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IMPACT OF DUNE VEGETATION ON WAVE AND WIND EROSION

A case study at Ängelholm Beach, South Sweden

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Abstract

At several places in South Sweden, dune vegetation is removed from coastal dunes with the purpose to increase biodiversity in sandy habitats. At these sites, also morphological changes take place as the dunes are no longer stabilized by vegetation. In this case study at Ängelholm Beach in South Sweden, the effect of vegetation removal on dune erosion by wind and waves is evaluated. Analyses of volume and land cover changes show that wave and wind erosion increased due to the vegetation removal. Sand was transported away from the beach and dune system, into a forest behind the beach, and dune front erosion during storms increased by 2–4 times, compared to dunes with the vegetation intact.

Key words – dune vegetation, aeolian transport, dune erosion, coastal dunes

Sammanfattning

På flera platser i Södra Sverige avlägsnas dynvegetation från sanddyner utmed kusten för att öka biodiversiteten i sandiga miljöer. På dessa platser sker även morfologiska förändringar, eftersom dynerna inte längre stabiliseras av vegetationen. I den här fallstudien utvärderas effekten av vegetationsborttagning på dynerosion från vind och vågor. Analys av volym- och marktäckningsförändringar visar att såväl våg- som vinderosionen ökade till följd av vegetationsborttagningen. Sand blåste iväg från strand- och dynlandskapet in i en skog bakom stranden och erosionen på dynens främre del ökade med 2–4 gånger, jämfört med dyner med intakt vegetation.

1 Introduction

Historically, wind-blown sand has caused major nuisance in South Sweden, both along the coast and in the inland (Lidbeck, 1759). The Swedish botanist Carl von Linné described in his travel journals from mid-18th century how the wind-blown sand destroyed arable land and spread into the cities, forming sand piles analogous to snowdrifts (Gullander, 1975). At this time, sand fences were set up to stop the sand drift and dunes were formed. On these stabilized dunes, dune grass was introduced to bind the sand, and conifer forests were planted (Gullander, 1975). These measures had in the early 19th century successfully stopped the sand drift and consolidated the dunes (Johnmark, 2010). The sandy habitats in South Sweden then became less dynamic and their flora and fauna were altered.

The sand-binding vegetation is now being removed at sites in South Sweden within the project Sand Life (Sand Life, 2016). The aim of Sand Life is to increase biodiversity on sandy grounds, but the operations also impact physical processes such as wind driven sand transport, storm erosion, and dune recovery after storms.

Vegetated dunes constitute today an important flood protection along large coastal stretches in South Sweden. With rising sea levels, the importance of flood defence as well as the pressure on the beach and dune systems is expected to increase (Leatherman *et al.*, 2000). The vulnerability of the coast to storms depends on the height of the dunes and the recovery of the dunes after storm events (Durán and Moore, 2013). In many areas it is therefore important to protect coastal dunes and mitigate erosion that will lead to a weakened flood defence.

