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Coastal management and long-term foredune behavior: characterizing semi-natural foredune evolution

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ABSTRACT

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Management interventions applied to foredunes often aim at stabilizing the foredune, restoring a pre-storm situation or stimulating foredune growth. Whether and how the often localized and intermittent interventions may interfere with the evolution of foredune morphology over time spans of many decades, can be investigated trough comparative case studies of managed foredune behavior. At the heart of such studies are analyses of long-term monitoring data sets of foredune topography with sufficient temporal and spatial resolution. A comparative analysis of such large data sets requires a method that can be applied across data sets from different sites. In this paper we explore the use of autocorrelation to characterize spatial and temporal variability in foredune morphology. Application to a 45 year data set of annual elevation surveys across semi-natural foredunes on the island of Schiermonnikoog (The Netherlands), revealed differences between a foredune that was initiated by erecting sand fences on a beach plain (sanddrift dike) and a foredune that developed seaward of it. Differences concerned the persistence in deviations from temporal and alongshore trends in crest elevation and crest position. Besides, it was shown that the sanddrift dike had a gentler seaward facing average slope than the foredune that developed later on. The presented results indicate that autocorrelation, including a procedure to deal with missing data, can be a useful addition to characterize alongshore and temporal variability in foredune behavior.

ADDITIONAL INDEX WORDS: *sanddrift dike, autocorrelation, Schiermonnikoog*

INTRODUCTION

Coastal dunes provide various services to society, such as protection against flooding, recreation, and nature conservation. As a result, humans will often interfere with the natural dynamics of coastal dunes when these negatively affect these functions. For example, local storm erosion of the foredune will reduce the safety level of dunes as flooding defense, or the resulting steep dune front can be perceived as a public safety issue (collapse). Usually, the applied management interventions aim at restoring the pre-storm situation. As such they should result in an increased recovery rate from an erosional event as compared to post-storm recovery rates occurring without human intervention.

The above raises the question whether the usually localized and intermittent human interventions will actually interfere with the long term evolution of the foredune area (i.e. over many tens of years). This is especially of importance for the flooding defense functionality, as we can expect natural drivers of coastal behavior, such as storm climatology and mean sea level stand, to change over the next century.

To increase insight in the above issue we performed a case study on the morphologic behavior of managed foredunes in relation to type and intensity of management (Bochev-van der Burgh et al., 2011), along the west-facing mainland coast of the Netherlands (Fig. 1). In that study it was shown that pro-active management measures, like shore nourishment that builds an erosion buffer, had a more profound effect on foredune shape and variability than reactive measures that were only applied when storm damage had occurred or blowouts had developed (e.g. by locally flatting the dune front by ground moving equipment, planting marram grass, erecting sand fences).

To investigate whether these findings have a more general applicability, a logical next step would be to extend this type of analysis to managed foredunes in other geographic settings, potentially including other types of coastal management measures. A minimum requirement for such comparative studies is the availability of long-term monitoring data sets of foredune morphology (elevation transects) spanning at least several decades with sufficient temporal resolution (e.g. annual). Such data sets do exist for example for other parts of the Dutch coast, such as Schiermonnikoog, or for the Danish west coast. Unfortunately, the landward extent of elevation surveys or cross-shore resolution is not always sufficient to use the EOF-methodology as applied in our previous study (Bochev-van der Burgh et al., subm.). Therefore, we needed an alternative approach to characterize the spatial and temporal variability in foredune morphology.

In this paper we will explore the use of autocorrelation to characterize spatial and temporal patterns in morphologic variability. We will present results for the evolution of a sand-fence initiated foredune, or sanddrift dike, and a subsequently formed new foredune seaward of it, both located along the north-facing coast of Schiermonnikoog Island, The Netherlands (Fig. 1 and Fig. 2). These dunes were classified as semi-natural foredunes by Arens (1994).

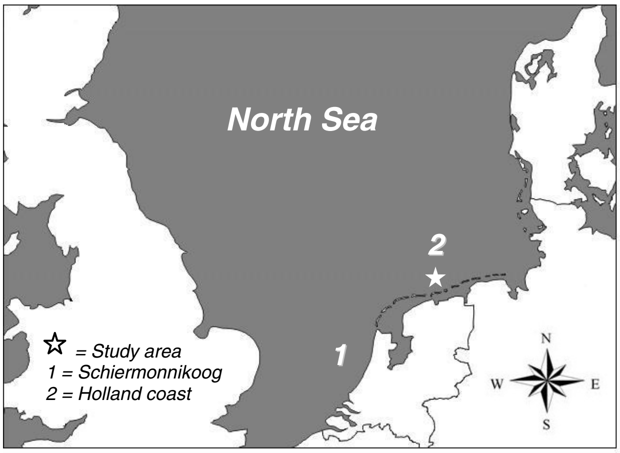

Figure 1. Geographic setting of the study area.

