2 The Coastal Foredune: A Morphological Basis for Regional Coastal Dune Development

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2.1 Conceptual Setting

Coastal dunes are ubiquitous elements of the dune-beach system that exist along the shores of many water bodies in the world where waves and currents interact with available sediment and local vegetation to create combinations of form and habitat at the water-land interface. They occur in a variety of dimensions from minor hummocks of 0.5 m to huge ridges measuring more than 100 m in elevation; from a single, shore-parallel, linear ridge with a width of a few tens of meters to a complex of dune forms that extend inland tens of kilometers. From a geomorphological perspective, the commonality associated with this myriad of forms and situations is the amassing of sand to create a depositional landform proximal to the shoreline.

The fundamental concept in coastal geomorphology is that processes of wind, waves, and currents act upon the sediments to produce a set of landforms that are causally related. This relationship is described as a process-response model and it is the conceptual foundation for all geomorphological inquiry. In coastal areas of adequate sediment supply, the coastal process-response model is the beach profile: the accumulation of sand that extends from the offshore bar, through the dry beach, and into the adjacent coastal foredune where vegetation stabilization is a further active element of the morphological process (Fig. 2.1). This dune-beach profile is the basic sand-sharing system whose components respond to variations in energy level and to mobilization of sand from one portion to another. Each component episodically stores and releases sand in an exchange of sediment, a classic closed system.

The coastal foredune is the uppermost and inlandmost component of the sand-sharing system. It has accumulated sand in association with a range of pioneer vegetation types to create a positive landform perched above the dry sand beach. It is the most conservative portion of the profile, undergoing

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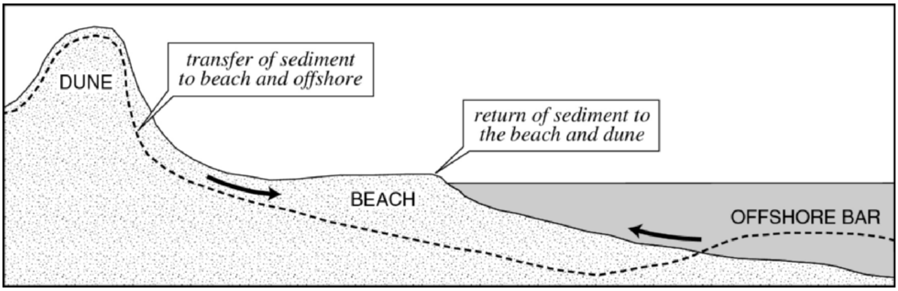

Fig. 2.1. Exchange of sand within the sand-sharing system

dimensional and temporal changes of far less magnitude and frequency than the sand beach or the offshore zone. In this simple profile, the coastal foredune exists at the boundary between the coastal processes to its seaward and continental processes landward. However, many coastal zones are not so simple as this profile and there are many instances of variable dune configurations and areas immediately inland of the dune-beach profile that appear to be morphodynamically related to the processes active in the sand-sharing system. Within this complexity lie some of the basic issues regarding the geomorphology of coastal dunes. Such as, are there constraints to the configuration of the foredune relative to some aspect of the delivery system? Is there a developmental sequence and what are the variables that affect the morphological characteristics of the foredune? How is the dunal topography inland of the dune-beach profile integrated into the regional dynamics? Is all coastal dunal topography site specific?

