Dune management challenges on developed coasts

By

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Lillian Street in, Kitty Hawk, NC, October 2015. (Photo credit: North Carolina DOT, used with permission.)

Sand dunes are large coastal features typically formed when wind-blown sand is trapped and stabilized by vegetation. Located between the backbeach and inland features, they are an essential component of the coastal sediment budget and a primary control on the backshore ecosystem. In this role, coastal dunes provide essential ecosystem services, including habitat for endangered species such as piping plovers, sites of high tourism value, groundwater recharge zones, and protection of coastal infrastructure and properties from wave erosion and storm surge flooding. Foredunes that back many sandy beaches can be maintained naturally by the interactions between littoral processes (sand supply delivered to the beach by waves), aeolian processes (sand transport by wind over the sub-aerial beach), and critical ecological processes (sand trapping and vertical accretion by plants). Recent scientific research has focused on sediment movement between the beach and dune, including interactions between ecology and morphology (e.g. Sherman *et al*. 1998; Lancaster *et al*. 2013).

Dunes protect low-lying, developed coastal areas from elevated water levels and wave erosion associated with coastal storms (Sallenger 2000). The value of dunes has been recognized for decades (USACE 1962), but dunes have only recently been included as a "design feature" in shore-protection projects (USACE 1995). Today, coastal dunes are recognized as a cost-effective method of protecting community infrastructure from storm damage (NRC 2014). The expanded use of beach nourishment facilitates dune building by providing a sand source, accommodation space for dunes to form, and potential reduction in wave-induced erosion. Despite the value of dunes for shore protection and environmental benefits (Everard *et al.* 2010), their basic function as "dynamic" landforms and their role in providing these benefits isn't always well understood or appreciated by coastal landowners and beach users, and therefore sometimes not incorporated into design specifications.

Because of uncertainty in the forces that form and maintain dunes, managing a dynamic dune system at a range of spatial and temporal scales requires an adaptive management approach that is based on sound, scientific knowledge of coastal dune processes and grounded by systematic, accurate monitoring. This type of approach requires effective communication of reliable and accessible information across complex stakeholder networks, which can be challenging. An adaptive management approach to dune restoration and coastal protection is enhanced when all stakeholders have a basic understanding of the problem. The problem-solving process actually depends on individual and societal attitudes and perceptions, whose inclusion can improve the ability of coastal managers to achieve solutions that ensure a resilient coastal system. For example, high dunes in some areas, which offer greater storm protection, can be a point of contention for residents and visitors who wish to have easy access and a clear view of beaches for recreation purposes.

This paper represents a synthesis of ideas generated by nearly 100 members of the coastal science and management community who participated in the American Shore and Beach Preservation Association's (ASBPA) "Dune Management Challenges on Developed Coasts" workshop in Kitty Hawk, North Carolina, 26-28 October 2015, to identify ways to overcome the perceived gap between the research of scientists and engineers and the needs of management practitioners and other stakeholders. The purposes of the workshop were to (1) identify the challenges involved in managing, restoring and/or building dunes on developed coasts; (2) determine the highest priority research needs for managing dunes on developed coasts; and (3) identify approaches to help bridge the gap between scientific knowledge and management implementation. The workshop aimed to promote a non-technical dialogue and information sharing between researchers and managers/policy makers to collaboratively identify ways the technical community could provide and communicate solutions for design, natural evolution, and maintenance of dunes for consideration by practitioners. The consensus of the workshop participants was that successful dune management requires an adaptive and flexible approach that is: (1) locally-specific, educational, and engaging to stakeholders and (2) systems-based, considering the combined aspects of social, ecological, and morphodynamic processes. This paper aims to summarize not only the workshop discussions but also recent research on coastal dunes, a request made by managers who were in attendance.

MANAGEMENT CHALLENGES

The inherent uncertainties of beach and dune evolution, competing interests among stakeholders, and multi-scale physical, environmental, and socio-economic forces complicate the management of developed coasts. Management challenges discussed at the workshop focused on how to: (1) balance natural and human-use values when determining dune functions and needs; (2) sustain dynamic dunes given spatial and temporal constraints from static human development; (3) address long-term physical process challenges such as sediment supply, sea level rise, and chronic erosion; (4) manage stakeholder expectations and interests over both short and long time-scales; (5) provide improved education and outreach programs to support appropriate dune construction and management; (6) improve management planning and policies; and (7) prioritize funding challenges. The need to better incorporate input from social science was also identified as an emerging and important theme across the listed management challenges.

Balance dune functions

Sand dunes provide protection against wave run-up and inundation during storms, a niche for plants adapted to dynamic coastal conditions, habitable substrate for invertebrates, feeding areas for primary consumers, and higher trophic levels, nesting sites, refuge areas and corridors for migration (Peterson and Lipcius 2003; Everard *et al.* 2010). The greatest economic value of dunes is the protection they can provide for human infrastructure (Costanza *et al.* 2006). The value in reducing storm risks is related to dune elevation relative to prevailing storms, which determines susceptibility to wave overwash and flooding as well as sediment volume, which dictates the ability of the dune to withstand storms and maintain the integrity of the crest height (NRC 2014). Additional factors affecting the capacity of the dune to withstand storm hazards include sedimentary composition (Palmsten and Holman 2012), topographic complexity (Houser 2013), interaction with the built environment (Nordstrom *et al.* 2012), and vegetation (Feagin *et al.* 2015) — including invasive beach grass dynamics (Seabloom *et al.* 2013).

