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**Abstract**:

Beach replenishment places a meter or more of new sand on the beach and nearshore in order to restore width and elevation to some prior, or desired, configuration. The consistent infrastructure-protective and economic benefits gained by such restorations are well documented. The ecological consequences are, however, less certain. The placement of a thick layer of sediment often, but not always, results in widespread ephemeral reductions or depletions in population abundance for most or all resident species. Most peer-reviewed studies report that a recovery of the post-replenished beach ecosystem does occur, often within the first year following replenishment, though there are exceptions. Post-disturbance recovery is implied in these instances in the broad context of restoring populations back to levels observed, or were assumed to have been in place, prior to the changes brought about by the disturbance event. The idiosyncratic complexities of the beach ecosystem, however, often makes characterization of pre-disturbance conditions problematic. Ecosystems may be better understood as existing in a perpetual state of dynamic dis-equilibrium where change in both space and in time are the only constants. Such complexities may offer at least a partial explanation for the absence of explicit comprehensive definitions for post-replenishment recovery in the literature. Perhaps the best that can be offered is one based on restoration to some predefined similarity and not pre to post event parity. Further, though many investigators state that disturbances such as beach replenishment represent finite duration “pulse” disturbance we here proffer that beach replenishment is always a “press” type disturbance in that the resultant ecosystem will in some way be indelibly altered by impacts associated with the event—a circumstance that further complicates the process of establishing a suitable predefinition for recovery. Evidence does exist that suggests that the character of the post-replenished beach ecosystem, and thus recovery can, at least to some limited degree, be engineered through careful project design and implementation, paying close attention to those local factors (e.g., sediment characteristics, event timing) that are known, or thought to be, important to sustain suitable habitat for indigenous flora and fauna.

**Introduction**:

It is estimated that some 30 percent of all sandy beaches worldwide suffer from some form of chronic beach erosion (Luijendijk et al. 2018). In response, jurisdictions in ever increasing numbers are turning to beach replenishment to ameliorate or reverse these persistent shoreline losses. Beach replenishment is a strategy that introduces new sediment to the beach to restore elevation and width lost over time due to removal from erosion (Finkl and Walker, 2004). The protective benefits that beach replenishment affords to economic and recreational interests along developed and developable coastlines are well established (Nordstrom, 2005; Houston, 2020), justifying its sometimes prohibitively high pecuniary costs (Nordstrom, 2005). Viewed through the lens of infrastructure protection and value enhancement, post-replenishment outcomes are almost universally positive (Houston, 2020; Dean, 2003). From an ecosystem perspective, however, consequences and outcomes from replenishment are less certain ( Leewis et al. 2012; Schlacher et al. 2012; Nordstrom, 2005; Peterson and Bishop, 2005; Adriaanse and Coosen, 1991). This uncertainty is especially acute over the long-term where little peer-reviewed research exists on potential cumulative effects, and much debate surrounds what is thought to be known about impacts of beach replenishment to sandy beach ecology (Manning et al. 2014; Peterson et al. 2014; Viola et al. 2014; Leewis et al. 2012; Schlacher et al. 2012; Wilber and Clarke, 2007; Speybroeck et al. 2006; Nordstrom, 2005; Peterson and Bishop, 2005; Green, 2002).

Beach replenishment involves the placement of a layer of sediment from 1 to 4 meters in thickness across the eroded surface (Leewis et al. 2012). Surveys in the immediate aftermath of this placement report that mortalities for infauna buried under this sediment load often, though not always, approach 100 percent (Hayden and Dolan, 1974; Leewis et al. 2012; Viola et al. 2012). Following this rapid transformation, most replenishment impact studies in the published literature report having observed a response leading to some type of ecosystem recovery (Martin and Adams, 2020; Leewis et al. 2012; Schlacher et al. 2012; Jones et al. 2008; Menn et al. 2003; Gorzelany and Nelson, 1987; Manning et al. 2014; Rakocinski et al. 1996; Reilly and Bellis, 1983; Peterson et al. 2006; Peterson et al. 2014; Wooldridge et al. 2016; and others). Most often this recovery is expressed as the restoration of species abundance (the resident population counts for the species present) and diversity (the number of species present) to levels assumed to represent the ecosystem as it was structured prior to replenishment. Detailed definitions for what constitute recovery in any explicit sense are, however, largely absent in the peer-reviewed literature. Nor has a more formal, broad, and unified definition for ecosystem recovery as yet been proposed. These actualities might suggest that there remains much that is still unknown about the structure and function of sandy beach ecosystems, and that these gaps in our knowledge stand in the way of such a definition. Or they might suggest that situational complexities resulting from natural idiosyncrasies governing system ecology, coupled with more recent human-induced modifications to the beach ecosystem, make such definitions problematic to formulate. Or perhaps the truth lies somewhere in between. Research to-date offers, as yet little upon which to decide.