2.2 The Dichotomies of Inquiry

The inquiry into the formational processes and the configuration of coastal dunes has produced a spate of conferences and papers (Gimingham et al. 1989; Nordstrom et al. 1990; Carter et al. 1992; Pye 1993; Favennec 1997). A review of these contributions reveals a number of geomorphological dichotomies in coastal dunes that cannot be completely bridged. Sherman (1995) describes a division in coastal dune studies that is largely the product of different scales of study. He identifies research on sediment transport processes, on the dune form itself, and of regional dune systems. The most elemental inquiry focuses on the instantaneous or event-driven transfers of sand in the beach profile that are narrowly confined in both space and time (microscale). The early research products of Bagnold (1941) and Belly (1964) laid a foundation for the theory and concepts of eolian transport in ideal situations. However, the beach is not an ideal planar surface and these early eolian transport equations do not provide satisfactory solutions to the quantities of sand moved about in the beach/dune environment. More recent research has focused on non-linear beach characteristics such as variable slope, topography, and vegetation type and density that affect sand transport in this milieu (Hotta 1985; Arens 1994; Dijk et al. 1999). Namikas (2002) has described the nature of non steady-state flows that spatially restrict transport across beach zones. Reviews of the influences of these "coastal variables" on rates and mechanics of winds transport are represented in McEwan and Willetts (1993), Trenhaile (1997), Sherman et al. (1998), and Bauer and Sherman (1999).

Mesoscale inquiry proceeds from the very spatially and temporally limited sediment transport studies to episodic accumulation of sand and the creation of foredune morphology. This is also a conceptual and methodological jump because the emphasis shifts to the response end of the geomorphological model. As noted by Sherman (1995) and Livingstone and Warren (1996), there is a temporal discontinuity between short-term sediment transport and the multi-year time span of morphological foredune development. Inquiry into the latter topic tends to focus on net dimensional topographical changes. Questions about rates and vectors of change relate the quantity and distribution of sand accumulation in the foredune in distinct temporal spans to the effectiveness of sediment delivery into various portions of the foredune cross section (Gares 1992; Arens 1997), or to the effectiveness of vegetation to trap and collect sand (Chap. 4: Wiedemann and Pickart; Chap. 5: Lubke; Chap. 8: Maun). Others track the mobility of the foredune as a morpho-/sedimentological unit in response to major storm events (Ritchie and Penland 1988) or to multi-year displacements of foredune crestlines both alongshore and cross-shore (Psuty and Allen 1993). Still others try to tighten the process-response association by relating vectors of transport to changes in foredune configuration (Hesp and Hyde 1996). Kurz (1942) and Hesp (1989) associate vegetation types with the development of foredune configuration from scattered hummocks to a coherent ridge, whereas Bate and Ferguson (1996), Garcia Novo et al (Chap. 10), and Martinez and Garcia-Franco (Chap. 13) relate stages in inland transport to interaction with vegetation types. This mesoscale inquiry at the multi-year to decadal level emphasizes development of the foredune and subsequent transfers of sediment inland of the dune-beach profile.

Macroscale inquiry involves the investigations into major dune complexes that have been evolving over periods of centuries to millennia (Sherman 1995). The treatises by Cooper (1958, 1967) as well as the papers by Olsen (1958) and Inman et al. (1966) describe dune systems that emanate from a coastal location but become regional geomorphologies. These sites of massive dune systems record a complex heritage of sediment availability and dune phenomena that extend tens of kilometers inland, often incorporating

