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Long-term Changes of Coastal Foredunes in the Southwest Atlantic

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ABSTRACT

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Remote sensing techniques and fixed-site observations were used to evaluate vegetation, habitat and physiographic characteristics of coastal foredunes in southern Brazil during the last 50 years. The results demonstrated a gradual increase of edaphic stability and biological diversity in foredunes during several decades, followed by a rapid and profound attenuation of these attributes. The changes in regional hydrology, as a result of long-term and large-scale impoundment and more recent and localized drainage activities, are appointed as the major cause for foredune modifications in this part of the southwestern Atlantic.

ADDITIONAL INDEX WORDS: *Brazilian coastal foredunes, remote sensing, dune hydrology, dune vegetation changes.*

INTRODUCTION

Coastal foredunes respond to a variety of environmental processes at different scales of time (RITCHIE and PENLAND, 1990; CARTER *et al.,* 1990a). Their morphodynamic and vegetation characteristics adjust to changes in climate and to sand supply from the beach, which confers them both transient attributes as well as importance in terms of coastal stability (ARENS and WIERSMA, 1994). Foredunes are particularly vulnerable to processes triggered by human interference which often initiate periods of accelerated sand transgression, accompanied by changes in coastal stability and biological diversity (HESP, 1991). Foredune landscape changes due to sand mobilization (CARTER *et al.,* 1990b) are rapid and apparent after one or two years, while changes associated with sand stabilization and plant succession, though profound, may only be recognized after decades (VAN DER MEULEN and JUNGERIUS, 1989).

Coastal foredunes in southern Brazil represent the most recent formation of a holocenic sequence of dunes and depressions in the southwestern Atlantic (VILLWOCK and TOMAZELLI, 1995). They extend about one to two kilometers inland and are typically composed of incipient embryo dunes which may develop into one or two, up to 5 m high dune ridges in front of dry and seasonally flooded wet slack and marsh areas (CORDAZZO and SEELIGER, 1993; SEELIGER 1992, 1997; COSTA *et al.,* 1996). During the latter half of this century, these foredunes have increasingly been impacted by changes in regional hydrology (SEELIGER and COSTA, 1997). This study aims to evaluate the long-term changes of vegetation characteristics, habitat diversity and physiography in coastal foredunes of southern Brazil.

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MATERIAL AND METHODS

Regional changes in composition and cover of foredune vegetation during the last 50 years were determined along 60 km of southern Brazilian coast (32° 21′ S to 32° 52′ S), using remote sensing techniques (LINDGREN, 1985; CIVCO *et al.,* 1986; DE PIETRI, 1995) based on vertical aerial black-and-white photographs taken in 1947 (1:40.000), 1966 (1:60.000), and 1996 (1:60.000). The aerial photos were digitized with a flatbed scanner (100 dpi, 256 gray tones) and images were optimized for quality and joined for perfect overlap with Adobe Photoshop. A 1.5 km wide foredune area was defined following operational steps provided by geographic information and imaging software (Idrisi 2.0). Owing to image resolution and reflective characteristics of the dune vegetation, three groups of similar pixel grey tones could be determined with the color tolerance tool (range 10) of Adobe Photoshop. Different pixel groups of 1996 images were photo-interpreted and georeferenced (Garmin 45) in the field and identified as three environmental/vegetation units, corresponding to 1. areas without or with sparse herbaceous vegetation (dry unit), 2. areas with dense herbaceous vegetation (wet unit) and 3. afforestation areas (pine unit). The total area of different environmental/vegetation units in 1947, 1966, and 1996 was calculated using GIS software (MapMaker Pro).

