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# Measuring Interactions of Surface Elevation and Vegetation Dynamics on the Zandmotor Dune Landscape

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**Abstract.** The natural functions of coastal dune systems are under threat. Rising sea level, changing wave and wind climate and increasing human activities in coastal areas lead to ‘coastal squeeze’. An option to mitigate the effects of coastal squeeze can be creating seaward space through artificial beach widening. The Zandmotor mega nourishment placed in 2011 near The Hague (The Netherlands) is used as an example of creating new coastal space. Morphological changes at the Zandmotor have been studied extensively. The sedimentation-vegetation dynamics and its influence on long-term dune landscape development remain underexplored. Here we show that the presence of vegetation has contributed significantly to the increase in dune volume on the Zandmotor landscape. We used publicly available remote sensing data: elevation maps and aerial images. We found only sedimentation in the dune area on a bi-annual scale indicating that wind does not cause erosion at this timescale. Furthermore, we found that the vegetation cover is increasing over time and is often growing around the peaks of the elevation profile. Also, vegetation often stays at/around the same location and multiplies. The presence and growth of vegetation contribute to a significant increase in dune growth, reaching up to  $53 \text{ m}^3/\text{m}/\text{year}$ . Our results demonstrate that the presence of vegetation has contributed significantly to the increase in dune volume on the Zandmotor landscape. The insights about sedimentation-vegetation dynamics and its influence on dune growth, gained at the Zandmotor, may inform the development of strategies to mitigate coastal squeeze, enhance dune resilience and adapt to the challenges of climate change and human activities.

**Keywords:** Sand Engine · Coastal squeeze · Coastal dunes · Remote sensing

## 1 Introduction

Coastal dune systems face pressures from rising sea levels, changing wave and wind climates, as well as from increasing human activities in coastal areas. These pressures lead to ‘coastal squeeze’ [1] at many locations. Coastal squeeze threatens the natural functions of dunes, including flood protection, habitat provision and recreational space [2]. To mitigate coastal squeeze, two options to create more space for coastal dune

landscapes are proposed: releasing landward pressure by removing coastal infrastructure, or creating seaward space through artificial beach widening. An example of creating seaward space is the Zandmotor project, which was initiated near The Hague (The Netherlands) in 2011 [3] (see Fig. 1). The Zandmotor has successfully expanded the beaches, formed new dunes, enhanced biodiversity and provided recreational space. Initial studies have focused on its morphological changes and sediment dynamics [4, and references therein], however its long-term landscape evolution and potential additional benefits remain underexplored.

The long-term landscape evolution is closely related to the interrelation between vegetation growth and sedimentation/erosion processes. This sedimentation-vegetation dynamics determine when, how and where new dune will develop [8–10]. Initially, the Zandmotor was a barren surface of sand only without any vegetation. Over time, however, patches of vegetation began to establish, acting as roughness elements that trap sediment and reduce erosion. This interaction has facilitated the growth of some new dunes to heights exceeding 5 m. The mutual feedback between sedimentation processes and vegetation patterns highlights the dynamic nature of the Zandmotor's landscape and its evolving natural features.

This study aims to measure interactions of sedimentation processes and vegetation dynamics on the Zandmotor and to explore the long-term evolution of its landscape. By using publicly available elevation maps and aerial photographs, and analysing changes in sediment distribution, vegetation cover and overall landscape dynamics, we will develop a comprehensive understanding of the Zandmotor's impact.



**Fig. 1.** Aerial images of the Zandmotor in a) September 2011 and b) July 2024 provided by Rijkswaterstaat.

## 2 Study Area and Methods

The Zandmotor is a mega nourishment of approximately 20 million  $\text{m}^3$  of sand that was placed in an area of 2.5  $\text{km}^2$  at the beach [3]. It was created as a pilot project, following the 'building with nature' approach. Building with nature aims to make use of natural processes in a proactive way to build, maintain and reinforce dunes and their accompanying protective functions, while providing opportunities for nature as part of the infrastructure development process [6]. Three goals were defined: 1) stimulate natural dune growth for the benefit of safety, nature and recreation; 2) generate knowledge development and innovation; 3) create attractive (temporary) recreational and natural areas.

## 2.1 Transect Profiles

Over the length of the whole study area cross-shore transects are drawn with a 100 m spacing. The length of the transects depend on the location of the dune foot in March 2024. The dune foot level along the Dutch coast is widely assumed to be +3 m MSL [5, 6] and is therefore used in this analyses as well. The landward end of the transect is determined by the bicycle path along the Zandmotor, i.e. a stable point in time. In total 70 cross-shore transects are created. Along every meter of each transect the values of the DTM's are extracted. A moving average window is applied with a window size of 6 (m).