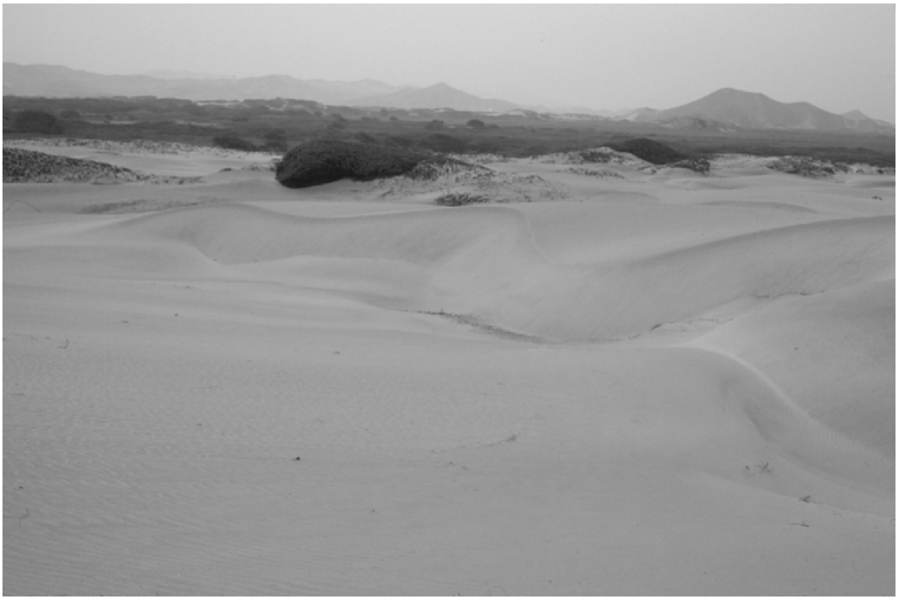

Fig. 2.2. Sand dunes and sand sheets transgressing inland in coastal Peru. Inland transfer of migrating dune forms, episodically stabilized, associated with sites of river discharge

Holocene, Pleistocene, and older formations (Tinley 1985; Illenberger and Rust 1988).

Livingstone and Warren (1996) indicate a dilemma in classifying coastal dunes because some of the descriptive morphologies could easily be far inland and totally independent of the coast. Some dunes may be located near the coast because of the proximity to a source of sand (Fig. 2.2), whereas others are morphodynamically related to the ambient coastal processes (Fig. 2.3). Dune forms that are in active interchange of sediment with the beach are causally positioned to occupy the upper portion of the beach profile. Other dune forms that derive their sand from a beach source but are inland of the beach profile and essentially function independent of the beach exchange processes may be coastal dunes because of geography but not a direct product of coastal dynamics. Further, dunes located inland of the beach profile may have been stranded because of coastal progradation and thus may retain all of their characteristic morphologies, but are no longer in active exchange of sediment with the beach.

Some classifications of coastal dunes attempt to address the spatial dichotomy by describing the dune form in a sequential relationship (Pye 1983; Goldsmith 1985) or stages in stability and inland transport (Short and Hesp 1982; Short 1988). A simple distinction between the foredune (primary dune) which is in active exchange with the beach and those dune forms which are

Fig. 2.3. Coastal foredune accumulating and releasing sand in exchange with the beach. Some sand is building the seaward face of the foredune whereas transport inland is broadening the foredune crest and the leeward slopes, Island Beach State Park, New Jersey

located inland of the beach exchange (secondary dune) is a foundation for creating a morphodynamic classification (Table 2.1), which can be further segmented by specific forms and dimensions, to distinguish between coastal dunes and dunes at the coast (Davies 1980; Psuty 1989; Paskoff 1997). This classification incorporates dune morphologies developing in the foredune location as well as inland dunes separated from beach interaction, such as actively migrating parabolic dunes or other transgressive morphologies. The former is the primary dune whereas the latter are secondary dunes or features evolving from the initial establishment of primary dunes.

2.3 Dune Morphology Related to Sediment Supply and Dune-Beach Exchange

Whereas there are many situations that combine to describe site-specific coastal dune configurations, on a conceptual level, there is a foredune developmental sequence related to varying sediment availability. An appreciation that the coastal dune comprises a part of the dune-beach profile is important because it brings recognition of the holistic system within which factors of time and space affect the character of the beach and accompanying dune

Table 2.1. Coastal dune classification based on relationship to foredune sand exchange, morphology, and sequence in development, modified from Psuty (1989)