Environmental conditions and vegetation characteristics of foredunes were monitored during 16 years (1982–98) in a 30 m wide and 350 m long permanent strip transect perpendicular to the beach (32° 33′ S; 52° 23′ W), extending between

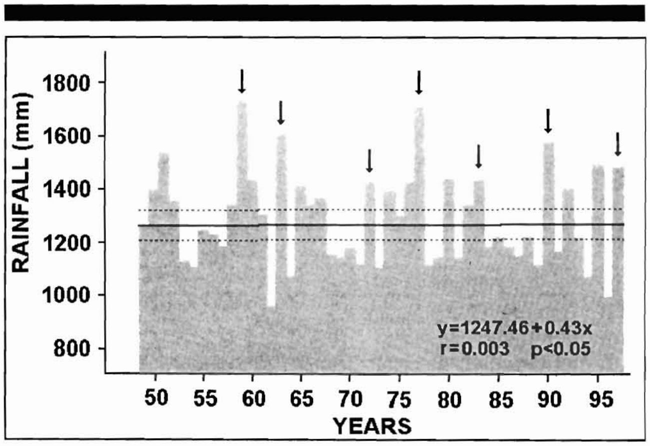

Figure 1. Annual precipitation means (shaded area) and regression (black line) with 95% confidence intervals (dotted lines) between 1949 and 1998 at the southern coast of Brazil. Arrows indicate El Niño years.

the leading edge of backshore vegetation and the inland freshwater marsh. The topography of foredunes was determined during the summer of 1983, 1986, 1996, and 1998 in 2 m intervals along the transect, using an automatic level (Wild NA 20). The ground water table was measured monthly between March and February of 1982/1983, 1984/1985, and 1988/1989 in frontal dunes, dry and wet slacks, and marshes. Water table levels were determined with a graduated measuring stick (1 cm intervals) in wells comprised of PVC tubing (10 cm ø). Tubes were placed vertically in the sand down to 2.5 m depth to ensure presence of ground water at all times. The distance of the water table was expressed in relation to the sand surface at first measurement. One-way analysis of variance (ANOVA), using Tukey's multiple range test, was applied to compare the ground water table distance among different years in each habitat. The composition of species and the total cover and biomass of the dune vegetation were determined in 1986 and 1998 in 170 sampling squares (25 × 25 cm) along the strip transect between the backshore and marsh area. Data of average monthly precipitation were provided by the Agricultural Research Institute of the State of Rio Grande do Sul. Since data prior to 1949 are sketchy and mean annual values are not reliable, only data between 1949 and 1998 were considered. Linear regression analysis was used to determine temporal rainfall patterns (WONNACOTT and WONNACOTT, 1982)

RESULTS

Despite wide fluctuations of total annual rainfall in coastal foredunes of southern Brazil between 1949 and 1998, especially in El Niño years, long-term changes of precipitation were not significant ($r = 0.003$) (Figure 1). During the same period, the foredune landscape and vegetation underwent profound changes. In 1947, foredunes were almost entirely (94%) comprised of dry habitats, represented by non-vegetated sand plains and/or by sparsely vegetated embryo dunes, frontal dune ridges, hummock dunes, and dry dune slacks with *Blutaparon portulacoides, Panicum racemosum, Spartina ciliata,* and *Andropogon arenarius,* respectively. During the following 20 years, humid habitats with dense herbaceous plant cover gradually increased until 1966, and in 1996 the total area (42%) of wet slacks, dominated by *Androtrichum trigynum,* and marshes with *Scirpus* etc. had exceeded that of dry dune habitats (30%) (Figure 2).

Afforestation of foredunes with *Eucalyptus saligna, E. grandis* and *Pinus elliottis* initiated in 1976 and in 1996 mature stands of trees covered about 28% of the area (Figure 2). Attempts to extend *Pinus elliottis* plantation into seasonally flooded wet slacks and marshes were preceded by their artificial drainage in 1986. The mean annual groundwater table fell significantly ($p < 0.05$) between 1985/86 and 1988/89 in foredune slack and marsh areas, with a decrease of 80 cm in frontal dune ridges (Figure 3).

The morphology and morphodynamic activities of foredunes changed little between 1983 and 1986. Frontal dune ridges, accompanied by a gradual density decrease of the principal sand-binding species *Panicum racemosum,* began to erode in 1988/89 and annual transgression rates increased with dune sand slowly advancing over marsh areas. During the following years the frontal dunes were totally obliterated and the dominant NE onshore winds transported beach sand without obstruction further inland, thus the total sand volume of the foredune area increased significantly. Between 1996 and 1998, sand sheets covered all dune habitats and transgression dunes moved inland at rates exceeding 31 m year^{-1}, with retention ridges developing against the leading edge of older *Pinus elliottis* plantations (Figure 4).