In this review we examine ecosystem disturbance, restoration, and recovery from the perspective of sandy beach reconstruction and enhancement as associated with replenishment. We begin by considering disturbances and how these act to alter the ecosystems impacted by them, be they from natural sources or human derived. Next, we look at the concept of equilibrium in the context of the environment, ecology, and ecosystem community structure, and the relationship between disturbance and system equilibrium. We then shift focus to a discussion on recovery, and in particular recovery in the context of beach replenishment and how it's considered and measured in many of the more recently published impact studies. Foremost here is the question of how, from theoretical and practical ecology systems perspectives, recovery might be coherently defined. Recovery could be viewed on one extreme as a concept universally applied, or on another as one whose character is unique and specific to a local environment and circumstance. Finally, we focus on how findings and conclusions from these many studies can, and in some instances already are, being leveraged to 'steer' the resultant ecosystem toward some ecologically desirable outcome.

**Replenishment Impact and the Beach Response and Recovery:**

The invertebrate communities found along sandy ocean beaches occupy environments characterized by frequent and sometimes rapid change. Most ocean-facing sandy beaches are subject to a host of physical environmental conditions (e.g., winds, waves, tides) that can vary widely in magnitude over short spans of time and distance. Evolutionary adaptation to these highly varying conditions affords species in these communities both a day to day high-stress survival capability (Adriaanse and Coosen, 1991), as well as some beneficial degree of longer-term resilience to more extreme disturbances such as those experienced during storms (Harris et al. 2011), from human interventions associated with development and recreational use (Afgan et al. 2020; Dixon et al, 2015), and, as we discuss here, beach replenishment (Peterson et al. 2014). But, while many species are highly adaptive, such resilience is not without limit (Jarmillo et al. 1996; Chapman, 1998; Schooler et al. 2019). Extreme disturbance events may subject indigenous flora and fauna to conditions that exceed their adaptive capacity to cope (Leewis et al. 2012). For most species and circumstances these stress accommodation limits are unknown (Nordstrom, 2005; Adriaanse and Coosen ,1991).

**Disturbances - Natural and Anthropogenically Derived:**

White and Pickett (1985) defined a disturbance within the context of the ecosystem as a discrete event that alters the physical environment and disrupts the biotic community and the associated services the community provides (Mori, 2011). Naturally occurring disturbances may consist of, but are not limited to events such as storms, wildfires, and floods. Such phenomena are recognized as everywhere occurring, intrinsic to all systems, and in general cannot be avoided (White and Jentsch, 2001). Humans have also contributed change to the physical environment in varying degrees (White and Jentsch, 2001). Anthropogenic impacts along the sandy beach, for example, take the common forms of high-frequency, lesser-magnitude disturbances such as daily visitor foot traffic and off-road vehicle use, and low-frequency, but greater impact-magnitude events such as beach grooming, bulldozing, and replenishment. All of these further contribute to a diverse array of potential perturbative impacts to the sandy beach. Replenishment in particular is seen by many as of special concern for the high mortalities that consistently, though not always, result (Speybroeck et al, 2006; Gorzalany and Nelson, 1987). The addition of beach replenishment to this list of human contributions is a relatively recent one, but as replenishment frequency is expected to increase in the coming decades as a result of climate-change-induced eustatic sea level rise (Houston, 2020; Nordstrom, 2005) its contribution to the array of potential ecosystem disturbances is expected to become increasingly important (Leewis et al. 2012).