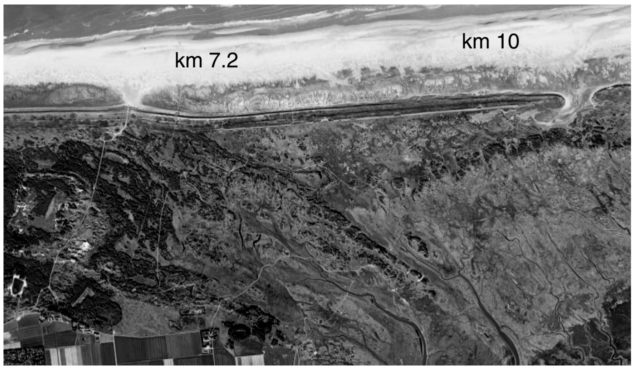

Figure 2. Field site on Schiermonnikoog.

STUDY AREA AND DATA SETS

Schiermonnikoog is a barrier island in the north of The Netherlands. Its North Sea facing coastline has been prograding at a rate of roughly 4-5 m/yr (Stolk, 1989). The tidal range in the area is 2.2 m and the mean annual significant wave height is 1.1 m. Winds mainly blow from the west (70% of the time), while shore perpendicular northerly winds induce most onshore directed sand transport on the beach (Van der Wal, 1998).

In this paper we will characterize the evolution and variability of a linear foredune with an anthropogenic origin, a so-called sanddrift dike, and a new foredune that later on formed seaward of this sanddrift dike. The sanddrift dike was initiated between 1959 and 1962 by erecting sand fences on a beach plain such that a straight sand dike was formed. Storm damage was repaired by planting marram grass and sand fences. The dike originally extended from km 7 to km 13, but east of km 10.4 it repeatedly breached and since the eighties that section was no longer maintained (De Groot, 2009). In the present analysis we focus on the part of the sanddrift dike between km 7.2 and km 10, for which occasional storm damage was repaired. The intensity of such management interventions has been low in this area, and since 1990 no interventions measures have been applied at all.

Around 1985 a new foredune started to develop in front of the sanddrift dike. The initiation of this dune was fully natural and not related to any human intervention (C.Visser, *Rijkswaterstaat*, pers. comm.). Around that same time, east of the study area also natural foredune formation occurred (De Groot, 2009). To the west however, several kilometers away from the study area, the development of foredunes has been reported to be stimulated until 1988, e.g. by erecting sand fences (Arens, 1994).

Information on the long-term morphologic behavior of the sanddrift dike and the second newly formed foredune is derived from morphometric analyses of a long-term topographic data set. This data set consists of a 45 year period (1965-2009) of annual elevation surveys of the sub-aerial part of the coastal profile at 5 m intervals along 15 cross-shore transects. These transect have an alongshore spacing of 200 m and we analyzed transects between km 7.2 and km 10.0 (Fig. 2). No surveys were available for the years 1998, 2001, and 2003.

METHODS

In this explorative study we use dune crest elevation and dune crest position as indicators of foredune evolution and variability therein. Potentially, time series and alongshore series of these indicators could be characterized using methods like harmonic analysis (Psuty and Allen, 1993) or spectral analysis (e.g. Holman et al, 1993). However, the data series at hand for Schiermonnikoog, but also for other potential study areas, are too short to apply such methods. Typically, decadal time span time series of annual surveys of foredune topography have a length ranging between 30-45 data points, while alongshore series typically consist of 15-50 transects (several kilometers of coastline with similar management, and a couple of elevation transects per kilometer). As an alternative we will use autocorrelation to characterize length and time scales of persistence in morphologic variability.

Autocorrelation provides a measure of similarity between subsequent values in an equally spaced data series. This measure is defined as the linear correlation coefficient between the data series and a lagged version of itself (time lagged for time series, spatially lagged for alongshore series). The sample estimate of the autocorrelation r_k is defined as follows (Davis, 2002):

$$r_k = \frac{\frac{1}{(N-k)} \sum_{i=1}^{N-k} \left(x_i - \overline{x}\right)\left(x_{i+k} - \overline{x}\right)}{\frac{1}{N} \sum_{i=1}^{N} \left(x_i - \overline{x}\right)} \quad (1)$$

where N = number of data points in the data series, $\overline{x}$ denotes the average of all values in the series, x_i denotes an individual value, and k is the lag at which the correlation is considered.