As discussed during the workshop, the USACE reviewed the performance of several federal storm damage reduction projects following Hurricane Sandy and found that projects backed by dunes generally performed better than those without dunes (USACE 2013). However, the benefits of engineered dunes for reducing coastal flood risks are not sufficiently quantified to predict their damage reduction potential. Increasing human pressure to develop the shorefront through time, and risk from coastal hazards associated with rising sea levels and possible changes in storminess accentuate the need to find ways to maximize the resource value of dunes in limited space.

Sand dunes also have direct human benefits beyond shore protection, including consumptive (mining, harvesting, waste disposal, extraction, and recharge of water) and passive (aesthetic, psychological, cultural and environmental heritage, and educational) benefits. The ability of dunes to provide natural and human values in developed areas is often diminished because dune dimensions are reduced either intentionally or unintentionally to facilitate shorefront construction, provide unobstructed views of the water, maximize space for beach recreation, or provide easy access to the beach. The ability of dunes to form and evolve can also be restricted by backshore raking for litter removal or vehicle traffic (Houser *et al.* 2012), both of which eliminate vegetation and beach wrack that trap blowing sand (Nordstrom *et al.* 2011; Nordstrom *et al.* 2012).

Generally, dunes designed primarily for shore protection are often maintained as stable, linear structures, similar to a sedimentary dike, with little diversity of topography and vegetation. In contrast, natural dunes vary in elevation and width (Elko *et al.* 2002) and present a more hummocky landscape with blowouts, depositional lobes, low swales and high ridges that provide a more diverse mix of habitat types. The lack of diversity of topography and vegetation in engineered dunes in developed areas may limit their ability to provide the full suite of benefits provided by natural (i.e. geomorphologically and ecologically dynamic) dunes.

Sustain dynamic dune systems

The factors influencing temporal and spatial scales of dune erosion and recovery differ on undeveloped and developed coastlines. Humans can affect the likelihood for dunes to form or grow, ultimately impacting the benefits dunes provide. Buildings, roads and shore protection structures can restrict the quantity of sediment and the space available for dunes to form; whereas, beach nourishment projects can re-establish sediment budgets and space for dunes. Natural dune evolution processes in undeveloped settings can lead to diverse morphological and ecological states. Humans alter these states and their trajectories through size, shape, and vegetation modifications (Godfrey and Godfrey 1973; Walker *et al.* 2013; Brodie and Spore 2015; Swann *et al.* 2015).

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Temporal constraints on dune evolution

Episodes of dune erosion are dictated by storm frequency and magnitude on developed and undeveloped coasts alike. Under natural conditions, dunes eroded by major storms can take years to decades to achieve their pre-storm morphology, depending on their initial height and volume and the frequency and magnitude of subsequent storms (Morton *et al.* 1994; Mathew *et al.* 2010; Houser *et al.* 2015). Human actions can speed the rate of dune recovery. Dunes can be constructed in a matter of weeks by bulldozers returning sand spread inland as overwash fans. Sand fences can be used to trap sand, encouraging dune growth within a year or two. Using vegetation to initiate dune growth on the backshore will often create a more naturally functioning dune, but it may take longer to be as effective as fences in trapping sand (Miller *et al.* 2001). The longer-term evolution and maintenance of dunes created by humans, however, depends on the positioning and morphology of the incipient dune, the sediment budget of the beach-dune system, and their maintenance by aeolian processes. Dunes that form by natural processes allow spatially-dependent dune plant communities to keep pace with topographic changes, thereby providing surface cover and root structure that maintains sand accretion and contributes to erosion resistance. Despite the advantages of building a dune using vegetation alone, the vulnerability of landward facilities in the initial years following major storms often encourages human intervention to accelerate the process of dune growth.

Spatial constraints on dune evolution

Beaches and dunes are part of a linked sediment exchange system that spans the coastal margin. The conditions for dune formation are fairly simple: an available sand source, wind strong enough for sediment mobilization, and an obstacle to trap sand (beach wrack, vegetation, microtopography, driftwood, sand fencing). In general, the wider the beach (or available sediment fetch), the greater the likelihood that dunes will form and survive (Short and Hesp 1982; Sherman and Bauer 1993; Hesp 2002; Aagaard 2004; Houser and Ellis 2013). Dunes also can persist landward of sandy beaches in relatively sheltered environments, such as estuaries and small bays, due to low wave energy and moderate to high aeolian activity.

Dune erosion by storm waves supplies sediment to the beach and nearshore, if dunes are not overtopped by waves. After the storm, recovery of the potentially increased width of the beach then provides a source for wind-blown sand and a wider buffer against erosion of incipient dunes during mild storms, allowing dunes to grow. Dunes can reform, even when wave attack and periods of dune destruction are frequent, although their morphology and associated vegetation types (eco-morphodynamic state) will differ from locations subject to less frequent wave attack (Roman and Nordstrom 1988; Wolner *et al.* 2013).

Waves from more intense storms transport sand inland via overwash. Under natural conditions, the sand may remain within the coastal system and may build new dunes farther inland (Godfrey *et al.* 1979). This process occurs when space exists landward to accommodate the migration or re-formation of landforms and habitats, and human efforts do not prevent it. Human development or actions that restrict overwash have reduced the formation of new washover habitat (Elias *et al.* 2000). This habitat has become rare in developed areas, resulting in increased threats to species that make use of it, such as piping plovers (Maslo *et al.* 2011; Schupp *et al.* 2013). Additionally, in developed barrier island environments, limiting natural overwash processes also prevents the island from migrating inland and maintaining its width and elevation relative to sea level. A key challenge in developed areas is finding and maintaining a balance between high dunes for storm protection and the need for barrier islands to migrate in response to sea level rise to maintain back-barrier marshes through overwash (Walters *et al.* 2014; Rogers *et al.* 2015). Additionally, coastal dunes can also migrate landward by wind erosion of the seaward side, with deposition on the landward side (Ollerhead *et al.* 2013). However, the inland transfer of sand is often prevented by human action to avoid inundation of properties, buildings, agriculture and infrastructure.