Individual ecosystem disturbances can be partitioned into three variably overlapping phases: the stressor event, the ecosystem's immediate response to the stressor, and later post-event system restoration and recovery (Kelly and Harwell, 1990). In the case of beach replenishment, the stressor is the replenishment operation itself--the placement and mechanized distribution of a thick body of new sediment on the native beach over a span of a few days to several weeks. The placement of new sands on a beach is often assumed to be a finite duration "pulse" type disturbance, one where some type of biotic recovery back to pre-disturbance conditions would be expected (Petersen et al. 2014; Bender, 1984). The magnitude of the immediate response to this sand placement is expected to be severe (Leewis et al. 2012; Speybroeck et al. 2006; Green, 2002). While some investigators observe little to no biological impact in the immediate aftermath of replenishment (Menn et al. 2003; Hayden and Dolan, 1974 and Gorzalany and Nelson, 1987), most report that replenishment results in the rapid and complete mortality of most resident infauna on the impacted beach (Martin and Adams, 2020; Corbett and Walsh, 2017; Wooldridge et al. 2016; Manning et al. 2014; Peterson et al. 2014; Viola et al. 2014; Leewis et al. 2012; Schlacher et al. 2012; Jones et al. 2008; Bioldeau and Bourgeois, 2007; Colosio et al, 2007; Fenster et al, 2006; Peterson et al. 2006; Wilber et al. 2003; Peterson et al. 2000; Rakocinski et al. 1996; Adriaanse and Coosen, 1991; Reilly and Bellis, 1983).

**Ecosystem Recovery - The General Case:**

Once impacts associated with replenishment construction operations are eased the beach is expected to enter a restoration phase that results in recovery. One generic definition for such recovery points to a system's "return to a normal state..." (Jones et al. 2008). Tailoring this definition for general application to ecology, we assert that a post-disturbance recovery might be thought of as an endpoint state or normal condition that an ecosystem will naturally return to if left without any further disturbance for a sufficiently long span of time. The assumption here is that ecosystems seek some natural stable equilibrium condition. Recovery then would be defined around and based on this equilibrium condition (Mori, 2011). In theory then, recovery has been gained when this equilibrium state is restored on the impacted site (Wilber and Clarke, 2007).

**Equilibrium Theory and Recovery:**

Several definitions for equilibrium as it applies to the ecosystem have been proposed. The most simplistic expresses equilibrium as a steady-state phenomenon whereby environmental parameters such as species abundance and diversity fluctuate little over time (White and Jentsch, 2001). The circumstance when species recruitments continuously match mortalities to maintain a stable population, or when the relative abundance within and between species groups maintain a constant proportion, could both be interpreted as criteria for defining the steady-state ecosystem equilibrium condition. Strict steady-state equilibrium is, however, thought to be rare (Romme et al, 1998). A less stringent definition, and one historically adopted by many investigators, is one in which parameters can vary. In this case the permissible variation is constrained within defined boundaries such that, while species abundance and diversity can change over time to a much greater degree than permitted in the more conservative steady-state model, large excursions that could include species extinctions or successions are not permitted to occur (Turner et al. 1993). If we should adopt this latter definition for equilibrium here, we can look to examples on the sandy beach where species abundances will vary by some amount over short spans of time and distance but maintain a para-stable state over longer periods. Events which then force the ecosystem beyond this defined equilibrium domain (e.g., storms or replenishment) are considered perturbations (White and Pickett, 1985) or disturbances (White and Jentsch, 2001). Disturbances, by this definition, take an ecosystem beyond its normal range of conditions (e.g., seasonal biological recruitment, meteorological, or climatic cycles) such that changes outside of what is considered the normal range occur (Mori, 2011; White and Jentsch, 2001). . One such disturbance example associated with an invertebrate species response to beach replenishment is described in Figure 1.