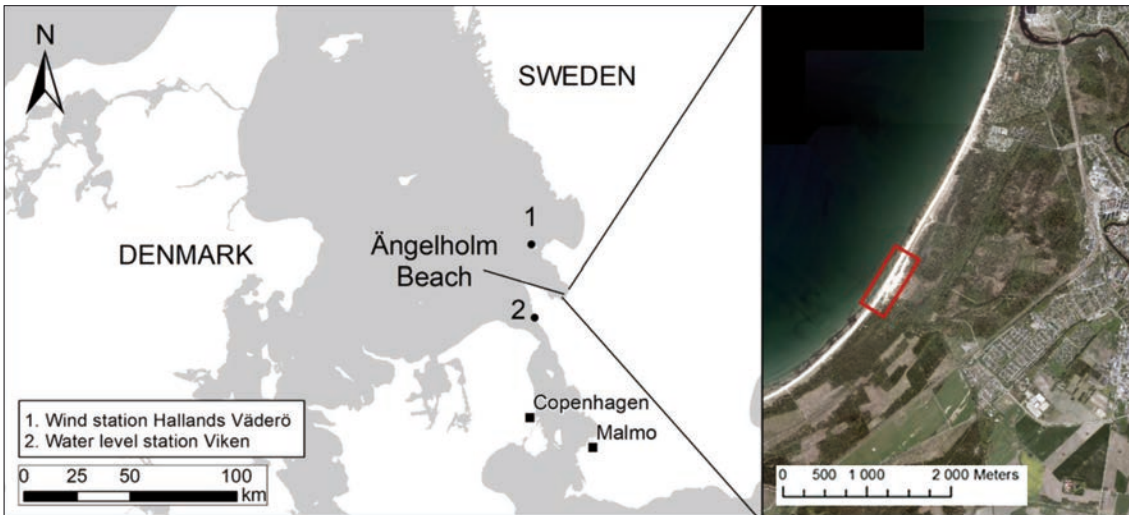


Figure 1. Overview map and aerial photo. The study area is marked with a red rectangle.

The aim of this case study is to investigate the impact of vegetation removal on physical processes at one of the Sand Life project sites. In this paper the morphologic changes due to vegetation removal are quantified based on topographic surveys and the spreading of sand is mapped using land cover analysis. Sand volumes lost from the beach system by wind transport are estimated using empirical equations, and storm damage between vegetated and non-vegetated foredunes are compared to assess dune stability under hydrodynamic impact.

1.1 Study area

The study site, with an area of 16 ha, is located at Ängelholm Beach in Skälderviken Bay, South Sweden (Figure 1). Dunes are present in 2–3 rows with crest heights of about 3–4 m. The beach in front of the dunes is approximately 50 m wide and the coast has a long-term accreting trend (Palalane et al., 2016). The grain size is approximately 0.15–0.20 mm.

Within the study area, dune vegetation was removed by Sand Life in 2014. In some parts, the vegetation was removed from the entire dune landscape and in other parts only from the second and third dune row, leaving the front dune intact. When the vegetation was removed, the dunes were excavated and the sand was strained to remove root parts from undesired plants. Thereafter the dunes were rebuilt by returning the sand without vegetation (Sand Life, 2014). The dune vegetation mainly consists of the dune grasses *Ammophila arenaria* and *Leymus arenarius* together with bushes of *Rosa rugosa* and different other types of low vegetation. Behind the dunes, there is a beach forest with mainly pine trees (Figure 2 and 3).

This study covers the period from the vegetation removal, which was completed in March 2014, until January 2017. The period includes three storm events with observed dune erosion; the storm Egon in January 2015, Gorm in November 2015, and Urd in December 2016. In table 1 wind speed and direction as well as still water level are presented for the storms. The meteorological

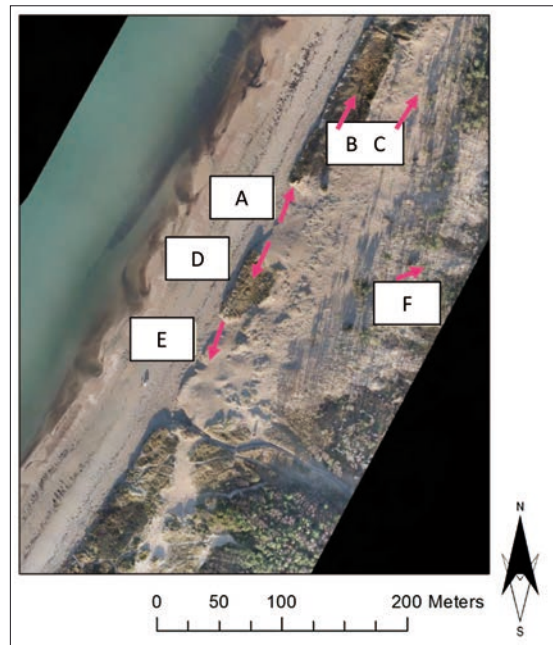


Figure 2. Photographed areas. Arrows indicate position and direction of each photo.

Table 1. Highest measured wind velocity, wind direction, and highest still water level for each of the storms Egon, Gorm, and Urd.

