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Spatio-temporal geomorphological and ecological evolution of a transgressive dunefield system, Northern California, USA

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ABSTRACT

A series of historic aerial photographs in addition to the U.S. Coast Survey 1870 map were used to document evolution of the coastal barrier and transgressive dunefield system at the Lanphere-Ma-le'l Dunes on Humboldt Bay, California, USA, between 1870 and 2016. Geomorphic units (shorelines, foredunes, nebkha, blowouts, parabolic dunes, deflation basins, and dunefields) as well as vegetation alliance were mapped in ArcGIS at approximately decadal intervals and compared among three subareas delineated based on large scale geomorphic differences that coincided with contrasting biological invasion and management histories. Sand inundation events in the 1930s and 1940s led to deterioration of the foredune and burial of deflation basins in the south, with the transgressive dunefield directly abutting the backshore in places. The transgressive dunefield in the north differentiated into parabolic dunes that decoupled from the foredune complex earlier than in the southern subareas, which have retained undifferentiated transgressive dunefields. Shoreline progradation increased dramatically following the historic 1964 flood, but exhibited a north-south gradient consistent with the Mad River to the north acting as the primary source of sediment, and effective north-south littoral drift. Biological invasions of *Lupinus arboreus* in the north and *Ammophila arenaria* in the south contributed to stabilization post-1965, but concomitant increases of native vegetation in other areas suggest these biotic processes were subordinate to other forcing factors. A notable switch from an erosional to a depositional system occurred coincident with the Pacific Decadal Oscillation (PDO) shift from a cool to a warm phase in the late 1970s, suggesting climate forcing as a major driver of dune evolution. Changes in the rate of vegetation stabilization per time interval post 1948 are correlated with change in mean monthly PDO index for the same intervals. Alongshore gradients of sediment availability and tectonic subsidence are likely superimposed on climatic controls. Stability of the dune system reached its maximum extent in 2000, despite erosional effects of the 1998–2000 La Niña event and invasive plant removal projects in the 1990s. Increased storminess (2015–2016 El Niño) resulted in decreased shoreline stability in the most recent interval, coincident with sharply declining rates of progradation and a reduction in mean monthly PDO index. This study provides insights into how transgressive dune phases can be formed, sustained and decoupled, as well as how they change their geomorphology over time. The absence of relict foredunes in the study area and elsewhere on the North Spit barrier suggests that the foredune-blowout-parabolic dune complex may build to quite large proportions for some time, and then be destroyed or destabilized to such a degree that the sediments comprising the complex are released to form a new dunefield phase. Ruptures along the Cascadia subduction zone are a likely mechanism for transgressive dunefield initiation, both in the past, and likely in the future.

1. Introduction

There have been relatively few studies worldwide on the historical evolution of coastal barriers dominated by parabolic dunes and/or transgressive dunefields (the two types often co-occur) and their associated major landform units such as deflation basins and plains. There are a number of reasons for this lack of attention: 1) aerial photography is limited, since most aerial coverage only began around the late 1930s to early 1940s; 2) a datable and historical record is easier to obtain in foredune plains and beach ridge plains; 3) the east coast-centric nature of most USA dune studies; and, 4) a dearth of studies on the geological and geomorphological evolution of transgressive dunefields more

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widely (Hesp and Thom, 1990; Hesp, 2013). While several geological studies have been conducted on the age and evolution of coastal transgressive and/or parabolic dunefields (e.g. Orme, 1990; Clemmensen et al., 2001; Forman et al., 2008; Dillenburg et al., 2009; Dillenburg and Hesp, 2009; Arbogast et al., 2002; Peterson et al., 2007; Hansen et al., 2010; Hesp and Walker, 2013; Forman, 2015), the number of historical studies is few. Martinho et al. (2008, 2010), Miot da Silva and Hesp (2010), and Hesp (2001) examined transgressive dunefield historical changes from the late 1940s based on a limited number of aerial photographic periods in southern Brazil and New Zealand respectively, and found that as a transgressive dunefield phase migrated inland, parabolic dunes and deflation basins and plains gradually developed.

In this paper, we present the first long-term historical analysis of geomorphological and vegetation changes to a coastal barrier on the west coast of North America, at the Lanphere-Ma-le'l dune system (part of W.S. Cooper's (1967) Humboldt Bay, California Locality 3 system). The study spans the period from 1870 to 2016, for the purpose of documenting historical change and to explore the relative roles of climate, geology, landscape inheritance, species invasions, and management in shaping the present-day dune landscape. Three subareas were defined to facilitate analysis: 1) a northern section dominated by parabolic dunes and highly influenced by the introduction of *Lupinus arboreus*, 2) a central region of the transgressive dunefield, lacking large parabolic features, where there was minimal influence by invasive vegetation, and 3) a southern region of the transgressive dunefield, also lacking large parabolic dunes, where *Ammophila* invasion and subsequent restoration occurred. These three areas portray contrasting geomorphological development and invasion/restoration patterns with the potential for differing ecological outcomes. As Rhemtulla and Mladenoff (2007, p.1) state, “reconstructing these historical patterns and processes is key to understanding how present conditions came about, how ecosystems function, and in contributing to wise management and restoration decisions.”

