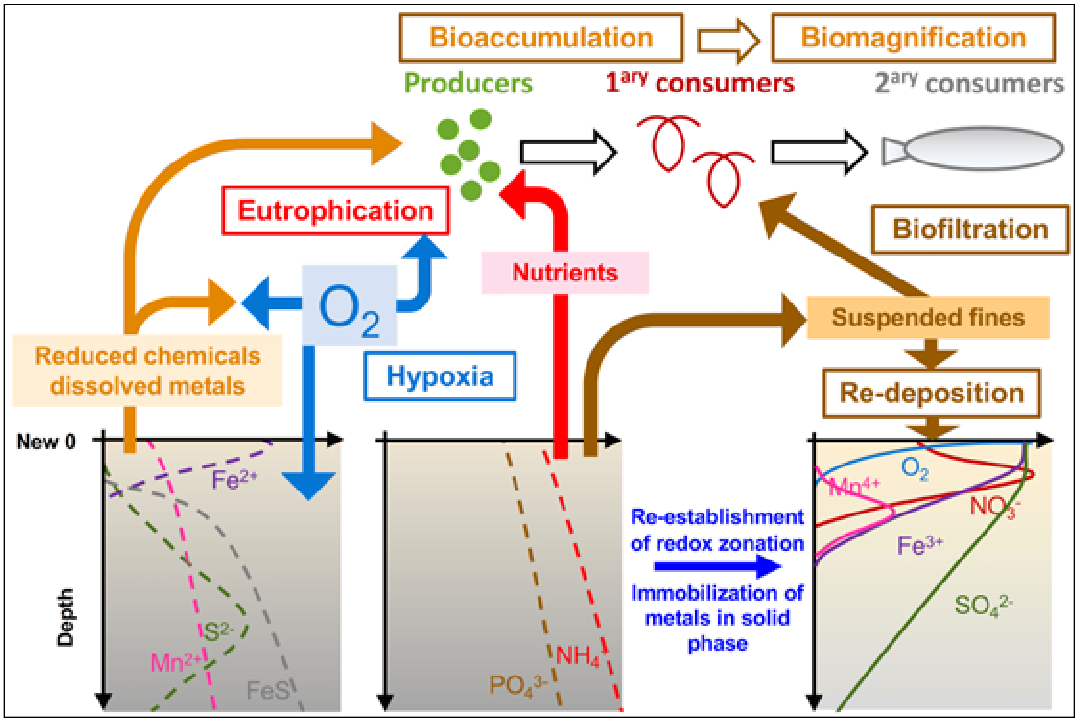


Figure 8. Overview of potential processes at a source area following a dredging event that removes the surface oxic-suboxic layers of sand (compare with Figure 7). Arrows indicate fluxes of matter and boxes indicate phenomena or processes related to effects. The typical food web depicted above is intended to represent both benthic and planktonic communities.

deeper sedimentary layers (Figure 7d). The aforementioned post-depositional flushing of the sand column will result in the sequestration, immobilization and modification of nutrients by sand microbiota (e.g. Rasheed *et al.* 2009, Schutte *et al.* 2018). In addition, the beach fill will lengthen the distance, and therefore the time, over which sand microbiota can respond to and modify nutrients in groundwater, both from natural sources but also anthropogenic sources such as septic tanks (Figure 9c). Grain mineralogy and the consequent microbial habitat will also affect microbiological activity. The greater the carbonate content, the greater the grain surface area and benthic microbial abundance, hence the greater the bioreactive potential of the new sand column to reduce nutrient release to coastal waters. The extent of nutrient enrichment during placement and sediment-water-groundwater interactions should be further investigated to understand this potential benefit of a nourished beach.

RECOMMENDATIONS

In the previous sections, we have discussed several processes potentially taking place during the nourishment process at both source sites and placement sites whose occurrence and extent remain relatively unknown at this point. Based on that discussion, we recommend the following actions to the research community and other stakeholders, in order to further illuminate the potential effects of beach nourishment activities on biogeochemical processes and conditions.

Recommendations to researchers

■ Establish time-series studies to monitor biogeochemical conditions and processes:

- before (baseline),
- during, and
- after

beach nourishment projects at both:

- source sites, and
- placement sites.

■ Key conditions and processes that should be prioritized for further study over time and space include:

- Water column oxygen, nutrients and metals (esp. pollutants of concern) in the particulate, colloidal, and dissolved phase;
- Sedimentary redox zonation and concentrations of major reduced and oxidized constituents, including organic matter, nutrients and metals, and chemical speciation kinetics;
- Microbial (including pathogen) abundances and activity rates;
- Groundwater-seawater exchange at the beach face, including using septic leachate tracers;
- Physical transport and exchange, including wave action, currents, and tidal pumping; and
- Sand permeability, grain size statistics, calcium carbonate content and grain surface area.