Dynamic features vs. static infrastructure

Natural dunes are inherently dynamic features that respond to changing environmental conditions and develop diverse habitats. As demonstrated by the workshop, interest in restoring portions of stabilized dune fields to enhance morphodynamics, landform complexity, and ecosystem resilience for native and endangered species is increasing (e.g. Nordstrom 2008; Arens *et al.* 2013; Hesp and Hilton 2013; Walker *et al.* 2013; Pye *et al.* 2014). Still, it is not known how much mobility can be integrated into dunes built for shore protection without sacrificing integrity as a barrier against overwash. Some engineering projects have been developed to allow for dynamic response by mechanically altering the dune (Schupp *et al.* 2013) or by judicial use of sand fences (Grafals-Soto 2012), but greater creativity in initial actions and greater commitment to follow-up activities could be explored.

Experiments comparing natural dune evolution to dune development influenced by humans, through the installation of sand fencing, for example, indicate that once dunes begin to be established, there is little difference in dune volume. Natural processes can enhance vegetation growth and diversity, but do not necessarily increase dune height (Nordstrom et al. 2012; De Jong *et al.* 2014). Because dune recovery after storms is not immediate, vegetation plantings, aided by fences, may be required to initiate further recovery by natural processes.

In addition, static human structures can directly affect dune evolution. Permanent footpaths across dunes can result in low elevation points where flood waters can intrude or wind erosion can focus, compromising an otherwise continuous stretch of dune height and volume. Oceanfront development restricts space for natural features to form. Undeveloped oceanfront areas, such as empty lots or protected natural areas, often have wider beaches providing more space for dunes to grow naturally. The extent to which dune systems in these areas should be managed by humans or maintained by natural processes is a challenge to find the balance of a predictable level of protection for the buildings and infrastructure surrounding them.

As with all natural systems, allowing dunes to be more dynamic and topographically variable may increase difficulties in predicting how dunes will evolve or how well they will be able to reduce damage to infrastructure as a function of wind and high water levels. In general, there was a sense among workshop participants that a greater reliance on adaptive management will be required in the future, and that incorporating new measures into initial designs will require stakeholder involvement, potential policy changes, and special project funding.

Address long-term physical processes challenges

Workshop participants noted that coastal managers are increasingly asked to develop management plans and strategies that address longer-term climate change impacts and their potential effects on coastal erosion rates, flooding and shoreline development. Vast amounts of sediment are required for shore protection, beach nourishment, and landform restoration under present conditions, and the need will only increase with sea level rise and possible changes in the frequency and/or magnitude of coastal storms (Orford and Pethick 2006; Williams *et al.* 2012). On coasts where landward transgression is limited due to static human development and infrastructure, rising sea level can lead to reduced sediment supply, chronic erosion, and flooding problems. At these locations, it may be unclear as to whether a dune system is a sustainable, cost-effective solution for reducing storm damages.

The subaerial beach sediment budget is a critical factor in maintaining dunes seaward of human infrastructure. The volume of the subaerial beach can change in response to wave, current, and wind-driven cross-shore and alongshore transport, as well as human actions, like beach nourishment, as the active littoral zone sediment is exchanged between the surf-zone, beach, and dune systems. This morphodynamic response can occur rapidly during storms, seasonally with changing wave and wind climates, and on longer annual to decadal scales in response to changes in sediment supply and sea level, and may vary alongshore depending upon the nearshore bathymetry (e.g. Houser 2009) and underlying geologic strata. The interaction of all of these processes and timescales is important for determining the evolution of the coastal foredune system and its ability to persist. For example, narrow, steep beaches result in reduced sediment supply for dune growth, frequent inundation and destruction of recovering incipient foredunes, and smaller fetches over which wind can transport sediment, rendering natural dune recovery processes less effective (Short and Hesp 1982).

An example of particular interest to workshop participants is from the Town of Kitty Hawk, NC, where the primary foredune cannot sustain itself due to chronic erosion and frequent high water levels during storms. Without a significant fore-dune, flooding and damage to infrastructure can extend well inland, even during moderate coastal storms, creating substantial management challenges (G. Perry, pers. comm., 27 October 2015). When shoreline development is situated seaward of the foredune, the amount of sediment needed to construct a sustainable beach fill that will provide immediate and significant storm damage reduction can be cost-prohibitive (K. Willson, pers. comm., 27 October 2015). Abandonment with subsequent retreat is rarely an option for well-developed communities, and so managers must still "do something." In this case, the community has elected to construct an affordable beach and dune restoration project to reduce inundation during storms and encourage dune growth through natural and human-assisted (planting and sand-fencing) recovery processes. How this and similar solutions will perform over multiple year time-scales and in locations where there is insufficient space to support natural dune development, however, is unknown, and highlights the management challenge of finding sustainable, cost-effective solutions.

The natural response of coastlines to sea level rise, particularly on barrier islands, is to transgress landward through overwash processes. As discussed previously, dune systems on developed coastlines are often forced to remain static, not allowing them to recover and migrate with overwash processes over the longer-term functional timelines of shoreline transgression. The presence of human barriers to sediment transport in developed areas implies that much of the needed sediment to maintain a wide beach and dune system will have to come via nourishment operations using beach-quality sediment or via bypass operations at inlets. Determining how to effectively manage dune systems so that they can both adjust in the short-term and also adapt over longer time-scales to changes in physical forcing is critical to maintaining resilient coastal communities.