The structure of the foredune vegetation remained unchanged between 1983 and 1986. During the following years, the mean plant biomass decreased from 22.85 g dry weight m^{-2} in 1986 to 0.49 g dry weight m^{-2} in 1998 and the herbaceous plant cover decreased by 82%. Of the 73 plant species in the foredunes in 1986, only *Blutaparon portulacoides, Spartina ciliata, Hydrocotyle bonariensis, Androtrichum trigynum* and *Senecio crassiflorus* occurred in 1998, though *B. portulacoides* and *S. ciliata* had a wider distribution in backshore embryo dune areas.

DISCUSSION

Foredunes are an integral part of the larger coastal system because changes of their physiography, habitat characteristics and biological diversity are often influenced by processes which originate in adjacent environments. As elsewhere (CARTER *et al.,* 1990b), coastal foredunes in the southwestern Atlantic are influenced by natural processes, associated with the nearshore and beach environment (BERNARDI and SEELIGER, 1989; SEELIGER, 1992; CALLIARI and KLEIN, 1993), and by the regional climate which controls seasonal and annual fluctuations of the dune water table (CORDAZZO and SEELIGER, 1993; SEELIGER, 1998). During the latter half of this century the ground water levels in southern Brazilian foredunes have been increasingly influenced by large-scale impoundment and drainage activities (SEELIGER and COSTA, 1997). The construction of a highway (BR 471) a few kilometers inland of coastal dunes in the early 50's effectively altered the regional hydrology by impounding and slowly