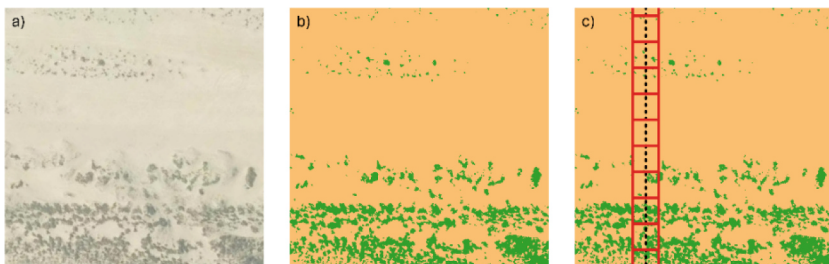
## 2.2 Dune Volume

The area under each transect profile is calculated for every year and multiplied by  $1 \text{ m}^2$ ; this area results in a total volume per year for each transect profile. We found that the trend over time of these volumes shows a (surprisingly) linear behaviour for many transects. Therefore, a linear line is fitted through the volumes over time. The fit of the line is computed with  $R^2$ . The slope of the linear line represents the volume change per alongshore meter per year of the transect.

## 2.3 Vegetation Detection

The vegetation presence is determined by analysing yearly RGB aerial photographs. First these RGB images are converted to greyscale images. To detect vegetation from these greyscale images, Otsu's method [7] was used. Essentially, Otsu's method identifies the optimal threshold based on the light intensity of pixels in the images. In this case sandy pixels (bright) are separated from vegetated pixels (dark) (see Fig. 2 a) and b)).

For every  $\text{m}^2$  along each transect the percentage of vegetated pixels is determined, shown in Fig. 2 c). These percentages of vegetated pixels are plotted on top of the elevation profile, to show the vegetation presence and changes in an intuitive way and couple them to sedimentation patterns.

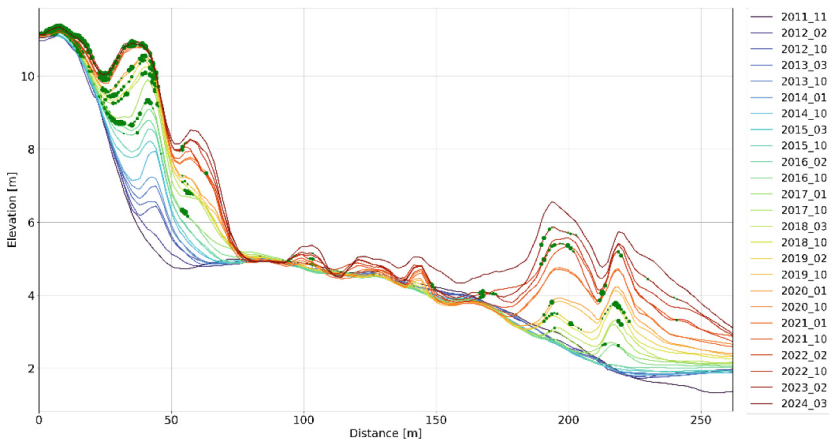


**Fig. 2.** Method to analyse the presence of vegetation. a) RGB image, b) classified image, sandy (yellow) and vegetated (green) pixels, derived from Otsu's method, c) example to calculate vegetation percentage per cell.

### 3 Results

Significant accumulation of sediment is found at many transect locations (see Fig. 3 for an example). The cross-shore transect in Fig. 3 is located just south of the dune lake on the Zandmotor. The first years (until 2016), sedimentation is mostly taking place just in front of the dune ( $x = 40$  m). In front of the dune a new (fore)dune is developing. After 2016, there is also sedimentation between  $x = 150$ – $300$  m. It is notable that over the whole transect (and the other analysed transects as well), there is (almost) only accretion. This accretion implies that the eroding factor of the wind force is not present and that (most) sediment is coming from the beach and the intertidal zone more seaward from the dune toe.