Many investigators, however, argue against the plausibility of these equilibrium paradigms (Mori, 2011; Moore et al. 2009; Kimbro and Grosholz, 2006; Wallington et al. 2005; Levin, 1999; Connell, 1978). Connell (1978) for instance, asserted that community structure is not well-enough organized or efficient to support longer-term stability in the face of variable environmental conditions and, consequently, a true equilibrium state is rarely realized. More commonplace, he and others hypothesize, ecosystems exist in varying states of dis-equilibrium, measured by changes in taxonomic composition and abundance (Connell, 1978) or by degree of species diversity (Kimbro and Grosholz, 2006). While much debate continues over equilibrium versus dis-equilibrium (Phillips, 2004), many ecologists today find that the idea of a hypothetical steady-state paradigm often fails to adequately predict and describe what is observed in the environment (Mori, 2011; Levin, 1999). More commonly it is maintained, ecosystems, as Connell (1978) suggested, are seen to exist in a continual disturbance-induced, disturbance-perpetuated state. Further, observation increasingly supports an idea that natural disturbances not only shape the landscape, but are an important, integral, and sometimes necessary part of that landscape (Mori, 2011; Wallington, Hobbs, and Moore, 2005; Phillips 2004; Perry, 2002).

The equilibrium paradigm debate is further compounded by long-term, generational (25-30 years) changes in human perception of what equilibrium might look like and how it would be expected to manifest in the environment---a phenomenon often referred to as the shifting baseline syndrome (Afgan et al. 2020; Vera, 2010; Jackson et al. 2007; Pauly, 1995). The shifting baseline syndrome suggests that cumulative effects from persistent disturbance, particularly those from anthropogenic sources, will over time progressively alter our human perception of the natural ecosystem. Such changes in perception are insidious in that they redefine presupposition--altering our beliefs and interpretations of how the natural, absent human disturbance, ecosystem might be expected to appear. For the ecologist interested in post-beach replenishment recovery, baseline targets would be established, and recovery judged under assumptions that chosen sites for reference represent some natural stasis when in fact, they may reflect conditions that greatly differ.

**Ecosystem Recovery and Replenishment in the Literature:**

Most contemporary investigators (Martin and Adams, 2020; Leewis et al. 2012; Schlacher et al. 2012; Jones et al. 2008; Bilodeau and Bourgeois, 2007; Colosio et al. 2007; Menn et al. 2003; Manning et al. 2014; Rakocinski et al. 1996; Peterson et al. 2006; Peterson et al. 2014; Wooldridge et al. 2016, and many others) whose work focuses on impacts tied to beach replenishment utilize the idea of a time-dependent restoration trajectory toward recovery as a means against which to monitor ecosystem response. Though not stated explicitly, in most every instance recovery was central to these investigations and the resultant conclusions. Of 21 contemporary peer-reviewed and published studies surveyed as part this present article’s preparation, 10 reported a complete recovery, 9 reported an intermediate or partial recovery, while only two of the 21 witnessed little to no recovery at all. In the latter cases, lack of recovery was based on observed, or nearly so, azoic conditions at the impacted beach site that persisted for at least the duration of the study. For those who reported partial to full recovery, again as observed over the course of each respective study period, recovery centered on the demonstrable reinstatement of a surrogate faunal assemblage along the replenished beach that was interpreted to be equivalent to that observed on either the impacted site prior to replenishment or to one or more prior-established reference or control sites. In these instances, the control sites represent a target benchmark against which restoration and recovery on the replenished beach could be gauged. The average monitoring time of the 21 studies was 15.8 months.

The experimental designs that establish one or more control sites to benchmark restoration and recovery grew out of methods developed back in the 1970s that relied on the inclusion of an undisturbed reference against which to judge the state of any disturbed ecosystem (Eberhardt 1976; Thomas et al. 1978). They form the supporting rationale for the Before-After-Control-Impact (or BACI) sampling schemes (Underwood, 1994; Green, 1979) that in various incarnations have enjoyed broad appeal and application in the ecological sciences (Underwood, 1994). Most of the refereed beach replenishment case studies published since 1990 employ some variant of the BACI scheme in their field methodology (Wilber et al. 2009). One or more biological measures (e.g., taxonomy, abundance, diversity) are typically tracked along both the impacted and control beaches. State of recovery is based qualitatively and quantitatively on comparative variance partitioning models that test for similarities and significance of differences (Ramette, 2007). Exploratory techniques include principal coordinates analysis (PCoA), correspondence analysis (CA), and multidimensional scaling (MDS) (Ramette, 2007), while confirmatory approaches often consist of analysis of similarity (ANOSIM) (Clarke et al. 2014), parametric multivariate analysis of variance (MANOVA), and relaxed-assumption or nonparametric permutational multivariate analysis of variance (NPMANOVA, PERMANOVA) (Anderson, 2014; Anderson, 2001). Practical limitations in measurements necessitate the acceptance of an assumption that a level of consistency exists within and between the control and impacted beach sites to allow direct comparison. It may also be assumed that the control sites offer a nominal representation of, if only hypothetical, the undisturbed (i.e., natural) condition. When the impacted site and the one or more control sites are in some measurable way equivalent, recovery is stated to have been achieved. That is, between the impacted site and the chosen controls there is no longer any statistically evident (as based on formal hypothesis testing) difference.