2. Regional setting

2.1. Study area

The study area is part of a larger coastal barrier system that extends from the Mad River mouth in the north to Table Bluff in the south in northern California (centered on 40.88° N) and encloses the tidally influenced estuary/lagoon Humboldt Bay (Fig. 1). The Lanphere-Ma-le'l Dunes are located near the northern end of what is known locally as the “North Spit” but likely developed as a continuous longshore barrier (rather than as a spit) as sea level rose and quasi-stabilized around 6000–7000 years B.P. A southern barrier, the “South Spit” extends from the southern Humboldt Bay jetty at the estuary mouth southwards to Table Bluff.

Humboldt Bay, a tidally dominated estuary (Costa and Glatzel, 2002), lies landward of the barrier system. The bay is enclosed by two spits now anchored by jetties first constructed between 1889 and 1891 and reconstructed between 1911 and 1925 (McCormick, 1989). At the present time, the North Spit barrier consists of a relict, forested transgressive dunefield, an active transgressive dunefield, suites of large, active and stabilized long-walled parabolic dunes, a large deflation plain, a suite of smaller, long-walled parabolic dunes, and a foredune/blowout complex. Cooper (1967) examined this dunefield during several visits between 1917 and 1925 in his seminal work on the dunefields of California. He argued that there were two obvious dunefield-forming phases present in Humboldt Bay, the current forested phase (“Flandrian Episode I") and the late Holocene, currently active phase (“Flandrian Episode II"). Leroy (1999) later described three identifiable phases of dune aggregation on the North Spit. Given the history of other similar dunefields (e.g. Roy et al., 1980; Thom, 1984; Hesp and Thom, 1990; Costas et al., 2012), it is likely that there are more than just two phases in this system, but no dating has been carried out.

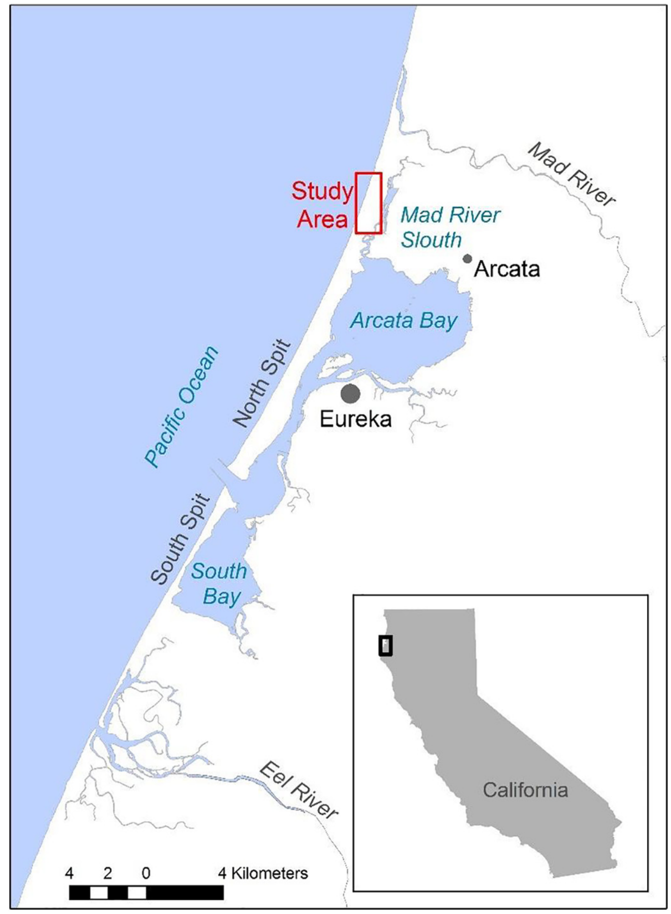

Fig. 1. Location of the study area on the northern barrier (“North Spit”) of Humboldt Bay (comprised of Arcata Bay, Entrance Bay, and South Bay), located south of the mouth of the Mad River.

In this study we examine in detail only one portion of the barrier system, encompassing 274 ha along a 3.6 km stretch of coastline on the North Spit. All but the northern 14% of the study area lies within Humboldt Bay National Wildlife Refuge. We divided the study area into northern, central, and southern subareas based on natural geomorphic divisions in the younger dune phase. The northern subarea circumscribes the area of large parabolic dunes, while the central and southern area describes two generalized lobes of less differentiated transgressive dunefields (Fig. 2). The three subareas also approximately correspond to three different exotic species invasion and/or conservation histories, providing an opportunity to examine resulting differences in evolutionary trajectories. The central, core area was placed in conservation ownership in the late 1970s and has a long history of protection and management. The southern subarea was protected between the late 1980s and 2005, while the northern subarea is predominantly recently acquired or as yet-unprotected land.

2.2. Climate

The region lies within the Csb class in the Köppen-Geiger climate classification and is temperate with a dry, warm summer. Temperatures are moderate year-round, while precipitation is strongly seasonally variable, with average monthly rainfall ranging from 0.4 cm in July to 16.1 cm in December (National Weather Service, 2018). An average of 96.7 cm of rainfall occurs primarily between the months of October and May (National Weather Service, 2018). Fog forms within a marine layer sufficient to reduce visibility to 0.4 km or less on an average of 50 days