Storm and date	Highest mean wind speed (m/s)	Wind direction	Highest still water level (cm, RH 2000)
Egon, January 10, 2015	22.8	W	160
Gorm, November 29–30, 2015	27.9	W	180
Urd, December 25–26, 2016	21.8	NW	177

data is collected from the wind measurement station Hallands Väderö and the water level measurement station Viken, operated by the Swedish Meteorological and Hydrological Institute (SMHI) (Figure 1). As the water

level gage is located outside Skälderviken Bay, the still water level is corrected for wind setup according to the method described in Palane et al. (2016). The wind speed is measured as a 10 min average, hourly observations.

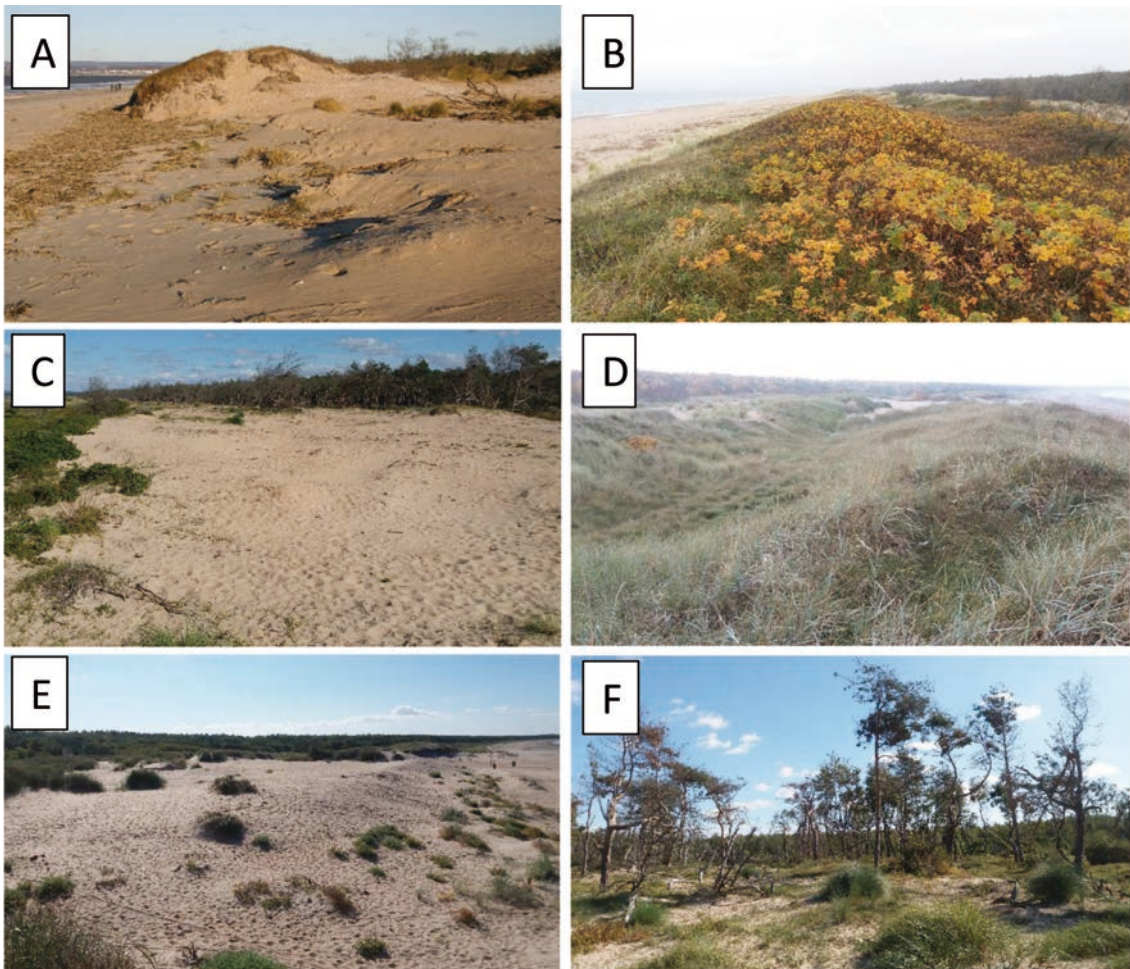


Figure 3. Photographs from the study area. Photograph A and E shows the non-vegetated front dunes, B a dune with *Rosa rugosa*, C the non-vegetated area behind the dune, D one of the vegetated dunes, and F the beach forest behind the dunes. The photographs are taken during field visits in the autumn 2016.