**Ecosystem Recovery – Definitions:**

O'Neill (1998) defined recovery as a return of the post-disturbed ecosystem to some baseline or normal condition. Use of the word "normal" as the recovery target implies the existence of some type of typical or equilibrium state for the system in question. Here, a post-disturbance restoration trajectory, such as one on a recently replenished beach, would be one that culminates in recovery to this normal or equilibrium state. However, as already mentioned, much debate surrounds the notion of ecosystem equilibrium, even to the point where some argue against its very existence. Ecosystems are complex, and this complexity is amplified by disturbance (White and Jentsch, 2001). This is true whether the disturbance comes from natural or anthropogenic events, or from some combination of the two (Mori, 2011). Thus, as a practical matter, in the face of so much uncertainty, there may be little to be gained by the investigator in attempting to rely on such assumptions as the existence of a state of normalcy or equilibrium, to be used as basis for assessing and defining post-replenishment beach recovery. Whether or not most of the published studies looking at beach replenishment impacts and recovery recognize this and so deliberately alter their approach accordingly is uncertain, but most investigators do appear to adopt a less stringent interpretation, one that delineates recovery simply as a restoration of the post-disturbed ecosystem to some pre-selected reference condition (Jones et al. 2008; Chapman, 1998). Jones et al. (2008) presents one of the very few explicitly stated and detailed descriptions of this relative comparative approach: "...recovery is considered to be the process of post-disturbance change in the chosen response variables that is complete when no impact remains." The authors go on to state that at the point of recovery any differences seen in the chosen response variables as measured between the impacted and control sites, along with their mutual interactions, are no longer statistically significant (Jones et al. 2008). The implication behind Jones et al.'s definition appears then to be one that focuses on recovery as defined by quantitative (statistical) similarity, not equality.

Though similarities exist across all sandy beaches, the distribution, number, and abundance of species that occupy them are in many ways unique to a given place and time (Colosio et al. 2007). The specific structure and function on display along a beach at a particular time is in part determined by current environmental conditions (e.g., wind and wave conditions, sediment composition) at the site, as well as the vagaries and idiosyncrasies inherent to most natural ecosystems and their resident flora and fauna (Calow, 1992). As substantial differences are commonly noted in species distributions and abundance on a given beach over periods of hours to a few days and distances spanning as little as a few tens of meters (Hayden and Dolan, 1974) it can be difficult to know with any degree of certainty whether or not a chosen control site will be a suitable surrogate for recovery tracking on the replenished beach (Nordstrom, 2005). Time, geographic distance. and the possibility of too much or too little separation between the controls and impacted sites in order to ensure independence between the two (no autocorrelation between sites) can be difficult to secure (Witmer et al. 2019). This difficulty would suggest that the chosen control sites might be either too close and so end up being inadvertently influenced by the disturbance event, or too remote and so differ enough in their ecological make up to call into question the credibility of the site as a suitable surrogate against which to gauge recovery in the impacted area. Though field sampling techniques such as BACI countervail some of these issues (Peterson et al. 2014; Underwood, 1994) the uncertainties that remain makes establishing a reliable recovery baseline representative of some relative natural or normal condition or state at a given beach site in almost all instances a logistical challenge. In light of this conclusion, we can surmise that a formal definition for recovery is likely limited to one as is presented by Jones et al. (2008) and a similar one by Schlacher et al. (2012) where a relative and stable similarity to what is observed, as opposed to a some more stringent parity criterion, would be the most realistic benchmark. With this result in hand the question might next be asked: does all of this recovery uncertainty really matter to the post-replenishment outcome and the character, and overall health, of the resultant ecosystem?