Primary dune	The foredune in the dune-beach profile. There is active exchange of sediment between these components of the profile. This is an area that has been accumulating sand and it represents a net positive sediment budget at this site. However, at various temporal scales, it could be gaining, losing, or have no net change in sediment budget. The foredune is usually a coherent, linear ridge. It may be transgressing inland as part of a shift of the entire dune-beach profile, or it could be stable in its geographical location, or shifting seaward. The foredune is dynamic and it is the only dune form that is totally dependent on a coastal location
Secondary dune	Active – Created by modification of the primary dune or by transfers of sand inland from the position of the primary dune. The general characteristic is active migration of sand represented by deflation hollows and parabolic or crescentic morphologies. The transgressive ridge form is increasingly crenulate as deflation processes modify the ridge. The secondary dune may apply to the dissected remnants of a primary dune or it may describe actively transgressing dunes inland of the primary dune. In either case, it represents a condition in which sand is being transferred inland and lost to the dune-beach sand-sharing system Stable – Dune forms that are no longer in the active foredune but are not transgressing either. These dunes may have been stranded because of coastal progradation or they may have become stabilized by vegetation during their passage inland. They may have the configuration of the linear foredune ridge if abandoned by accretion or may have any of the transgressive forms associated with previous mobility. This dune form is a paleo-feature that retains the morphology of the dunes but is not being maintained by dune formational processes
Sand sheet/washover	Areas of very active inland transfers of sand. There is no foredune form or function. These large bare sand areas may be at sites of high rates of erosion and constitute a continuous transfer of sand to inland positions, as in the case of washover fans. They could also be at locations where strong onshore winds propel sand inland to overwhelm pre-existing topography without any definitive dunal forms. Sand sheets and washovers represent a unidirectional movement of sand from its beach origin

form (Psuty 1988; Sherman and Bauer 1993; Hesp 1999). An early study by Carter (1977) drew attention to the exchange of sediment between these two components of the sand-sharing system, and a collection of papers on the concept of dune-beach interaction (Psuty 1988) repeatedly stressed that foredunes are intricately related to beach dynamics and to the sediment available to drive beach changes. In part, the emphasis on dune-beach interaction added wave processes to the dynamics of foredune development. Essentially, those processes that mold the dimensions of the beach also affect foredune dimensions directly by scarping and sediment removal, or they provide sources of sediment to be transferred into the foredune topography. Vellinga (1982) and Kriebel (1986) describe storm events that mobilize some of the foredune mass, promote sand exchange, and produce a morphologic response. Psuty (1989) and Davidson-Arnott and Law (1996) applied the concepts of changing sediment budget in the beach to changing sediment budget in the adjoining foredune along several kilometers of beach and identified spatial and temporal associations of transfers into the foredune.

Beach–dune interaction is a key ingredient in the morphodynamic classification of beaches proposed by Short and Hesp (1982) and Short (1988) from their studies in Australia. In an original organization of hydrodynamic energies interplaying with sufficient sediment, this classification describes a continuum of morphological response to ambient processes that range from very dissipative conditions (mobilization of offshore sediment supply) to very reflective conditions (no sediment mobilization). The modal conditions that give rise to sand transfer to the beach also support inland storage of sand in primary and secondary dunes.

Psuty (1988), Arens (1994), and Hesp (1999) favor the concepts of a continuum of morphological responses to ambient conditions and identify sediment availability as the dominant variable that drives development of foredune characteristics. Part of the rationale is that the foredune is an accumulation form and there must be a positive sediment balance at some time in the creation of the foredune for it to exist. In addition, inherent in either of the approaches is the overriding concept of a spatial and temporal continuity that draws together the different combinations of foredune types in a sequential pattern. And, importantly, these approaches support a developmental sequence that passes through stages in a continuum with diagnostic morphodynamics to describe position and potential shift along the continuum. Hesp (1999) further incorporates vegetation into the mix of variables that affect stability and mobility relative to foredune dynamics and sediment supply to create a broadly-based foredune model. Subsequent inland transfers of sand interact with inland dunal habitats in a wealth of transgressive morphologies (Chapman 1964; Willis 1989).

2.4 Continuum Scenario

There are a number of scenarios that demonstrate conditions of sediment balance and foredune morphologies in the context of a continuum. The conditions of sediment discharge at a river mouth and the downdrift sequence of associations offers an excellent spatial continuum, as does an elongating spit or a barrier island that is being displaced alongshore. Sequences of secondary dune development that foster inland systems can be incorporated within the coastal scenarios as temporal extensions or episodes of transgression.