2 Theory

Dune vegetation impact the morphological evolution mainly by three processes; it traps the sand so that wind transported sand from the beach is deposited in the dune and controls the dune shape and height. Further, dune vegetation may decrease storm erosion damages and facilitates dune recovery after storms.

2.2 Aeolian transport

Dunes in coastal areas are formed and built up by aeolian (wind) transport and accumulation of sand (Luna et al., 2011). The mechanics of aeolian transport is thoroughly described in the literature (see e.g. Herrmann, 2004). When the wind blows over a beach, it affects the sand grains with two forces; lift force and drag force. The drag force acts horizontal to the ground and in the same direction as the wind. The lift force on the other hand acts vertical to the drag force and develops from the difference in static pressure above and beneath the sand grain. The sand grains at the top of a sand bed moves when the lift and drag force exceeds the gravity of the grain. When the sand grains are moving, they impact each other through collisions. A collision between a moving grain and a resting grain generates a transfer in momentum which lowers the threshold for entrainment for the resting grain. This process is called saltation and requires a certain fetch length to be fully developed. The transport during such fully developed conditions can be calculated by equilibrium transport formulas relating aeolian transport rate to grain size, wind shear velocity (i.e. a measure of shear stress on the sediment grains), and a critical wind shear velocity for initiation of motion (see e.g. Bagnold, 1937).

When the wind blows over a beach with bare sand, the velocity of the wind decreases relatively gently and regular near the ground. On the other hand, if there is vegetation present the wind velocity decreases drastically closest to the ground. Sand is deposited in vegetated areas because the shear stresses generated by the wind there to lesser extent exceeds the critical stress needed to move the sand grains (Norrman, 1967).

2.3 Wave erosion

The impact of waves on dunes can be divided into four different types (Silva et al., 2016):

1. Swash; the waves only reach and erodes the foreshore and does not reach the dune.
2. Collision; wave run-up collides with the base of the front dunes, sediment is eroded from the dune, and deposited on the beach or transported offshore.
3. Overwash; the waves reach over the foredunes and wash sand landwards at the same time as sediment is eroded from dune as for the collision regime.

4. Inundation; the entire front dune ridge is inundated with water.

In this study, the focus is on erosion created by collision, as was observed during the storms within the study period.

In empirical studies with wave flume experiments it has been shown that vegetation decreases the damage caused by erosion, through decreasing wave energy by friction of the plants, by increasing turbulence, and by stabilizing the dune with the root system (Silva et al., 2016; Figlus et al., 2017). Vegetation is also important in the dune recovery after storm damages, through its sand trapping and consolidating ability.

2.4 Impact of vegetation on dune formation

Vegetation is of major importance for development of dunes on sandy beaches (see e.g. Luna et al., 2011). A sandy beach without any vegetation and with an unsaturated influx of sand becomes unstable if continuously exposed to winds. This generates dunes that migrates in the direction of the wind. If instead sand influx is limited and the sand loss is greater than the sand supply, small dunes will be generated, although soon decreasing in volume, and finally disappearing with the wind. On the other hand, if there is vegetation present on the beach, dunes will be formed even if the influx of sand is low. The higher the sand influx, the faster the build-up of new dunes as the sand accumulates more quickly upon the vegetated dune.

The formation of stable dunes in the presence of vegetation is explained by the wind dynamics around the plants (see e.g. Hesp, 2002). The wind velocity decreases abruptly at the plants, creating a local acceleration around them, and a flow separation behind them. The plants create a roughness that absorbs parts of the momentum which otherwise would have affected the sand grains so that wind transported sand accumulate at and behind the vegetation. Dune formation and their morphological evolution mainly depends on the vegetation density, distribution, coverage, and height together with the wind velocity and rate of sand transport (Hesp, 2002).