It has been argued that not only are disturbances an inescapable part of all ecological systems (Mori, 2011; Phillips, 2004) but they are also an intrinsic and some say necessary component to all ecosystems (White and Jentsch, 2001). Discrete disruptive events such as wildfires, floods, and storms occur over short spans of time yet leave behind effects that are felt for long periods thereafter (Mori, 2011; White and Jentsch, 2001). Moreover, many reason that such events are integral to the vitality and survivability of the ecosystem (Mori; 2011; Phillips, 2004). There is evidence that for some species such events are a strict necessity to ensure survival (Laska, 2001). Wildfires, for instance are often seen as undesirable, even disastrous events from a human standpoint (Noss et al. 2006), but fire is a necessity in the proliferation of the long-leaf pine *Pinus palustris*, a tree species native to the southeastern United States (Mori, 2011). Might this reasoning in some way extend to human-induced impacts, in particular large-magnitude ones such as beach replenishment? There is perhaps little evidence to suggest that replenishment provides any significant benefit to the survival of the beach ecosystem (Speybroeck et al. 2006)., even though replenishment can be seen as a process that rebuilds potential new habitat area lost to shoreline erosion. Nevertheless, in light of the impacts imparted by severe storms, held in contrast to that experienced during many replenishment projects (Wilber et al, 2003), it could be stated that while replenishment does indeed alter or change the indigenous ecosystem, it may not necessarily leave it diminished, only different. Furthermore, we may go on to state that the assertion earlier referenced that most replenishment projects be classified as finite duration pulse events (Peterson et al. 2014) is incorrect. While some investigators suggest that replenishment can, under certain circumstances, result in a longer duration "press" disturbance (Peterson et al. 2014), we assert that all beach replenishment projects, regardless of how carefully planned and executed, result in sustained change. The resultant new ecosystem thus emerging from replenishment will differ from that prior to the event.

**Engineering an ecologically favorable ecosystem recovery:**

Simple logic informs that ecosystem recovery, in whatever form it takes following any disruptive event, is in large part dependent on the post-event habitat's ultimate suitability for species recolonization. If the disturbance is human initiated, as in the case of beach replenishment, then the character of this post-event habitat will be dictated at least to some degree by the extent of the initial disturbance and subsequently in the decisions made during the design, and actions during the construction phases of the replenishment project. Thus, the character of the resultant replenished beach and its attendant array of habitats can in theory be manipulated, and the outcome in terms of recovery can theoretically be steered down a predictable path. As has already been discussed, however, it is unlikely that such control will be realized in practice. Instead, if the goal is to reestablish a prior habitat the engineer must be able to make decisions that best ensure such an outcome (Adriaanse and Coosen, 1991). The greater the degree to which the new beach can be ecologically and morphologically configured to resemble the old the greater the likelihood that the new ecosystem to emerge will resemble (i.e., appear to be similar to) that seen on the pre-replenished beach (Van Tomme et al. 2013). The key then is twofold: First, to expand our understanding of these natural systems and the life histories of the flora and fauna that occupy them, and second, to identify those attributes of the replenished beach design that are under the engineer's purview and then exploit these to steer the project toward the desired outcome that is in accord with the natural system.

A number of factors have been recognized as important contributors to the structure observed in macro-faunal beach communities. These factors can be condensed into five fundamental, large-scale elements (Defeo and McLachlan, 2013; Nel et al. 2014): 1) the geographic latitude of the beach; 2) the astronomical tidal range; 3) the beach type (based on the dissipative to reflective continuum of types as proposed by Wright and Short, (1983)); 4) beach sediment (sand) granulometry (e.g., size and distribution of sizes, shape, mineral composition); and 5) nearshore biological productivity. When an ecosystem is disturbed, additional factors come into play. Some of the more salient that are associated with beach replenishment include the time of year when the disturbance occurs relative to peak species recruitments and seasonal migrations (Cooke et al. 2012), and the spatial extent of the disturbance (Nordstrom, 2005; Leewis et al. 2012; Viola et al. 2014). For the engineer designing a replenishment project, control is limited to the fill sediment selected (number 4, above), the design beach profile and the means (i.e., construction practices) used to create that profile, the project timing, and its spatial extent. Here we define fill sediments as those added to restore (replenish) the eroded beach and native sediments as those present on the beach prior to replenishment.