Standard algorithmes for the calculation of autocorrelation cannot handle missing values. We dealt with missing values in our data set in the following way. For each lag k we defined two new variables y and z containing the values $x_1..x_{(N-k)}$ and the values $x_{(1+k)}$ $..x_N$ respectively, such that both y and z contain (N-k) observations. Subsequently, for a given lag k, observation pairs with a missing value in either y or z were removed. Next, for each lag k the correlation coefficient between y and z was calculated. As a consequence, autocorrelation estimates are sometimes based on less than (N-k) data points. Note that we deliberately choose not to interpolate values because this would artificially increase the estimated autocorrelation in these rather short data series.

The semi-natural foredune behavior will be studied from almost the initiation phase onwards, therefore an obvious trend in crest elevation, and possibly crest position, is to be expected over time. Potentially, alongshore trends in crest elevation and crest position may occur as well. Since autocorrelation is typically applied to reveal persistence or periodic patterns in stationary series the following analysis approach was taken for both crest elevation and crest position. First, a low-order polynomial function was fitted to characterize the temporal variation in alongshore averaged values. Next, at each alongshore location persistence in the time series of deviations from this polynomial was characterized in a correlogram (i.e. a plot of r_k versus lag k.). The presented correlograms are averaged over all alongshore locations. Subsequently, the same approach was followed for characterizing, for each year, the persistence in the alongshore series of deviations from a fitted low-order polynomial to the alongshore variation in time-averaged values. In this case the presented correlograms were averaged over all years.

The reference line for dune crest position used in this study is the local average position of the dunefoot in the middle of the studied period. The dunefoot is defined as the 3m +NAP contour, the level that is commonly used in the Netherlands to define the dunefoot (NAP = Dutch vertical ordnance datum, which approaches Mean Sea Level). To obtain a smooth reference line, we averaged the dunefoot position over the period 1978-1997 at each transect location. This period was selected because dune foot position data contained no missing values for the full strectch of studied foredune over this interval. Note that we defined a new reference line because the original reference line, the RSP line, is a historic reference line that did not line-up very well with the position of the foredune over the past decades.

RESULTS

The foredune that originated as a sanddrift dike started to stabilize around 1980, both in height (Fig. 4a) and position (Fig. 3 and Fig. 7a). As the dunefoot prograded further seaward, the development of a new foredune started roughly 50 m seaward of the sanddrift dike. (Fig. 3). The crest elevation of the sand drift dike stabilized around 8 m +NAP, whereas the crest elevation of the new foredune stabilized just over 9 m +NAP (Fig. 4a). Combining the positional data shown in Fig. 3 and the dune crest elevations shown in Fig. 4a, it appeared that on average the seaward slope of the newly developed foredune was steeper than that of the sanddrift dike (Fig. 5).

The persistence in the alongshore variation in crest elevation (Fig. 4b) appeared to be very similar for both the sand drift dike and the new foredune. Both show a weak positive correlation over 0.2 km. This positive correlation implies that in a given year, the crest elevation in neighboring transects tends to deviate in a similar manner from the average elevation that year (i.e. both below or both above average). This weak pattern in persistence of crest elevation variation did not change after stabilization of the sanddrift dike.

The persistence in temporal variation in crest elevation (Fig. 6b) as deviating from the time-averaged elevation (Fig. 6a) appears to differ between the actively growing sanddrift dike and the stabilized phase of the sanddrift dike. In the latter case crest elevation variations are uncorrelated from year to year, while in the accretion phase deviations from the average trend values tend to persist for several years.

The evolution of the alongshore-averaged dune crest position (Fig. 7a) is best approximated by a second order polynomial in the accretionary phase of both the sanddrift dike (1965-1984) and the new foredune (1985-2009). Of course no temporal trend exists for