3 Data and methods

No topographic surveys were performed by Sand Life just before or after the vegetation removal in March 2014. This study has used topographic data and aerial photography collected for other purposes, complemented with field data collected during the autumn and winter 2016/2017. Elevation data and aerial photography were provided by Ängelholm Municipality.

3.1 Land cover and spreading of sand

To investigate the spatial variation and changes of land cover over time, three orthophotographs from April 2010, November 2014, and December 2015 were studied. The land cover was divided into six classes: sand, forest (trees and bushes), dune grass vegetation, low vegetation, *Rosa rugosa*, and asphalt. The area of each class was then calculated and compared between the different years.

The orthophotographs from November 2014 and December 2015 were used to closer investigate the spreading of sand towards the forest behind the dunes. For each of the orthophotographs the area with bare sand in the dunes were manually marked out and the difference between them was calculated.

The sources of error in these analyses could be the specificity of classification of the different land cover types, since the border between them in the orthophotographs sometimes were a bit unclear. To take this into account, the numerical results were rounded off to hundreds of m².

3.2 Digital elevation models in 3D

Elevation data from April 2010, November 2014, and January and December 2015 were interpolated with the method Inverse distance interpolation, to raster data with a resolution of 1*1 m, creating digital elevation model (DEM). The elevation point data from April 2010 were collected by LiDAR and for the other occasions by photogrammetry. The data had been adjusted beforehand for vegetation. The study area was selected to contain as little forest as possible since the risk for errors in the data were estimated to be largest there. The DEMs were visualized in ArcScene with a vertical exaggeration of 3.7 to clarify the topography.

3.3 Difference in ground elevation

The change in ground elevation between the DEMs from November 2014 and January and December 2015 were calculated through subtraction of the older raster from the younger raster. The study area was focused on the part of the dunes where vegetation was removed in 2014 and on the vegetated dunes nearby. The resulting raster was divided into seven different classes to show the increase and decrease of the ground elevation. One of the classes, -0.2 to 0.2 m, were used as a buffer-class to account for errors in the elevation data.

Erosion on the front dune after each of the storms Egon and Gorm was calculated through comparing different areas from both the vegetated and non-vegetated front dunes (in volume per meter along the beach).

Sources of error in the DEMs may be uncertainties of

classification of ground data in vegetated dunes. Since the focus of the analysis concerns non-vegetated areas, the impact on the results are limited.

3.4 Estimated sand loss due to aeolian transport

The beach and the dune constitute a dynamic sand transport system where the dune functions as a sediment buffer for the beach. The dune also functions as flood protection for the hinterland. As long as the sediment is contained within the dune, the sediment is a part of the beach's sediment budget. Sand transported into a forest behind the beach is, thus, considered to be lost from the system and to contribute to beach erosion.

Potential aeolian transport leaving the dune system was calculated for the stretches of the coast where the vegetation had been removed completely, including the foredune. The transport was calculated for the period from November 2014 to December 2015, from when aerial photos and DEMs were available. Wind data was collected from the SMHI station Hallands Väderö (10 min average, hourly observations). Transport was calculated for onshore wind conditions with an angle up to 80° against shore normal. In general, when calculating aeolian transport for oblique wind directions, only the onshore transport component is accounted for, and the alongshore component is neglected. In this case, no correction for this cosine effect was made, as the sand is assumed to leave the dune landscape independent of wind directions, as long as the wind is onshore directed.

The potential aeolian sediment transport rate (m_{WE}), was calculated with an equilibrium transport formula (Lettau and Lettau, 1978):

$$m_{WE} = K_w \sqrt{\frac{D_{50}}{D_{50}^{ref}}} \rho_a \frac{u_*^2}{g} (u_* - u_{*c}) \quad (1)$$

where D_{50}^{ref} is the median reference grain size (0.25 mm), ρ_a the density of air, g the standard acceleration due to gravity, u_* the shear velocity at the bed, u_{*c} the critical shear velocity at the bed, and K_w an empirical coefficient set equal to 1.2 (Sherman et al., 2013). The median grain size, D_{50} , is estimated to 0.2 mm. If $u_* < u_{*c}$, $m_{WE} = 0$.