Manage stakeholder expectations and interests over short and long time-scales

In the U.S., most states operate under the Coastal Zone Management Act of 1972 (https://coast.noaa.gov/czm/act/), which emphasizes the importance of considering ecological, cultural, historic, and esthetic values as well as the needs for compatible economic development. In highly developed areas, pressure to focus management policies on maintaining the physical environment's ability to support urban, commercial, and tourism uses, can lead to management approaches which do not adequately serve all stakeholders (James 2000; Villares *et al.* 2006; Roca and Villares 2008; Lozoya *et al.* 2014). Determining how to balance the human desire for short-term stability (management of vulnerability) with long-term ecosystem sustainability (management of resiliency) is a great challenge for coastal managers, scientists, and politicians (Jackson *et al.* 2013).

A substantial body of literature has accumulated documenting the need to incorporate stakeholders in design of projects and co-production of knowledge (Safford *et al.* 2009; Nagy *et al.* 2014), indicating the benefits of a balanced mix of top-down and bottom-up communication. The state of Delaware conducted workshops and established an advisory committee to acquire stakeholder feedback as part of an update to its coastal development rules (DNREC 2015). When the state of Texas initiated its coastal management program in the early 1990s, involvement of stakeholders was critical to the success and direction of the entire program (NOAA 1996). These are two examples of ways coastal states provide channels of communicating the needs for beach and dune management programs that will engage local managers and residents.

Management of coastal environments is also complicated by inherent uncertainties about how dynamic coastal systems will behave over both short and long time-scales and under competing interests and changing physical, environmental, and socio-economic forces. Understanding how this uncertain system behaves at a range of spatial and temporal scales and developing appropriate solutions requires an adaptive management approach (Williams 2011; Conroy and Peterson 2013). For example, the "engineering with nature" approach incorporates natural and nature-based features into management plans (Bridges *et al.* 2015). This approach may enhance the natural resiliency of coastal systems as the "natural" aspect of features are allowed to continually evolve, but also introduces a lack of certainty when compared with more traditional hardened shoreline protection approaches. Workshop participants discussed that these newer approaches require strong communication between all stakeholders. Strong communication will allow all stakeholders to have a voice (Scheffer *et al.* 2003) and have access to reliable and accessible information (Folke *et al.* 2005) which enables an appropriate understanding of the problem and balanced decision making (Scheffer and Westley 2007).

After all stakeholders understand the problem and are able to voice their interests, local managers may be challenged with forming a stakeholder consensus in order to obtain acceptance of solutions. Ideally, all parties are informed of opportunities and constraints and the needs of stakeholders are balanced. When resources are restricted, local managers need to prioritize needs of stakeholders, such as maximizing hazard reduction function or providing habitat for endangered species. Alternatively, if preservation of shorefront vistas, access to the beach, and recreation space is prioritized, the final management plan may discourage formation of dunes, reducing their value for protection and other environmental services, even where good conditions for dune growth exist.

The desire for access paths can result in low points in the otherwise high dunes in the short term leading to increased overwash problems in the long term, and the desire for shorefront views may result in dunes that are too low to withstand high storm-induced water levels, decreasing coastal resiliency over the long term. Similarly, desire for large recreation spaces and retainment of property rights may result in narrower dunes that are restricted from building seaward, decreasing the dune's ability to withstand repeated collisions by waves. As presented during the workshop, the desire to maintain a suburban style of landscaping may cause owners to plant lawn grass or other exotic species that would not be found in a coastal location

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under natural conditions (City of Miami Beach and CMC 2015).

In contrast, some beach users may be sensitive to the state of the physical and biological environment placing great importance on beach ecosystem values (Lucrezi and van der Walt 2015). These stakeholders may place higher value on actions that provide care and stewardship of the coast (Tunstall and Penning-Rowsell 1998; Maguire *et al.* 2011; Voyer *et al.* 2015). Beach nourishment and restoration is also valued by many stakeholders who recognize that tourism can decline where beach widths have decreased (Houston 2008) and/or ecosystems have been degraded (McLachlan *et al.* 2013). As discussed at the workshop, stakeholder interests may also change over time as communities evolve—the coastal management plan may need to be updated to reflect new consensus or priorities (R. Trevino, pers. comm., 27 October 2015). Workshop participants stressed the need to better incorporate input from social science to ensure balance in prioritization of stakeholder desires toward resilient communities.

Provide improved education and outreach

As discussed in this paper and presented at the workshop, extensive scientific information exists on how dunes naturally evolve and maintain themselves, providing key ecosystem and storm protection functions; however, effective communication and dissemination of this information to local officials and to the public is often limited. While findings from academic studies are often presented in peer-reviewed journals with limited exposure to the public, some funding programs (e.g. National Science Foundation and NOAA/Sea Grant College Programs) require descriptions for public outreach and education in their calls for proposals. Many agencies use websites or other social media outlets to offer publications that provide for best management practices (e.g. Massachusetts Office of Coastal Zone Management); however, educating coastal landowners and beachgoers remains a challenge. Some workshop participants advocated for the need to, and benefits of, distilling and synthesizing research findings into more easily accessible summary documents that community managers and practitioners can use as they consider the role of dunes in local communities.

As discussed above, strong communication and education of all stakeholders are critical components for developing successful dune management strategies. Efforts to adequately educate all stakeholders are important, but ultimately the information may not be equally accessible to all stakeholders. For example, tourists and shorefront residents may be harder to reach than local officials, but their education is critical — expectations and actions of tourists can influence the way municipalities manage the shorefront, and expectations of the general public can affect the will to fund coastal projects.