2.4.1 River Mouth Discharge

This sequence relates the concept of a point source of sediment input and the relationship of dune morphology to the quantity of sand available at distances away from that source (Fig. 2.4). The general scenario incorporates discharge with adequate sand to cause shoreline accretion and seaward displacement of the shoreline at the river mouth but with slower accretion at increasing distance from the mouth. Near the river mouth, the coastal topography would incorporate many low abandoned foredune ridges (Fig. 2.5). Foredunes at this site would be small because beach accretion restricts time to transfer sand from the active beach to the adjacent foredune. Thus, rapid beach accretion and seaward displacement of the total beach profile would lead to a new foredune location and strand the previously-developed foredune morphology.

At increasing distances from the river mouth, the quantity of sand delivery would decrease and the rate of beach accretion would slow, increasing the duration of sediment transport into the foredune site. This combination of tradeoffs in sediment delivery is the basis for the morphodynamic continuum that is fundamental to the pattern of foredune development. Conceptually, the number of foredune ridges should decrease away from the river mouth discharge site until there is only one large foredune ridge in active exchange of sediment between the beach and dune. The presence of a large single fore-

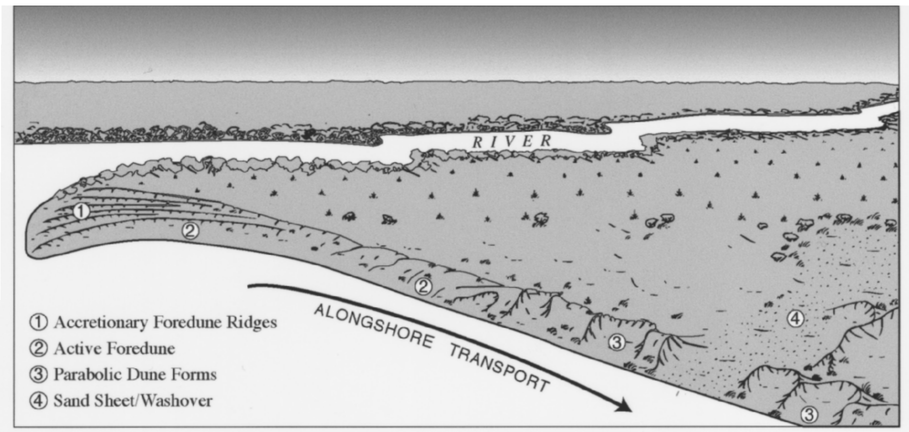

Fig. 2.4. Coastal foredune continuum related to a river mouth discharge site on a wave-dominated shoreline

Fig. 2.5. Curving lineations of abandoned foredune ridges, ca. 1.0–1.5 m relief, in an area of rapid shoreline accretion, Grijalva River, Tabasco, Mexico

dune ridge may exist beyond the point of shoreline stability. It may exist where there is slow shoreline erosion and the opportunity for transgression inland while the foredune is being maintained. Farther along the continuum, the negative beach sediment budget will be combined with a negative sediment budget in the foredune and the form will lose volume, become dissected, and incorporate morphologies that represent reduction of the dune-beach interaction such as blowouts and parabolic dune forms (Fig. 2.6). Still farther along the continuum, the dune forms will continue to diminish in dimension and extent. Eventually, the continuum proceeds to the situation where the foredune is essentially nonexistent and the profile migrates inland with washover fans or sand sheets penetrating into and across the interior morphologies.

The portion of the foredune continuum involving inland transgression of form and sediment can also lead to development of secondary dune landforms that are separated from coastal processes. This is an important element of the continuum because it is a spatial/temporal situation wherein inland transfer creates and maintains transgressive dune fields and sand sheets, thereby enabling the dichotomy of a primary coastal dune system that is dependent upon coastal processes and secondary dune systems that exist in the coastal area dependent upon mobilized sand.