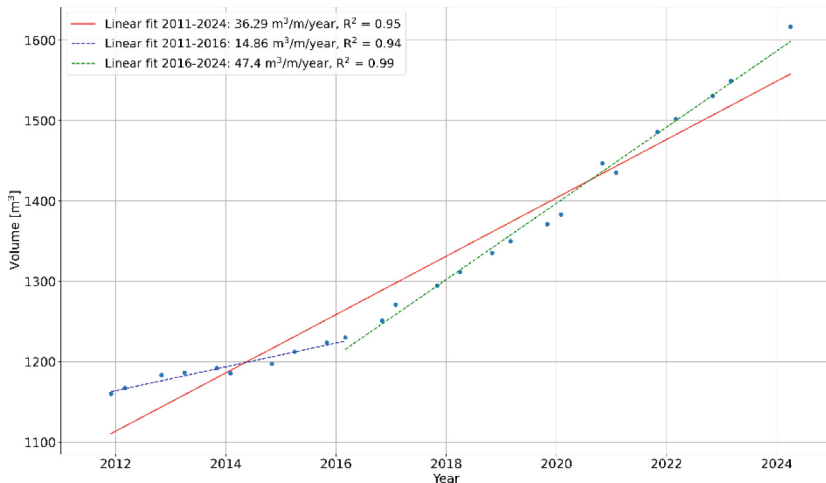
Vegetation develops mainly in places where accumulation takes place. In Fig. 3 the presence of vegetation is plotted also for each year where data is available. It shows that the dune ( $x = 0 - x = 50$ ) is (almost) completely vegetated after the vegetation has started to grow in 2016. It can be seen that the vegetation presence is increasing over time along this part of the transect. Between  $x = 160$  and  $x = 250$  the elevation profile shows a clear accretion of sediment. Along this part of the transect some vegetated patches have started to grow. Over time the vegetation cover is increasing in this area. Notably, the vegetation is often growing around the peaks of the elevation profile. Often vegetation stays at/ around the same location and multiplies, however occasionally vegetation has disappeared.



**Fig. 3.** Transect profile: cross-shore distance on the x-axis (0 m is bicycle lane, right is the seaward side), elevation in meters on the y-axis. Coloured lines represent profiles of different years. Green dots represent the presence of vegetation, extracted from RGB images. The larger the dot the higher percentage of vegetation per  $\text{m}^2$ . Note that vegetation data is only present for the following timestamps (year\_month): 2016\_02, 2017\_01, 2018\_03, 2019\_02, 2020\_01, 2022\_02, 2023\_02.

During the period between 2011–2024, dune growth rates seem to vary. Figure 4 shows the volume changes over time of the cross-shore transect shown in Fig. 3. It is clear that the volume of this transect is increasing over time. The linear fit (red line)

shows a trend of  $40 \text{ m}^3/\text{m}/\text{year}$ , which is at the upper limit of the volume changes found by [6]. The  $R^2$  of this fit is 0.94. However, a break in the slope in the development of the measured dune volumes in time can be seen. From 2016 onwards we found from aerial images that vegetation has started to develop. Vegetation traps sediment [8, 9 10, 11, 12] and therefore an increase in the trend of volume changes can be seen. The blue and green dashed lines show the linear fit over the two periods. The trend before the presence of vegetation is  $15 \text{ m}^3/\text{m}/\text{year}$  ( $R^2 = 0.90$ ), while the trend after the vegetation has started to develop is significant larger with  $53 \text{ m}^3/\text{m}/\text{year}$  ( $R^2 = 0.99$ ).



**Fig. 4.** Volume change within one cross-shore transect profile over time. The blue dots represent the measured volumes of the profile for each year. The red line is a linear fit through all points, the blue dashed line and the green dashed line are the linear fit through a period when vegetation was not yet present, and a period when vegetation has started to grow, respectively. The trend of the fitted lines and the  $R^2$  value are given in the left upper corner.

## 4 Discussion and Conclusions

Over the past 13 years, on the Zandmotor natural processes have led to the growth of a new dune area. These dunes have formed as a result of natural sediment dynamics and vegetation development, both of which are influenced by time, location and environmental conditions. Consequently, the distribution of the new dunes is not uniform and shows spatial variation. The volume growth of the dunes on the Zandmotor are consistent with dune growth elsewhere along the Dutch coast.

In this study we found that the vegetation cover is increasing on the Zandmotor over time. We showed that the vegetation is often growing around the peaks of the elevation profile. Often vegetation stays at/ around the same location and multiplies, however occasionally vegetation has disappeared. Besides, we found that the volume change per year before the presence of vegetation is  $15 \text{ m}^3/\text{m}/\text{year}$ , while the trend after the vegetation has started to develop is significant larger with  $53 \text{ m}^3/\text{m}/\text{year}$ . Therefore we can conclude that the presence of vegetation has contributed significantly to the

increase in dune volume on the Zandmotor landscape, highlighting its importance in coastal development.

These insights gained at the Zandmotor, about the interrelation between sedimentation and vegetation and its influence on dune growth, may inform the development of strategies to mitigate coastal squeeze, enhance dune resilience and adapt to the challenges of climate change and human activities.

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