Realistic expectations of the role that dunes play in the coastal zone are key. Dunes may assist in protecting coastal communities but, especially in areas where barrier islands are naturally transgressive and in the face of sea level rise, they should not be regarded as a panacea. The role of a dune during a storm is to withstand impact by large waves and surge — a scarped or heavily eroded dune is evidence that the dune was successful in absorbing that storm impact. Similarly, windblown sands and the landward progression of dunes are part of that dynamic environment, but oftentimes are perceived as a nuisance that must be controlled or stopped altogether. Stakeholder education and adaptive management can help to appropriately convey the advantages, limits, and potential morphologic states of nature-based solutions.

Effectively communicating accurate scientific information about dynamic three-dimensional landscapes which can have a variety of natural states is difficult. However, educational materials that take advantage of today's technology and state-of-the-art data sets — frequent aerial imagery (e.g. NOAA's Storm Response Imagery http://storms.ngs.noaa.gov/eri_page/index.html), time-lapse videos, or three-dimensional point clouds from Lidar or photogrammetry — may make visualizing changing coastal landscapes more accessible. Creation and effective dissemination of these materials, however, requires (1) scientists to make the data available for development of education materials, (2) social scientists and educators who develop these materials to have both resources and knowledge to exploit, display, and translate these data, and (3) local managers to help effectively distribute the educational materials.

Improve management planning and policies

Dune management planning and policy making is often the responsibility of local municipalities and counties. Ordinances and codes differ in the way dunes are addressed, reflecting differences in levels and types of development and land use, state beach and dune management policies, and the presence of other means of shore protection. More comprehensive decision support models could help guide policy and management implementation, particularly in viewing dunes as a multi-faceted resource to be managed adaptively.

An example of a local, adaptive effort for managing dunes mentioned at the workshop is the Nueces County (Texas) Beach Management Plan (Nueces County 2010). The plan follows rules promulgated by the state for dune protection and beach access (Texas Administrative Code §15.1-15.10, GLO 1993) that allow local governments to take the lead in identifying critical dunes and permitting activities that protect them. Through the local permitting process the Nueces County plan allows dunes to naturally evolve and protects them via building setbacks and mandatory dune walkover standards. As a result of implementing the plan, local citizens and coastal landowners are more aware of the integral role beaches and dunes have in storm protection.

Private residents and/or local communities often conduct beach scraping to restore damaged dunes. Most coastal states have oversight of modifications to the active beach, even if privately owned (NOAA 2000). Beach scraping is a controversial policy in terms of its effectiveness for long-term shore protection and environmental compatibility (Wells and McNinch 1991; McNinch and Wells 1992). An updated, comprehensive review of state permitting policies and regulations related to sand scraping and other beach and dune management approaches would benefit the national community of practice.

Development of best practice guidelines for dune building and subsequent management would help guide integrated beach and dune management. General principles for designing dunes to provide flood protection and enhanced ecological functions and values exist (Nordstrom *et al.* 2011), and dune management guidelines for use by municipalities and residents are readily available (Texas General Land Office 2015; Rogers and Nash 2003; NJSGC 2016). The rationale for building dunes for shore protection is often the focus, but the broader issues of environmental restoration, species conservation, and the need for adaptive management may require attention.

Prioritize funding challenges

Planning, installation, and maintenance of dune restoration are frequently implemented at the municipal level. The cost of both dune and beach restoration projects are likely to increase in the future as maintenance operations become more frequent and additional sediment must be added to overcome increasingly large sediment deficits. Large-scale dune building projects may require federal and state funding and long-term commitments for monitoring and maintaining beaches and dunes to achieve the desired level of protection (e.g. Kana 2012).

Shore protection alternatives have previously been assessed using the risk-standard approach (most commonly addressed in terms of the protection needed against the 1% chance return level event) and are presently justified federally through the benefit-cost approach that can measure the risk reduction benefits more directly in economic terms (NRC 2014).

Studies that provide reliable economic data to quantify benefits specific to dune-building projects are needed. For instance, the economic value of dune building projects can be estimated by comparing the storm-induced economic losses in areas lacking dunes with damages landward of areas with enhanced dunes (e.g. USACE 2013), but it is difficult to separate economic benefits of dunes from the beach nourishment projects that accompany them (NRC 2014).

Economists have developed a range of methods for estimating nonmarket value associated with environmental and social benefits (McNamara *et al.* 2011), but large gaps remain in the ability to accurately measure benefits (NRC 2014). Nevertheless, it is important to estimate the value of both ecosystem services and social benefits, and then communicate the value to stakeholders.

The uncertainties with future changes in sea level, sediment sources, and erosion rates may increase the need for proactive funding for adaptive management. Coastal managers will be challenged to design models for all of the lifecycle requirements (short- and long-term needs, tradeoffs, and uncertainties) required to execute adaptive management (Kelly *et al.* 2013). Long-term funding commitments will require stakeholder, community, and state manager buy-in, authorization, and appropriations.

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RESEARCH NEEDS

Workshop participants identified a number of specific research needs, ranging from remaining fundamental science questions (e.g. the nature of interannual- to decadal-scale dune evolution, shorter-term recovery dynamics from erosive events, dune ecomorphodynamics), to practical questions about project design and public education (Table 1). The specific suggestions were grouped into the following five research themes or goals:

1) Improve numerical *models* of dune formation, growth, and erosion to cross spatial and temporal scales,

2) Expand *observations* of beach-dune morphodynamics and sediment budgets over greater spatial and temporal scales,

3) Develop *systems-based management approaches* by integrating hydrodynamics, geomorphology, ecology, and coastal management,

4) Identify *success factors* and incorporate into dune *designs* and management plans, and

5) Quantify and convey *social and economic benefits* to a coupled natural/human dune system.