The mass flux m_{WE} was converted to a volumetric equilibrium transport rate (q_{WE}) of sand to the dunes by:

$$q_{WE} = \frac{m_{WE}}{\rho_s} (1 - P) \quad (2)$$

where ρ_s is the density of sand, 2,650 kg/m³, and P the porosity, assumed to be 40%.

The critical shear velocity was calculated from (Bagnold, 1937),

$$u_*^c = A_W \sqrt{\frac{(\rho_s - \rho_a)}{\rho_a} g D_{50}} \quad (3)$$

where A_W is a coefficient, set to 0.1.

The shear velocity, u_* , was calculated using the law of the wall,

$$\frac{u_z}{u_*} = \frac{1}{\kappa} \ln \left(\frac{z}{z_0} \right) \quad (4)$$

where u_z is the wind velocity at z meter above ground, z_0 is the aerodynamic roughness height and κ is von Karman's constant (≈ 0.41), z_0 was here parameterized as $D_{50}/30$ (see *e.g.* Zhang et al., 2015).

4 Results and discussion

4.1 Land cover and spreading of sand

Classification of land cover from April 2010, November 2014, and December 2015 are displayed in figure 4. The area of sand and vegetation, respectively, from this analysis are presented in table 2.

The spreading of the sand towards the forest is shown in figure 5. The area that has been covered with sand between November 2014 and December 2015 was calculated to 14,200 m².

In figure 4 it is clearly seen that the land cover between the years have changed. In April 2010 and in



Figure 4. Classification of land cover from April 2010, November 2014 and December 2015. Column A shows the orthophotographs, and column B shows the results of the classification.

Table 2. Area of the land cover that was sand respectively vegetation in April 2010, November 2014 and December 2015. The total area is 164,300 m².

Date	Vegetation (m ²)	Sand (m ²)
April 2010	134,000	30,100
November 2014	97,700	66,400
December 2015	87,400	76,700

November 2014 the area of sand increased due to the vegetation removal, but the sand area increased (with 16%) also between November 2014 and December 2015 when no vegetation removal was carried out. The reason for this is that the sand from the non-vegetated dunes has been spread with the wind into the forest behind. The sand which is blown into the forest leaves the beach's sediment transport system. This means that it no longer will take part in the reconstruction of the beach after storm events, and will contribute to a landward retreat of the coastline.

4.2 3D visualisation of elevation data

The DEMs from April 2010, November 2014, and January and December 2015 are shown in figure 6. The vertical exaggeration was set to 3.7 to clarify the topography.

The DEMs clearly visualize the change in topography due to the vegetation removal. As can be seen in the DEM for April 2010 that the front dune was a long and continuous dune ridge. In the DEM for November 2014, after the reduction of vegetation, the continuous front dune has been broken up, where the non-vegetated dunes are lower and flatter than the vegetated dunes. After the storms Egon and Gorm, illustrated by the DEMs for January and December 2015, the non-vegetated dunes continue to retreat and become even flatter compared to the vegetated dunes. Sources of errors are discussed in the next section.

4.3 Difference in ground elevation

The difference in ground elevation between the DEMs from April 2014 and January and December 2015 are displayed in figure 7.

The difference in ground elevation between November 2014 and January 2015 (containing the storm Egon) is to a large extent within an uncertainty interval of ± 0.2 m. However, on the front of the non-vegetated dunes a narrow band with orange-red can be seen which indicates a decrease in sand elevation of about 1 m.