Fig. 2.6. Downdrift of the Grijalva River mouth, the coastal foredune is 5–8 m in height, with blowouts and evidence of dissection. The foredune is actively transgressing inland over older coastal topography, near Tupilco, Tabasco, Mexico

2.4.2 Scenario Complexity

Wave-dominated shorelines at river mouths are excellent sites to demonstrate the application of the foredune continuum associated with the sequence of sediment supply and spatial arrangement of morphologies.

A site from the western coastal portion of the large Mezcalapa deltaic plain in the state of Tabasco, Mexico, records the interplay of variable coastal sediment supply, foredune development, and coastal dune habitats (Fig. 2.7). At times in its geomorphological development, the western Mezcalapa delta distributaries were sites of primary discharge and buildout. At other times, these distributaries were abandoned or were channels with very little discharge. The regional coastal geomorphology near the current Rio Tonalá river mouth provides evidence for a variety of forms and processes associated with discharge shifts. Initially, there is a general separation of geomorphological features that are produced by the fluvial processes of stream flow and channel development in the delta versus another group of features that are the product of wave, current, and wind processes at a shoreline. The contact of the two forms is largely shore parallel and consists of a transgressive dunal ridge of 10–15 m at the inner margin of these coastal forms that terminate or truncate the adjacent low-lying fluvial topography. Seaward of this dunal ridge is a topography of low abandoned foredune ridges, 1–2 m in local relief, whose

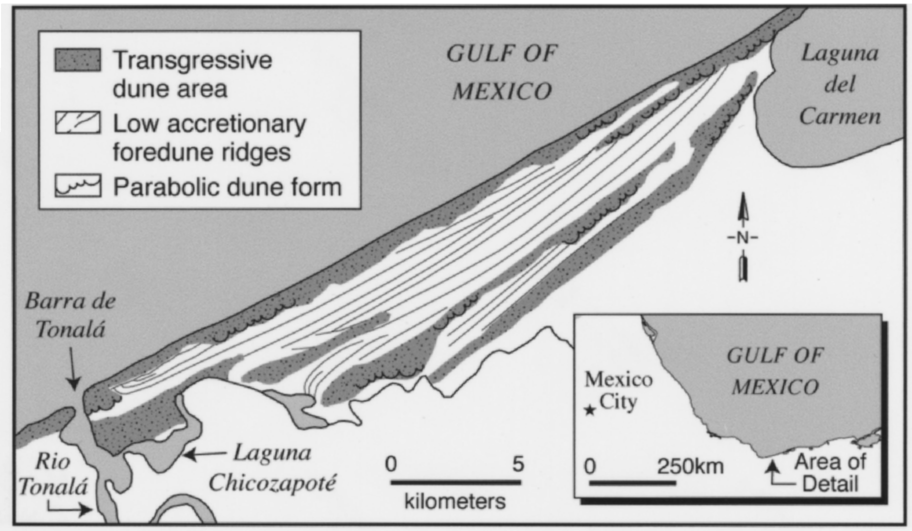

Fig. 2.7. Geomorphologic association of foredune types associated with changing sediment supply at the Rio Tonalá, Tabasco, Mexico

pattern displays a general arcing seaward in the vicinity of the discharge point of the Rio Tonalá. The arcing pattern is interrupted subsequently by a large foredune ridge, 5–10 m, that has transgressed inland and truncated the trends of the smaller foredunes. This large dunal ridge is quasi-shore parallel and is succeeded seaward by another series of low ridges that once again arc toward the Rio Tonalá mouth. This sequence is repeated several times to produce a variety of coastal dune habitats within short distances. The modern beach at this location is the site of an actively inland transgressing foredune.