Improve numerical modeling capability

Realistic models based on field data are needed to design projects and inform policy. Models of aeolian transport and dune evolution need to be developed and evaluated on time and space scales relevant to human-altered dunes (i.e., several years to decades). Based on the coastal science communities' understanding of hydrodynamics and sediment transport, process-based numerical models have been developed to simulate these storm-induced coastal change hazards. These models, such as the eXtreme Beach (XBeach) model (Roelvink *et al.* 2009) and CSHORE (Johnson *et al.* 2012), have been shown to perform skillfully in predicting dune erosion, overwash, and breaching processes (e.g. Splinter and Palmsten 2012). Significantly less attention has been paid to post-storm recovery processes which allow for beaches and dunes to rebuild and grow during calm conditions. Beach recovery is the aggregate of aeolian, hydrodynamic, and ecologic processes, and not all of these processes are included within storm response models.

To explore the simultaneous role of aeolian and ecological processes on dune evolution, the Coastal Dune Model (CDM; Duran and Moore 2013) has been developed to explore ecomorphodynamic feedbacks of vegetated sandy coastal systems. CDM solves for a 2D, spatially variable wind field and seasonally and spatially variable vegetation cover. Based on gradients in sediment transport arising from vegetation cover, slope effects, and wind velocities, the model solves for changes in subaerial beach morphology. CDM has been used largely as an exploratory model for dune behavior and is in the process of being validated as a field-scale model. CDM is currently being coupled with XBeach to allow process-based simulations of the nearshore, beach and dune system throughout multiple cycles of dune erosion and recovery following storms.

Future mechanistic modeling efforts are needed to better understand the role of interactions between nearshore, beach and dune systems, the role of climate change in altering beach and dune sediment supply, the effects of species composition on dune height and volume and the effects of natural vs. human activities on dune evolution.

Expand observations over greater spatial and temporal scales

Field monitoring of both short- (episodic to seasonal) and long-term (interannual to decadal) beach-dune dynamics and evolution is required to understand the physical processes that drive dune morphodynamics. This challenge is longstanding in coastal geomorphology as these processes span both terrestrial and littoral domains, have widely varying spatial and temporal scales of operation (from seconds to millennia and mm to 100s km), and have nonlinear interactions that can produce a variety of possible end states and trajectories.

Since the 1950s, geomorphology research has generally evolved into two dominant foci: broader "macro" scale interpretation of Quaternary landscapes (e.g. Holocene barrier development and evolution) and a finer "micro" scale study of physical process–response dynamics at the landform to sub-landform scale (e.g. airflow and sand transport dynamics over beach-dune systems). Over the past two decades, there has been a growing emphasis on "micro" scale process-oriented research that relies largely on site-specific, short-term experiments and/or simulations that are reliant on instrumentation and computational technologies. Recent progress on modeling sand transport on flat vegetated surfaces (Buckley 1987; Okin 2008; Leenders *et al.* 2011; Dupont *et al.* 2014) and over foredunes (Sarre 1989; Arens 1996; Chapman *et al.* 2013; Keijsers *et al.* 2015) is impressive, but predicting resulting erosion-deposition patterns and related dune evolution remains limited to a few novel simulations (Baas and Nield 2007; Duran and Moore, 2013) that often lack empirical validation.

Given this evolution in geomorphic research, a knowledge gap remains at the meso-scale (landform to landscape, interannual to decadal) (Sherman and Bauer 1993). This scale is key for dune management as it the operational scale for beach-dune sediment budgets, dune maintenance and recovery cycles, and plant community dynamics. In addition, this is the scale at which management decisions are made and implemented, human perceptions of risk and change are most aware, and many political and economic processes that govern coastal management resonate. Currently, there is comparatively little research on meso-scale beach-dune morphodynamics although new approaches have emerged using near-field remote sensing (e.g. vantage photogrammetry, unmanned aerial systems [UAS]) or high-resolution aerial Lidar and terrestrial laser scanning (TLS) surveys to quantify beach-dune geomorphic changes, transport event regimes, and/or sediment budget responses at the meso scale (e.g. Stockdon *et al.* 2007; Delgado-Fernandez and Davidson-Arnott 2009; Eamer *et al.* 2013; Walker *et al.* 2013). Ideally, a meso-scale approach can quantify both driving processes (i.e. frequency and magnitude regime of both erosive and transporting events) and resulting geomorphic and sediment budget responses (derived from digital elevation model (DEM) surface maps) that, in turn can provide a sound empirical basis for the development of predictive models (e.g. Delgado-Fernandez 2011) and computational simulations of coastal dune evolution (e.g. Duran and Moore 2013).

The majority of research on coastal dune dynamics has examined relatively natural, undeveloped systems (Stockdon *et al.* 2007), although there are a number of recent studies that include a broad range of environments (Stockdon *et al.* 2012), or even focus in more developed settings (e.g. Nordstrom *et al.* 2007; 2011; Jackson and Nordstrom 2012). It is important to recognize, however, that the dynamics and trajectories of each are governed by different geological, climatological, ecological, and oceanographic controls – all of which are superimposed on and confounded by human interventions and infrastructure.