There exists evidence to support the assertion that beach infaunal populations are closely tied to, and constrained by, the physical attributes associated with the native, and ultimately for the replenished beach the fill sediments placed there (McLachlin, 1996; Rakocinski et al, 1996; Green, 2002; Viola et al. 2014). The choice of sediment used during replenishment exercises influence on the post-replenishment ecological outcome (USACOE, 2002; McLachlan 1983; Gorzelany and Nelson 1987; Nelson, 1993; Degraer et al. 2003; Menn et al. 2003; Rodil and Lastra 2004; McLachlan and Dorvlo 2005; Colosio et al. 2008; Jones et al. 2008; Jannsen et al. 2011; Leewis et al. 2012; Schlacher et al. 2012; Manning et al. 2014; Peterson et al. 2014; Voila et al. 2014; Woolridge et al. 2016; Pagan et al. 2018). The choice of fill sediments used for replenishment may be the most important engineering consideration determining final long-term recovery (USACOE, 2002). The closer the physical characteristics or granulometry between native and fill sediments--their relative granulometric equivalence--the greater the chance that the replenished beach's resultant ecosystem will be aligned to that of the one in place prior to disturbance (Nordstrom, 2005; USACOE, 2002).

In addition to ecological considerations, many local, regional, and state-level requirements for replenishment projects often already require that fill sediments used for replenishment meet certain specifications for size and composition (USACOE, 2002) to match the native materials on the beach. Project timing (the time of year when the project is conducted) is also regulated in some instances. The impetus to incorporate these requirements into the replenishment permitting process has, however, been motivated principally by the desire to better ensure sand retention, maintain its protective and recreational attributes, and to realize the project's design lifespan objectives (USACOE, 2002; Nordstrom, 2005). Attention to impacts associated with the beach ecosystem and ecological outcomes are much less commonplace (Nordstrom, 2005). In fact, many communities resist the incorporation of environmental considerations into the project design for fear of compromising the beach's value as an economic resource (Nordstrom, 2005). Environmental impact statements are routinely sought as part of the permitting process--these are one common prerequisite for obtaining the necessary permits to conduct beach replenishment in many locations (Nordstrom, 2005; Wilber et al. 2009), but are criticized for their relative inaccessibility (Peterson and Bishop 2005). Most such documents are seldom published or easily accessible, and so knowledge of their existence, even among the scholarly community, is uncommon (Wilbur et al. 2009; Peterson and Bishop 2005).

**Conclusion:**

Ecosystem disturbances such as those associated with storms or beach replenishment, are events that subject some or all the resident biological community to stresses that exceed those normally encountered and result in a disruption of that community and its services for some period. Theory assigns recovery following such disturbance events as the set of conditions that the ecosystem will return to after the disturbance has passed and in the absence of any additional disturbances. This point of return can be considered the system's natural undisturbed equilibrium state. Recovery is realized when the disturbed site is restored to this reference state.

The equilibrium paradigm is based on two assumptions: 1) such an equilibrium state exists; and 2) that a system will restore itself to that base equilibrium state if left undisturbed for a sufficiently long period of time. However, much debate surrounds this notion of equilibrium with some positing that no such state exists at all. Many ecologists suggest that what is to be considered as natural equilibrium is a state that reflects more variability and dynamism than stasis. In other words, an ecosystem's baseline state is more likely than not to be one of dis-equilibrium.