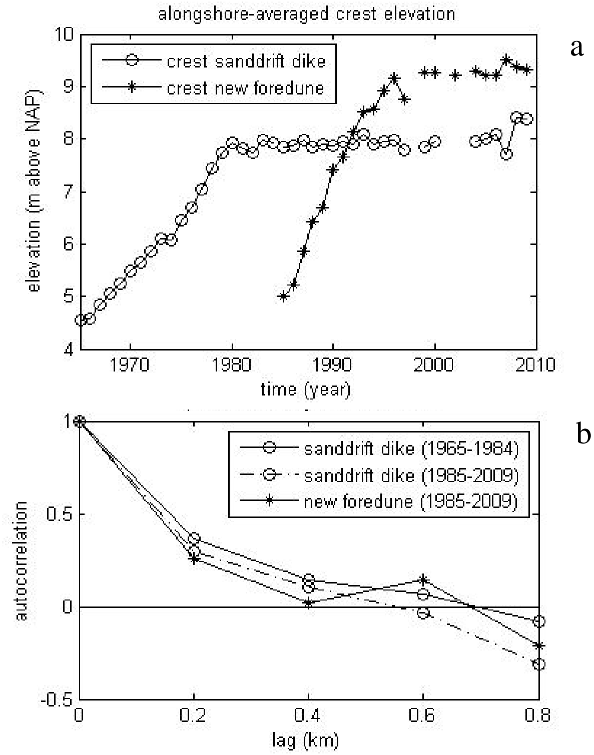

Figure 4. Temporal crest elevation variability. a) Alongshore-averaged evolution; b) Average alongshore persistence in deviations from alongshore-averaged temporal evolution.

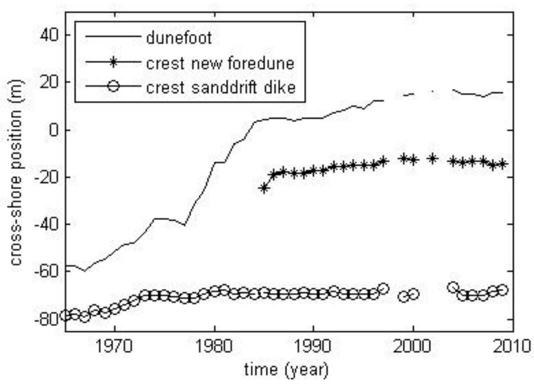

Figure 3. Temporal evolution of the alongshore-averaged position of respectively the dunefoot, the crest of the sanddrift dike and the crest of the newly developed foredune. Positive y-axis points seaward.

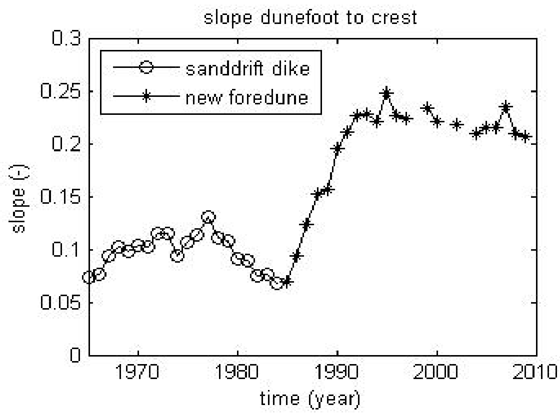

Figure 5. Temporal variation in the alongshore-averaged seaward slope of the sanddrift dike and the newly developed foredune.

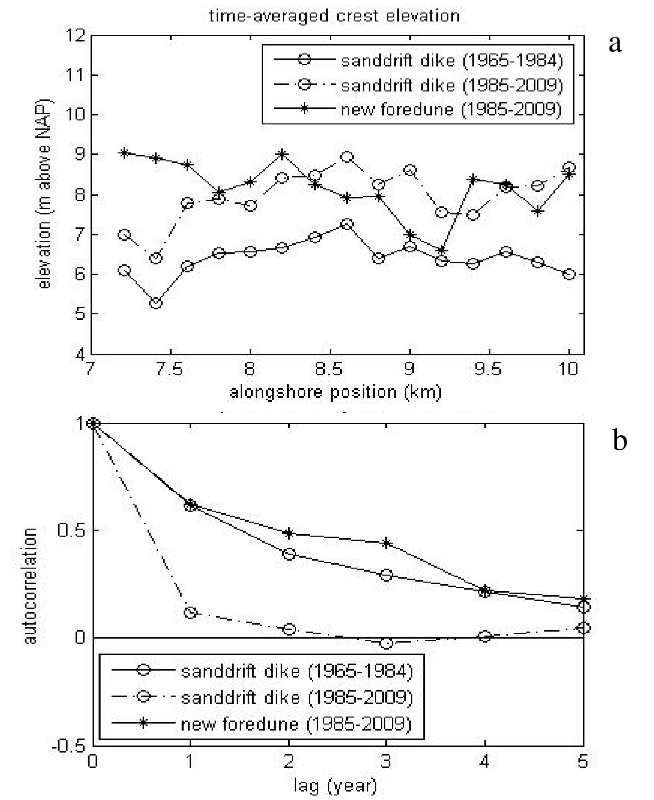

Figure 6. Alongshore crest elevation variability. a) Time-averaged elevation; b) Average temporal persistence in deviations from the time-averaged alongshore varying crest elevations.