An inventory of existing efforts wherein natural dune processes have been incorporated and, importantly, monitored for over sufficient time scales to detect performance and recovery from disturbance events is essential. Although it is possible that such instances are rare, field studies of projects implemented in developed areas (e.g. Nordstrom *et al.* 2002) can supply much-needed evidence of successes and failures. In parallel, there remains a need for further fundamental research on meso-scale dune behavior and recovery to erosive events so as to improve understanding of the linkages and exchanges between nearshore, beach, and dune components of the system. In addition, more information is needed on the interactions between plant communities, aeolian transport and sedimentation processes, and seasonal to interannual phenology and ecological dynamics, so as to better inform vegetation management and restoration efforts associated with dune building and maintenance. Such datasets, case studies, and empirical observations provide baseline information to form the basis for numerical and conceptual models. In recognition of the impetus of and needs identified by this workshop, participants stressed that this information be gathered not only from natural dune settings, often preferred for research purposes, but also to include developed areas subject to the additional challenges of human activities, infrastructure and development pressures.

Develop systems-based approach

It is important to better understand interactions between hydrodynamic, geomorphologic and ecologic processes and coastal management processes in dynamic dune systems. Coastal dunes evolve through the feedback between vegetative and sediment transport processes (Hesp 2002; Hacker *et al.* 2012). For example, in the U.S. Pacific Northwest, a suite of interdisciplinary field, laboratory, mesocosm, and computer modeling experiments have examined the relative role of vegetation in determining dune geomorphology with particular attention to how dunes of different shapes result in variable levels of exposure to coastal hazards (Hacker et al. 2012; Zarnetske *et al.* 2015). In this region dune shape is primarily a function of sediment supply and two species of non-native beach grasses (*Ammophila arenaria* and *A. breviligulata*). Over recent decades, *A. breviligulata* (American Beach grass) has increased its dominance over *A. arenaria* (European Beach grass) on dunes where it was originally planted and has actively spread to new sites formerly dominated by *A. arenaria*.

A species-specific biophysical feedback occurs between sand deposition and beach grass growth habit, resulting in distinctly different dune geomorphologies in locations dominated by these different grass species. The dense, vertical growth habit of *A. arenaria* allows it to capture more sand, produce more vertical tillers, and build taller, narrower dunes, while the less dense, lateral growth habit of *A. breviligulata* is more suited for building shorter but wider dunes. The species-specific feedbacks, along with invasion dynamics, have a first order effect on

Table 1. Research needs for dunes in developed areas.

Specifying functions of dunes

- Identify and quantify ecosystem services
- Identify the role in the food web of species found in the dunes
- Quantify the benefit (magnitude and cost) in reducing storm inundation, wind and wave damages to landward infrastructure
- Specify the role of dunes in barrier island evolution (including overwash areas, marshes, and inlets)
- Identify the implications of sea level rise on maintenance of functions

Overcoming constraints to dune formation

- Determine dune evolution under varying wave environments
- Identify sediment sources and sinks (cross-shore and alongshore) and impediments to transfers
- Determine potential for obtaining and using external sediment sources
- Identify long-term shoreline change rates and the impacts on dune development

Addressing needs for design of dune-building projects

- Develop realistic field-based models for dune building under space and time constraints
- Determine transferability of data and models from natural systems to engineered dune systems
- Determine metrics for success in providing storm-damage reduction and environmental benefits
- Identify drivers of landform and habitat zonation under natural and developed conditions
- Evaluate ways to accommodate shore-perpendicular access without threatening dune integrity
- Assess the roles of undeveloped and unprotected lots within developed and protected shoreline segments
- Assess tradeoffs between building dunes by natural processes versus using bulldozed sand from external sources, employing sand-trapping fences, or planting vegetation
- Assess the value of resistant cores inside dunes
- Identify the best ways of helping dunes evolve after initial construction
- Determine how much mobility is needed for diversity of landforms and habitats
- Determine how to balance mobility against the need for protection and stakeholder acceptance
- Specify requirements for adaptive management to overcome future unknowns

Addressing funding needs

- Develop criteria for protection levels and costs, given increasing sea levels and storm impacts
- Develop more reliable benefit-cost data for the spectrum of benefits provided by dunes
- Determine requirements for providing long-term maintenance and adaptive management
- Identify funding sources

Policy needs

- Identify tolerable risk
- Develop decision support models on levels of protection to guide policy and local actions
- Develop criteria for implementing managed realignment or favoring greater landform mobility
- Base strategies on existing successful strategies
- Make response to storm hazards proactive, not reactive

Education and outreach

- Find ways to explain the advantages and limitations of nature-based solutions
- Find ways of integrating physical and social processes in decision-making, including economic benefits
- Ensure two-way communication pathway to obtain stakeholder expertise and **support**
- Gear messages toward actual capabilities of local stakeholders (identify achievable options)
- Ensure stakeholders (and policy makers) have realistic expectations
- Target tourists and non-coastal residents to broaden the support base for coastal projects
- Inform property owners of the significance of their participation on municipal and private lands
- Determine level of understanding of stakeholder groups and target guidelines
- Make guidelines easy to understand and useful without losing comprehensiveness
- Share existing successful policies and practices

the region's exposure to coastal hazards, in the present day and under a range of climate change and invasion scenarios (Seabloom *et al.* 2013).

Identify success factors and incorporate into dune designs and management plans

Metrics, functional timelines, and evaluation criteria are needed for determining when and how to construct dunes, employ fences, plant vegetation or incorporate resistant cores within dunes, and assess overall project performance. The ways dunes can be built by human efforts are better known than the advantages and disadvantages of these constructed dunes. There is a need to quantify the value of dunes, once built, in terms of erodibility and ability to evolve to provide habitat or aesthetic resources. Metrics needed to quantify success of dunes in providing storm damage reduction include beach berm width and elevation, dune shape, dune volume (in relation to wave erosion and overwash), frequency and magnitude of high water levels, rates of vegetation growth (initial and recolonization), and requirements for recovery and sustainability of entire systems (beach/dune/barrier island).