■ Interface with contractors, planners and regulatory agencies to benefit from existing monitoring plans or protocols implemented during beach nourishment projects.

■ Tie-in to the provisions and goals of the National Integrated Implementation Plan (USCRP 2016).

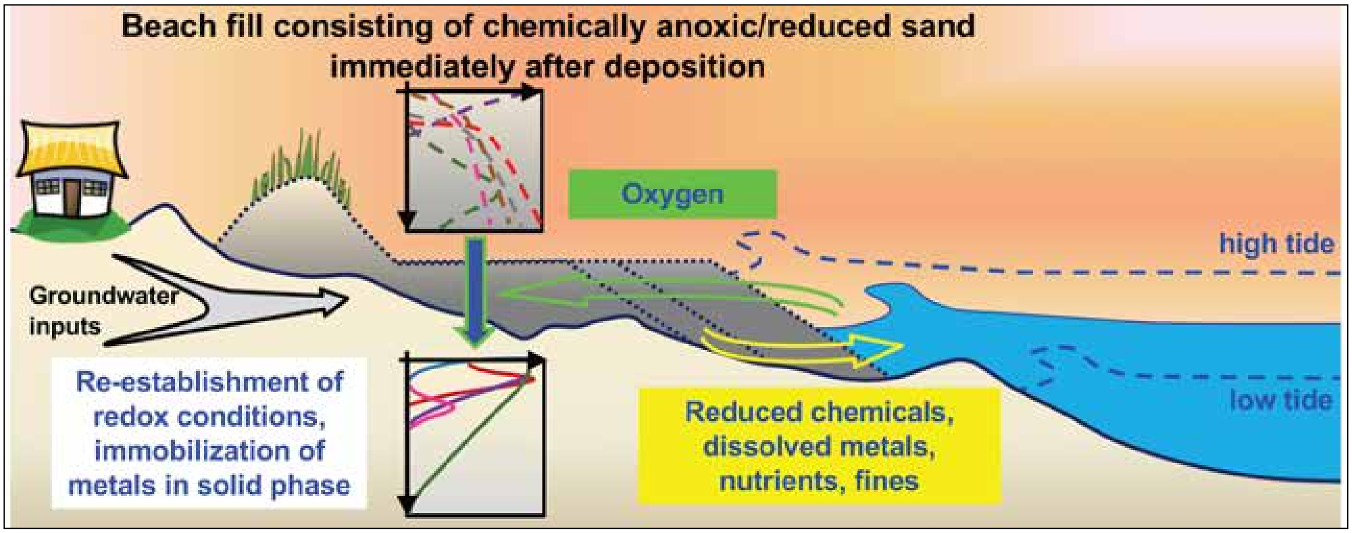
■ Form a subcommittee under the task force described following to develop specific guidance and goals for the time-series studies described above, taking into consideration the scientific and statistical rigor necessary for conclusive outcomes (e.g. Peterson and Bishop 2005).

Recommendations to policy makers, planners, contractors, and the public

■ Form a task force under the auspices of the ASBPA or another initiative consisting of researchers and practitioners to specifically focus on the following recommendations:

- Expand the types of biogeochemical information collected and knowledge generated before (baseline), during and after beach nourishment projects at both source and placement sites;
- Facilitate the exchange of knowledge generated from these synergies in an efficient, transparent and ethical manner; and

Figure 9. Overview of potential processes occurring during and after a sand deposition event during beach nourishment. (A, above) Deposition of anoxic/reduced sand. Compare with color of existing sand nearby (see Figure 7c) (Photo: N. Elko). (B, below) Potential processes following a sediment placement event. Arrows indicate fluxes of matter. See Figure 8 for more details on impacts.



- Examine the impact of new knowledge on current monitoring practices, both mandatory and voluntary, during beach nourishment projects.

- Explore framing all activities pertaining to (the biogeochemistry of) beach nourishment within the context of sustainability concepts such as the Blue Economy, Living Shorelines, etc., that may highlight the benefits of sustained sandy shores.

CONCLUSIONS

Our synthesis of the literature identified numerous potential biogeochemical implications of the beach nourishment process at both the source area and the renourished beach, as those stem from fundamental precepts of environmental biogeochemistry. Reduced sediments are rich in mobile contaminants and, as they are exposed to surface water during the retrieval process, they may enhance oxygen demand, fuel primary productivity, and supply contaminants to a broader area. Restoration of oxic conditions may proceed rapidly due to the rapid exchange of oxygen between the water column and the underlying sand column. Moreover, a longer beach face cross-section may ensure adequate time is provided for surface and subsurface water flows from land to ocean to be modified by the sand column. Identifying how these expected processes materialize in the case of beach nourishment projects provides a great opportunity for synergies between researchers and practitioners who can also highlight important services sandy shores provide to natural and human environments.

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