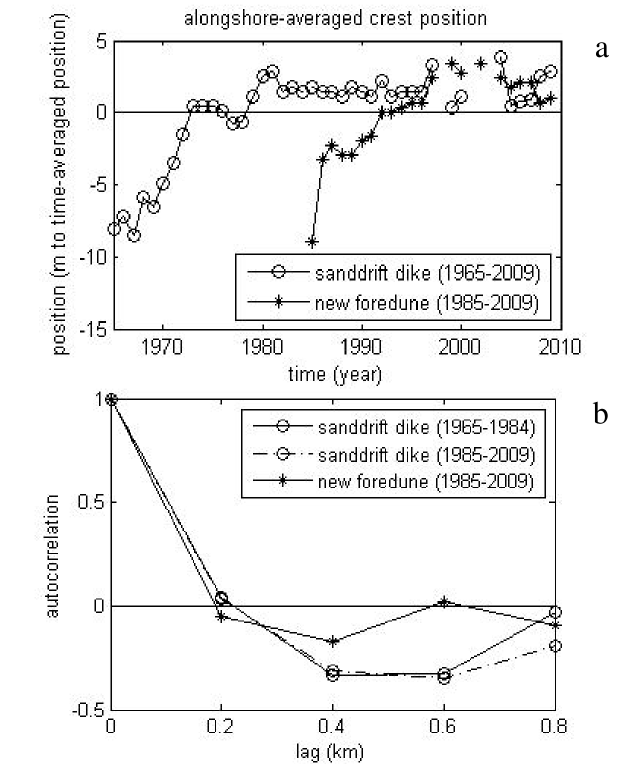

Figure 7. Temporal variation in crest position a) Alongshore-averaged evolution (both shown relative to their time-averaged position); b) Average alongshore persistence in deviations from alongshore-averaged temporal evolution.

the crest position of the sanddrift dike in its stabilized phase (1985-2009). Note that the crest migrates seaward as the foredune increases in elevation, as does the dunefoot (Fig. 3, Fig. 4a and Fig. 7a).

Regarding the alongshore persistence in deviations from the trend value in a given year, it appears that no difference exists between the accreting and stabilized phase of the sanddrift dike (Fig. 7b). In both phases a tendency for weak negative correlation around lags of about 0.5 km exists. This implies that the dune crest is not linear, but undulates at a certain (weakly) preferential length scale. That is, if the crest is locally located more seaward than the alongshore averaged position in a given year, it will on average be located more landward 0.5 km away from that location (and vice versa). For the newly developed foredune, to the contrary, the alongshore variation in crest position appears to be uncorrelated (for a transect spacing of 200 m and more), i.e. no preferential length scale is apparent.

Finally, the dune crest position appears to exhibit an alongshore trend for the sanddrift dike, where the crest is positioned roughly 15 m more seaward near km 10 as compared to km 7.2 (Fig. 8a). Regarding the temporal variability in deviations from this trend, it appears that these are uncorrelated from year to year for the stabilized sanddrift dike, whereas deviations persist for several years during the accretionary phase (Fig. 8b). For the accreting new foredune only a weak and opposite alongshore trend in time-averaged dune crest position exists (Fig. 8a). The persistence in local temporal deviations from this trend is weaker than that for the sand drift dike (Fig. 8b).

DISCUSSION AND CONCLUSION

This paper aimed at exploring the use of autocorrelation in characterizing spatial and temporal persistence in morphologic variability and presenting some first results on the morphologic behavior of semi-natural foredunes at Schiermonnikoog.

Regarding the use of autocorrelation in characterizing morphologic variability, the issue of statistical significance of the observed differences between correlograms needs to be raised. The correlograms shown are either alongshore-averaged (Fig. 6b and Fig. 8b) or time-averaged correlograms (Fig. 4b and Fig. 7b). We did so in order to summarize the overall picture of persistence in temporal and alongshore variation respectively, but also to increase the reliability of the autocorrelation estimates at the various lags. The individual correlograms do deviate to some extent from the average correlograms, and sometimes even considerably, but overall trends are well represented by the average correlograms. Actually, the averaging of the correlograms can be seen as a way to increase the reliability of the estimate of the true underlying correlogram, similar to the procedure of segment-averaging in spectral analysis to increase the reliability of spectral estimates (Hegge and Masselink, 1996). Note, however, that in our case the data series on which the individual correlograms are based are often not independent, such that appropriate confidence interval cannot easily be calculated. For reference, Appendix 1 provides a table of the 95% confidence intervals for estimates of the correlation coefficient based on N-size samples of independent observations.