The transgressive/regressive dune sequence and its ecological niches have been created because of the variation of sediment supply discharged through distributaries along the western margin of the delta interacting with hurricanes and strong frontal storms. The low ridges are abandoned foredunes associated with rapid coastal progradation and seaward displacement. The larger transgressive dune ridges are primary and secondary coastal dunes that have developed during times of shoreline erosion but with sufficient sand transferred inland to maintain a net positive sediment budget. This was the situation that created the transition at the junction of the coastal and fluvial topographies, and the alternation of sediment supply has been repeated several times to create the larger foredune ridges cutting through the low curving abandoned foredunes. Some of the inland ridges remained actively-transgressing inland with blowouts and parabolic dune forms despite being separated from the sand source at the shoreline, thereby becoming a complex of secondary dune forms.

2.5 General Model

Although the coastal foredune is part of the dune-beach profile in form and function, it is possible to separate it conceptually from the beach. Both the beach and the foredune are forms of sediment accumulation and they each develop morphological responses to their short term and long term sediment balance. The beach widens and narrows in response to changes in sediment supply. The dune gains and loses height and width relative to a gain or loss of sand. A stylized depiction of the relationship between the two parts of the profile relates the sequence of morphological expression in the foredune as driven by sediment supply (Fig. 2.8). The essential gradient in the model is from conditions of very high to very low sediment input and a differentiation of beach versus foredune response to this gradient. The output of the model is the sequence of foredune morphology, either spatial or temporal or both, along a continuum of evolutionary development of the foredune. The depiction is dimensionless. The association is relative sediment supply and it is subject to leakage from the sand-sharing system, so that inland transfers to sustain dune development landward of the foredune could be affecting sediment balance. Indeed, there is a position in the continuum that maximizes the potential for a transgressive foredune as well as inland transfer and secondary dune system development. Such a situation may accompany dissection of the foredune through development of parabolic forms that transgress inland while remaining part of the foredune (Fig. 2.8).

The essential element of the model is that with a positive sediment supply to the beach, the dimensions of the foredune are inversely related to the rate of beach accretion. High rates of shoreline progradation do not permit much time for sand transfers into the foredune position, and thus the foredune accumulation is never very great. As beach progradation slows, the opportunity to transfer sand to the foredune increases and thus there is an increase in the dimensions of the foredune related to the association of tradeoffs described above. The most problematic component of the model is the situation when the shoreline is stable or with a minor negative sediment budget. Evidence from the field (Psuty and Allen 1993) and numerous examples of well-developed foredunes on eroding coasts suggest that conditions do exist where the transfer of sand into and to the lee of foredune is similar to the losses on the seaward side of the foredune during erosion episodes. The example of large foredune forms at the shoreline near the mouth of the Rio Tonalá at present and at several instances in the past suggests that foredunes can persist during times of regional negative budget affecting beach position. The model uses this suite of information to depict maximum foredune growth during the period of minor regional shoreline erosion and transgression. Obviously, the foredune can also recover sediment volume and increase in dimension during episodes of beach recovery.