Research on use of fences and vegetation is extensive (e.g. Woodhouse *et al.* 1977; Knutson 1977; Miller *et al.* 2001), but many time-specific and site-specific challenges remain. For example, fence designs that accumulate most sand initially are not necessarily the best designs for later years, and similar types of fencing can yield considerable differences in dune volumes, depending on location (Mendelssohn *et al.* 1991).

Natural aeolian accretion can facilitate sustained dune building, growth of vegetation, and habitat formation on restored dunes and reduce the need for further maintenance (Smyth and Hesp 2015). Alternatively, continued use of sand fences, once a dune has been built, can perpetuate cultural boundaries, limit public access or restrict natural evolution of foredunes (Grafals-Soto 2012). Identifying the likelihood for human-altered dunes to evolve by natural processes could reduce the tendency to over-manage dunes.

Metrics are also required to determine success of dunes in providing environmental benefits (e.g. Schlacher *et al.* 2014). The concept of resilience, absorbing damage, recovering after disturbances, adapting prior to future disturbances (Schultz *et al.* 2012), can apply to the benefits provided by dunes. Height and volume, which are critical in providing protection, are only two of the important factors affecting resilience. Dunes designed for shore protection often have a single flat-topped ridge to maintain a predictable level of protection against wave run-up and flooding and maintain integrity of the crest during erosion. Recent investigations of sediment transport and vegetation diversity point to the advantages building dunes with greater topographic complexity, including a double ridge crest and intervening swale (Grafals-Soto 2012; Smyth and Hesp 2015), which enable the dune system to better recover and adapt. Greater dune elevation and topographic variation can compensate for reduced beach width in providing for greater species richness (Bissett *et al.* 2014).

Understanding of implications of incorporating resistant cores in dunes is limited, but interest in these hybrid dune forms is likely to grow if restrictions in space require structural solutions as backup protection (Irish *et al.* 2013). Combinations of techniques for dune building might be more successful than a single technique (Mendelssohn *et al.* 1991), indicating the need for evaluation of more complex designs, as well as flexible management programs and policies.

Finally, vegetation metrics are needed to quantify ecological and storm-damage reduction benefits and design a dune system that can retain the habitat value of natural dunes in developed areas. Studies of vegetation are common, at least for the dune-building species, but studies of the significance of human altered dunes to fauna are poorly represented, except for endangered species.

Quantify and convey social and economic benefits

Workshop participants agreed that quantifying the costs and benefits of the entire beach/dune system will be important to develop informed decisions on management challenges, funding levels, and funding sources. Managers and researchers need to understand personal, social, institutional, and cultural perceptions of the risk amongst stakeholders, which in turn requires an understanding of the governing system, stakeholder relationships and public perception (Olsen 2000). However, there is a paucity of studies into community perception and understanding of coastal risks and barrier island resiliency. Further study would stimulate and assist management decisions of beach and dune systems, from the construction of hard structures to re-nourishment projects, dune restoration, beach raking, and decisions about beach access.

RECOMMENDATIONS

The challenges and needs identified in this paper reflect the backgrounds of the workshop participants and emphasize engineering, geomorphology, ecology and municipal planning. There is a clear need to engage a broader range of social scientists to find out how physical science and economic evaluations can expedite social decision-making. There is also more dune research occurring in the U.S. than many workshop participants realized, highlighting an opportunity to leverage existing facilities and resources and for nationwide information sharing.

At present, a limited national approach has been taken in designing research projects or applying the results to management. Because the physical and social constraints differ between shorefront communities and between state and local levels of government, broadening the scope of a nationally consistent effort will be challenging. However, the usefulness of results of individual studies will be increased by coordinating efforts in data collection and management, maintaining centralized databases and products, and developing an effective means of information sharing. Data and research results that are broadly available and well-communicated would enhance scientific progress. The connection between scientists/engineers and coastal managers can be addressed through a strong, diverse community of practice (COP) that provides a forum to exchange ideas.

The COP would serve to advance the field and create new directions in research by increasing interdisciplinary collaboration and engagement across academia, federal and state agencies, and community managers. The COP could achieve its goals by leveraging resources and facilitating the exchange of ideas and results to move the state of the art of dune management and research forward, to develop community standards, and communicate the results to stakeholders.

The workshop participants agreed that the American Shore and Beach Preservation Association (ASBPA) was an ideal organization, with its partners, to coordinate and foster the new COP, through continued workshops and an online presence.

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Editorial

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range provided by the IPCC. The State of California, my employer, is one such group, with sea level rise projections that are based on a National Research Council report developed specifically for the western continental U.S. Jim’s paper should spark some interesting discussions and people are encouraged to submit additional Coastal Forum pieces to add to or counter Jim’s discussion.

Articles in this issue all come back to the proliferation of coastal data and observations and questions about how to use them. Jim Houston notes that some agencies use the likelihood of new information as a reason to use sea level rise projections that are outside the range provided by the IPCC. The IPCC process provides for a 5-year update cycle that systematically allows new data to be vetted and incorporated into trends and projections. Perhaps coastal areas need to consider a quasi-systematic procedure for updating erosion and shoreline change data that blends together recent episodic events with longer-term historic trends. The loss of 30-50 feet of coastal bluff in Pacifica does not start a new 15-25 feet per day erosion rate but it calls into question whether the 2 feet per year erosion rate remains appropriate for Pacifica. This question is especially important to other properties in the city that are experiences episodic erosion during the 2015-2016 El Niño season.

Traveling from one coast to another, I am encouraged by Tim Kana’s optimism that some of our efforts at coastal management are working well. I hope he and others will continue to encourage current and future coastal professionals to continue chipping away at important coastal issues.