Another issue of concern is the influence of the cross-shore spacing of elevation measurements on the observed persistence in crest position. The relatively large persistence observed in

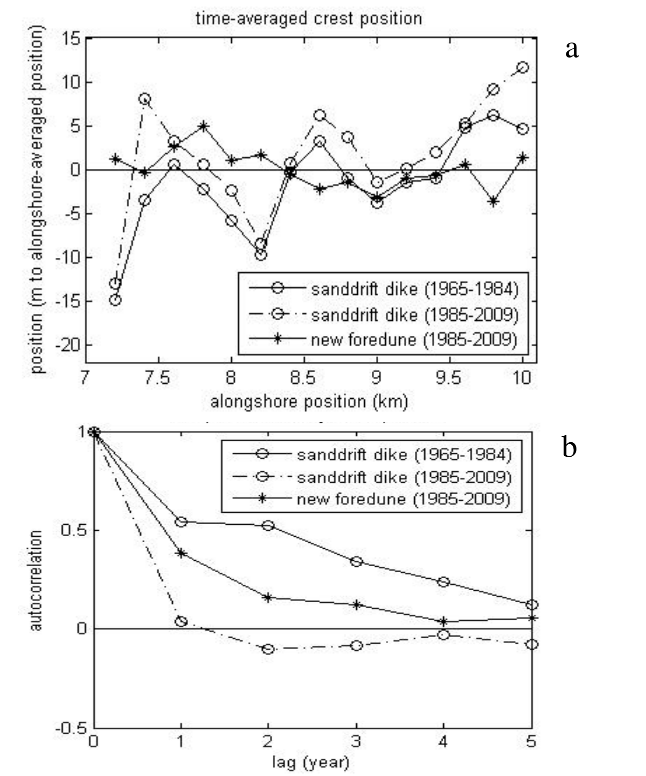

Figure 8. Alongshore crest position variability. a) Time-averaged position; b) Average temporal persistence in deviations from the time-averaged alongshore varying crest positions.

temporal deviations in crest location when an alongshore averaged trend existed (accretionary phase) (Fig. 8b), may to some extent have been amplified by the fact that elevation data was surveyed at 5 m cross-shore intervals. As a consequence, crest position measurements can only change in units of 5 m, whereas the annual change according to the alongshore averaged quadratic trend was generally less than 1 m/yr. Note, that this effect cannot explain all persistence in the deviations, because this effect is present for both the sanddrift dike and the new foredune, which exhibit different temporal correlograms (Fig. 8b).

Regarding the long-term morphologic behavior of semi-natural foredunes, differences were revealed between the sanddrift dike and the new foredune in the persistence of deviations from temporal and alongshore trends in crest elevation and crest position. For instance, the sanddrift dike seems to exhibit a weakly preferential length scale in the alongshore variation in crest position, which was lacking for the new foredune. Explanation of the observed differences in foredune behavior, in terms of possible differences in external conditions (such as wind conditions and beach width) or management interventions, is beyond the scope of this paper.

To conclude, the presented results indicate that autocorrelation, including a procedure to deal with missing data, can be a useful addition to characterize alongshore and temporal variability in foredune behavior.

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APPENDIX 1

The confidence intervals shown in Table 1 are calculated using Fischer's Z transform. The two sample sizes (N) represent the maximum and minimum number of data points underlying the autocorrelation estimates presented in this paper.

Table 1: 95% Confidence intervals for estimates of correlation coefficient r based on sample size N of independent observations.

	N= 315 (~lag 1)		N=225 (~lag 5)	
r	r_lower	r_upper	r_lower	r_upper
0	-0.111	0.111	-0.131	0.131
0.1	-0.011	0.208	-0.031	0.228
0.2	0.092	0.304	0.071	0.322
0.3	0.196	0.397	0.176	0.415
0.4	0.303	0.489	0.284	0.504
0.5	0.412	0.579	0.395	0.592
0.6	0.524	0.666	0.509	0.678
0.7	0.639	0.752	0.627	0.761