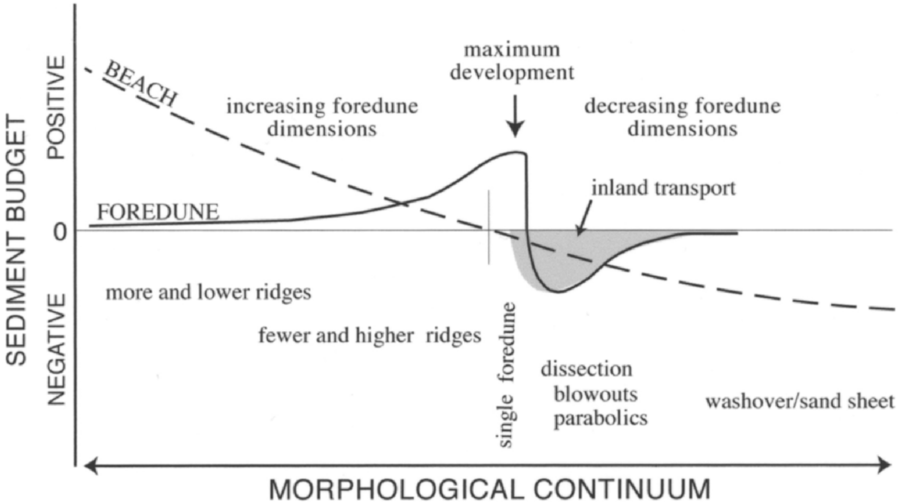

Fig. 2.8. Conceptual model of relationship of sediment budget of beach to sediment budget of foredune, inland transfer of sand, and resulting topographies in a sand-sharing system. Opportunities for maximizing foredune development (*dark line*) and maximizing inland sediment transport (*gray shading*) to support secondary parabolic dunes are closely-positioned and may overlap within the spatial/temporal continuum. With continued beach erosion, there will be no sand accumulation in the foredune to support inland transfer and thus washover and sand sheet processes will dominate the extreme negative sediment budget stage of the continuum

The transgressive portion of the continuum may also be the time of dune morphology decoupling from the interaction with coastal processes and to the establishment of parabolic or secondary dunes. However, at some point in the negative budget scenario, the foredune must be losing more sediment than is being transferred to it leading to dissection of the foredune ridge and reduction of its morphological identity.

Variation in sediment budget can drive considerable complexity in coastal foredune development, in ecological niches and sheltered areas, and in subsequent transfers of sediment and morphology inland. Indeed, secondary dune topography in the coastal zone may exist after the beach and foredune are completely eroded, such as cliff-top dunes and inland dune systems. Importantly, the foredune model establishes that there is a place in the continuum that favors inland transfer and is supportive of regional dune development. The conceptual basis for secondary coastal dune formation may assist in understanding the evolutionary establishment of coastal dune forms and habitats as an episodic inland transfer of sand that supports dune form and function away from its coastal origin. Further, a recognition of the dichotomies attendant to the scales of foredune research and concepts should prove helpful in interrelating morphology and vegetation types following the efforts of Godfrey et al. (1979), Hesp (1989, 1999), Sarre (1989) Wiedemann and Pickart (Chap. 4), and Maun (Chap. 8).

2.6 Humans as a Variable

Whereas there is natural variation in sediment availability and transfers in the coastal zone that result in a sequence of primary and secondary dune morphologies, there are likewise human manipulations of the processes, the sediments, and the landforms. It is difficult to escape the imprint of humans because the effects can range from direct manipulation to indirect influence of processes and responses (Davis 1956; Walker 1990; McLachlan and Burns 1992; Nordstrom 2000). Human impacts do not render the conceptual coastal dune continuum model invalid, but they do impart another variable because humans can alter the sediment budget, mold and destroy dune morphologies, and displace shorelines. In essence, human activities can overcome the slow migrations in morphological response along the continuum to produce large jumps from one point to another, or a stepped response to an alteration of form or sediment supply, as described when beach fill provides a superabundant source of sand for eolian transport into the foredune system (van der Wal 2000; Marques et al. 2001). Or conversely, human actions can support a steady state scenario and continuously balance the sediment delivery to allow a desired mode in the sequence to be maintained (Chap. 15: Kooijman; Chap. 16: van der Meulen et al.; Chap. 16: Moreno-Casasola; Chap. 20: Heslenfeld et al.). Human impacts are part of the system and it is folly to ignore the role of human agents in manipulating processes, sediment availability, as well as morphological/ecological responses.

2.7 Conclusions

Dune-beach interaction and sand-sharing are key elements in understanding development of the foredune under a variety of sediment budget scenarios. Conceptually, the foredune stores and releases sediment as it waxes and wanes in concert with the erosional or accretional trends of the adjacent beach. Spatially, the foredune may pass through a sequential morphological development associated with alongshore distance from a sediment source. Temporally, the same sequential development may occur as the sediment supply varies. At stages in the model, inland transfers of sediment from the foredune may support development of transgressive coastal dune forms that broaden the areal extent of the dunal features. Further, episodic oscillations of shoreline position may also strand foredune morphologies inland of the active shoreline. Human activities are additional factors affecting coastal dune characteristics in any stage of the process-response scenarios.

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