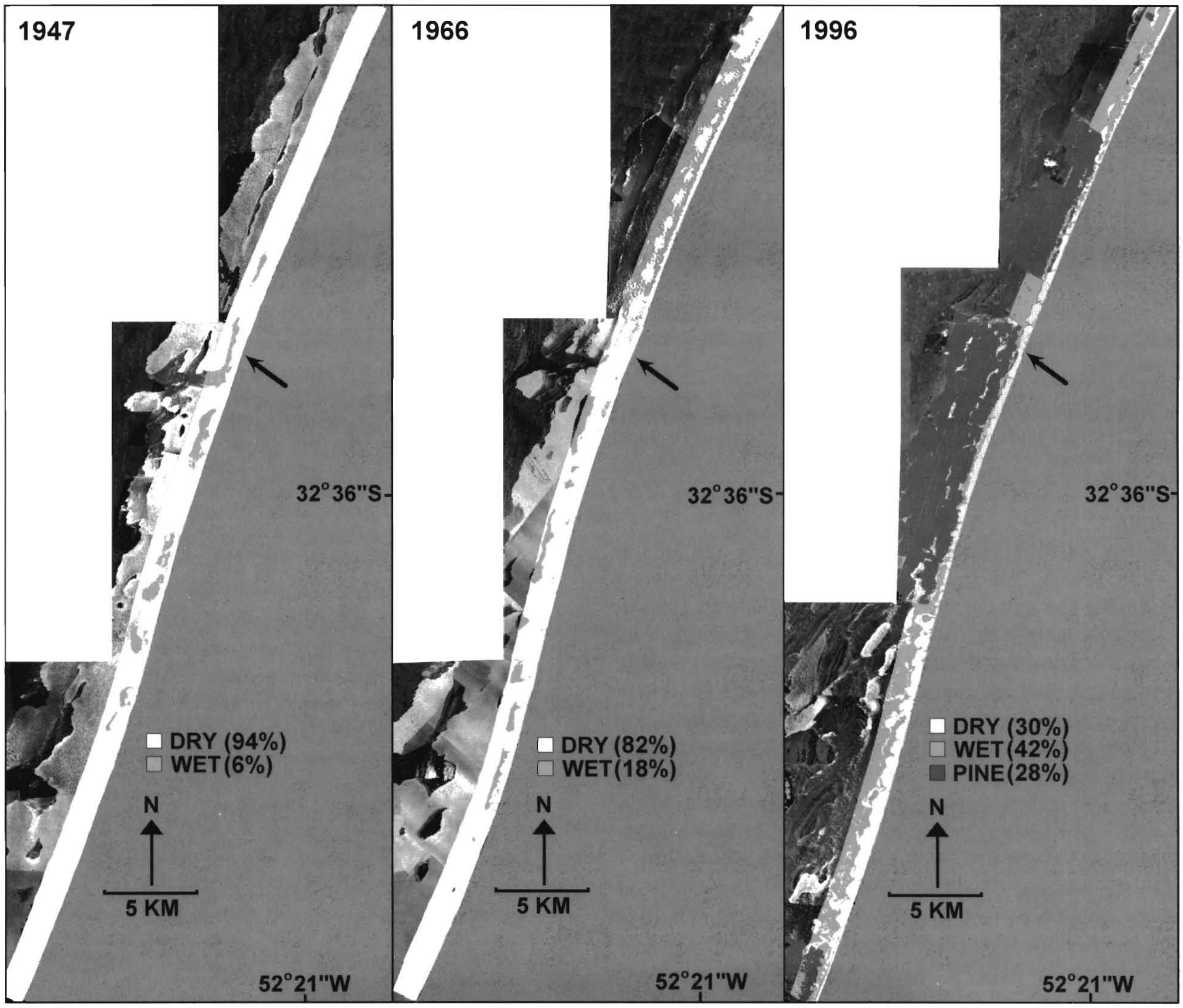

Figure 2. Environmental/vegetational units in southern Brazilian coastal foredunes in 1947, 1966 and 1996 with percent cover of total foredune area. Arrow indicates location of permanent sampling site with strip transect.

raising the water table in the entire dune system during the following decades (TUCCI, 1996). Since groundwater level changes generally introduce abiotic and biological processes with long-term effects on dune ecology (GROOTJANS *et al.*, 1991), the physiography, habitat, and vegetation characteristics of southern Brazilian foredunes underwent profound modifications, despite stable regional rainfall patterns over the last 50 years. However, contrary to the detrimental impact of water extraction on groundwater-bound dune vegetation (VAN DIJK, 1989), the gradual appearance of phreatophytes provided a clear indication of the diversifying effect impoundment had on the foredune ecosystem.

Much of the foredune area, originally occupied by dry habitats (94% in 1947), evolved during the following decades into wet dune slacks and transitional marshes (42% in 1996). These humid habitats offer ideal growth conditions for a diverse assemblage of plants, comprised principally of *Androtrichum trigynum, Phyla canensis, Baccopa monnieri, Pluchea sagittalis,* and *Paspalum vaginatum,* inundation-tolerant species of drier sites (*Andropogon arenarius, Hydrocotyle bonariensis, Spartina ciliata*) as well as marsh species, like *Juncus acutus* and *Typha domingensis* (CORDAZZO and SEELIGER, 1987; 1993). Since changes in vegetation structure also tend to alter the degree of physical protection, microclimate, and organic matter accumulation (VAN DER MEULEN and JUNGERIUS, 1989), the introduction of new habitats favored the establishment of a rich insect fauna (*i.e.* Coleoptera, Diptera, Hymenoptera, Lepidoptera, Hemiptera). Furthermore, several amphibians and reptiles (the sand toad *Bufo arenarum arenarum,* the sand frog *Pleurodema darwini,* the lizard *Liolaemus occipitalis,* the hognose snake *Lystrophis dorbignyi*) became associated with the humid dune habitats (GIANUCA, 1997). The increased diversity of habitats and associated vegetation are also exploited as nesting sites by most

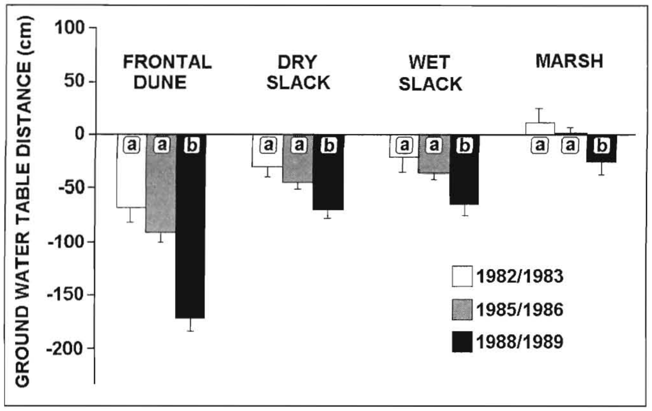

Figure 3. Average annual ground water distance with standard error in foredune habitats before (1982/1983; 1985/1986) and after (1988/1989) drainage. Different letters represent significant differences according to Tukey's multiple range test at 5% significance.