Ecosystem recovery from disturbance, where that recovery reflects a return to some known baseline state, viewed from a perspective where dis-equilibrium is the norm, asserts that a unified absolute recovery target or definition perhaps cannot be known, or known only with great difficulty. In the absence of an absolute reference, an investigation must appeal to relative definitions for recovery that center on restoration of a disturbed system to some assumed equivalent reference state or condition. In this case relative refers to references built from observations at locations considered to be environmentally equivalent to the impact site. Equivalence is based on site-to-site comparisons made using a pre-selected set of environmental response variables. Recovery is then defined as that point of equivalence when no statistically significant difference remains between the response variables at the impact and control locations. Underlying this definition is the implication that recovery is based on some quantifiable similarity and not system equality. In the case of beach replenishment investigators implicitly describe recovery as an observed congruence between a selected set of baseline biotic attributes measured across one or more control beach habitats prior to the replenishment event (either at the impacted site itself measured before replenishment or one or more adjacent sites not receiving replenishment sands) and those same attributes monitored across the post-replenished beach. Congruence is defined and observed using statistical means when significant differences across biological variables between the impacted and control sites vanish.

Ecological restoration is seldom used as the principal justification for beach replenishment and the minimization of ecological disturbance during replenishment construction operations is often not a primary concern. Permitting requirements, nevertheless, often require some accounting of beach ecosystem impacts and anticipated outcomes. For the engineer who might consider ways to minimize ecological disturbance, leveraging what is known about sandy beach ecosystems and their response to replenishment is a useful first step. Many factors appear to play a role, but only a subset of these factors are within the engineer's purview. Evidence thus far points to a more favorable ecological outcome to replenishment coming through careful selection of the fill sediments utilized. Factors such as time of year, and delivery and dispersal methods (to perhaps lessen initial impact severity) play a role, but the greatest likelihood of realizing a desired ecosystem response (i.e., a robust, diverse ecosystem) hinges on the degree to which granulometric equivalence between native and post-replenishment fill sands is achieved.

Natural disturbance events are thought to be an inescapable part of all ecological systems. They are also arguably an intrinsic and even necessary component to those ecosystems. It is as yet unclear, however, the place of disturbance impacts as tied to human activities such as beach replenishment in shaping these systems. The restoration of new habitat in place of that lost due to chronic shoreline erosion along the replenished beach may or may not result in habitats more or less robust than those existing prior, but they will in some or many ways differ. This difference suggests that the assertion that most replenishment projects are finite duration pulse-type events is incorrect. We assert that all beach replenishment projects result in sustained change. The resultant new ecosystem thus emerging from replenishment will differ from that prior to the event. Further, quantifying these differences is impractical, and for now likely impossible. Many questions remain unanswered and most aspects of sandy beach biological community structure and function, and the community responses to disturbance events be they natural or anthropogenically-sourced, singular or successive, remain unknown. Whether or not these resultant changes prove to be ecologically for the better or for the worst is something that is as yet to be learned.

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**Author Contributions**:

Paul Paris participated in the field surveys, in laboratory sample processing, analyses of the data, and as lead author in preparing the manuscript.

Anya Leach participated in the field surveys, in laboratory sample processing, and made contributions to the manuscript

Reide Corbett participated in the field surveys and made contributions to the manuscript

**Conflict of Interest Statement**:

There exists no conflicting or competing personal or financial interests between authors and any other body or institution, either internal to the Coastal Studies Institute and East Carolina University nor with any other external individuals or public/private entities in association with this manuscript nor any section therein.

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**Figure Caption**:

Figure 1: Potential short-term (single recruitment season) response of the species Donax variabilis to a single beach nourishment event. The perturbative signal seen for the summer 2015 recruitment season is superimposed on, and in this instance is interpreted to amplify, the regular warm season abundance peak. The amplification here is possibly the result of the nourishment fill sands used that were slightly finer than those native to the beach and nearshore system. This resulted in sediment (sand) size characteristics that presented to the species more favorable environmental conditions for foraging and survival, albeit for only a single season. More typical seasonal populations are observed in subsequent years (2016 onward) as the fill and native sands quickly homogenized and the resultant grain size distribution profile was restored to pre-disturbance conditions. Confounding this interpretation is the unusually large peak see on the Control beach for the pre-nourishment 2014 season, which suggests that drivers other than beach nourishment may play an influential role in year-to-year abundances for the species.

**Figure 1**:

Chart, line chart

Description automatically generated