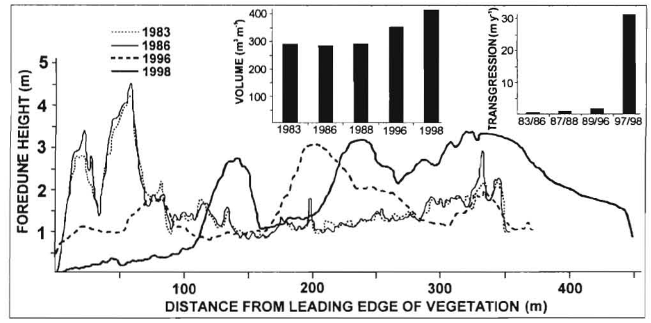

Figure 4. Topography, sand volume, and sand transgression rates in southern Brazilian coastal foredunes between 1983 and 1998.

resident and several migrating shorebirds (VOOREN, 1998) and they represent feeding sites for the skunk *Conepathus chinga,* the armadillo *Dasypus hybridus* and the fox *Dusicyon gymnocercus* (GIANUCA, 1997).

The gradual development of foredune areas with more stable substrate and denser herbaceous vegetation cover attracted large-scale afforestion with the non-indigenous species *Eucalyptus saligna, E. grandis* and *Pinus elliottis* in 1976. Despite the commonly observed secondary effects of increased evapo-transpiration by stands of trees on dune vegetation, changes in the structure of foredune vegetation and the size and diversity of habitats were negligible during the first 12 years after planting (CORDAZZO and SEELIGER, 1987; 1988). However, after forestry operations attempted to extend *P. elliottis* plantations into wet slack and marsh areas proximate to the beach in 1988, a significant drop of the foredune water table induced large-scale morphodynamic and biological modifications. The almost immediate loss of all phreatophytes in humid habitats as well as the rapid decrease in plant diversity, cover and biomass of dry habitats during the following years was directly related to water stress which, even after water table levels become re-established, generally requires a considerable amount of time for recovery (HESP and THOM, 1990; ZUNZUNEGUI *et al.,* 1998).

Most structural changes of plant populations or communities disturb the foredune landscape (CARTER *et al.,* 1990b) but, within the context of beach/dune sediment flux, any process that influences the performance of the sand-fixing vegetation on frontal dunes is likely to assume a decisive position (JUNGERIUS, 1989; HESP, 1991). The effective binding of beach sand in frontal dunes by *Panicum racemosum* populations during summer (COSTA *et al.,* 1984) and the return of dune sand to the beach during winter storms (CALLIARI and KLEIN, 1993) represents a major feedback loop. Although the *Panicum* population on frontal dunes is commonly grazed upon by cattle, grazing does not appear to put the stability of frontal dunes at risk (COSTA *et al.,* 1984). However, the significantly lower water table levels in frontal dunes together with grazing pressure led to the total loss of *Panicum racemosum* populations within less than three years and thus disrupted the feedback loop. As a consequence, the dominant NE onshore winds have eroded the frontal dune ridges and sand from the beach is transported without any further obstruction inland. The massive sand input and high transgression rates have effectively inundated all ecologically important foredune habitats and have eliminated the associated vegetation and fauna of hummock dunes, dry and wet slacks and marshes.

At present, southern Brazilian foredune diversity has been reduced to embryo dune habitats with stands of *Blutaparon portulacoides* and *Spartina ciliata,* unstable sand plains without vegetation, and retention ridges against the leading edge of mature *Pinus elliottis* plantations. The large-scale and long-term environmental and vegetation changes suggest that management must consider all of the roles played by foredunes in order to attain socio-economic values distinct from their ecological importance (VAN DER MEULEN and JUNGERIUS, 1989).

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