Between January and December 2015 (containing the storm Gorm) the loss of sand in the non-vegetated front dune is greater and clearly seen as a wide red band parallel to the dunes. The same pattern is seen in the

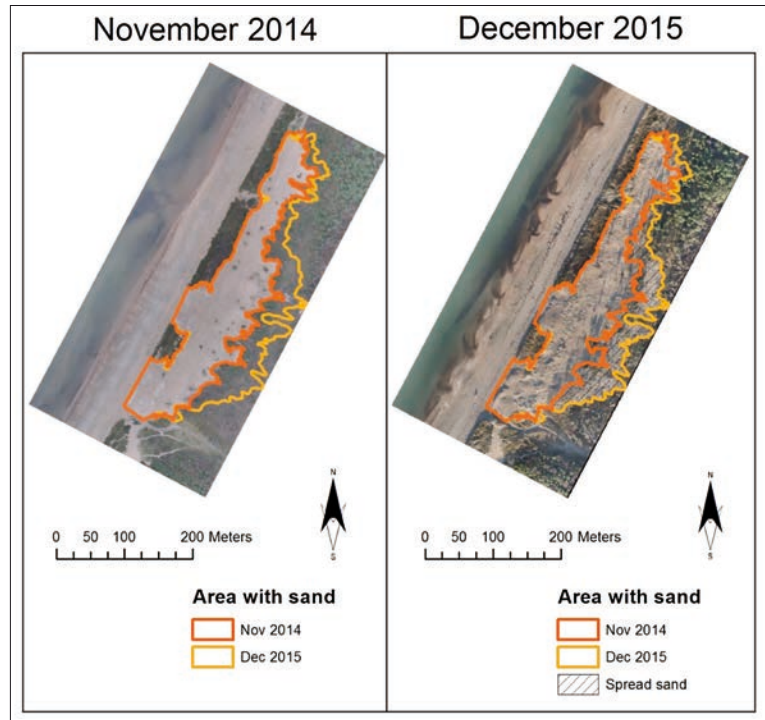


Figure 5. The spreading of sand towards the forest (marked with black lines) between November 2014 and December 2015. The area with spread sand was calculated to 14,200 m².

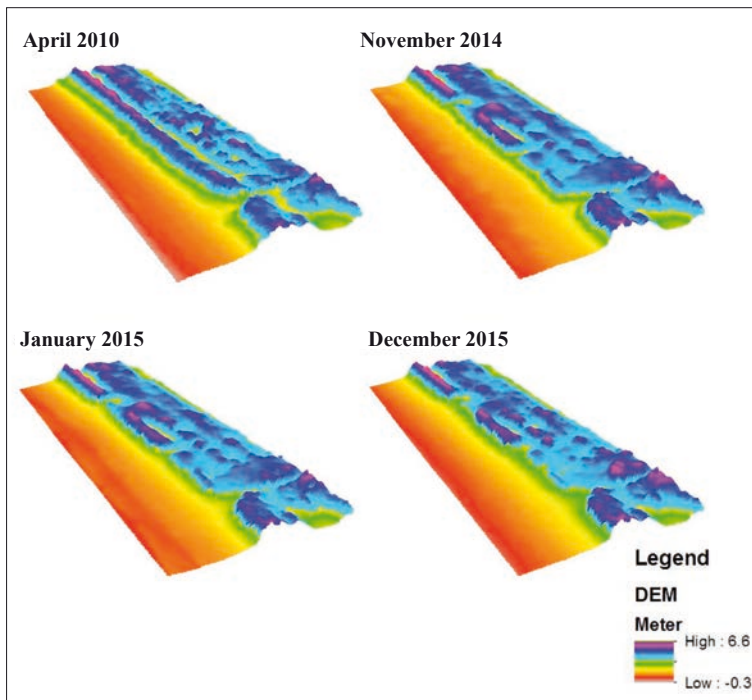


Figure 6. Digital elevation models shown in 3D for April 2010, November 2014, and January and December 2015. The vertical exaggeration was set to 3.7. The actual size of the study area is 343*129 m.

difference between November 2014 and December 2015 (containing both storms).

The results show that the non-vegetated front dunes erode 2–4 times more than the vegetated front dunes. This observation was confirmed during the field visit, where it was evident that the non-vegetated dunes had retreated further inland than the vegetated dunes, see figure 3. This is likely due to the absence of vegetation and roots that would help to stabilize the dune during wave attack or trap the sand in the recovery phase after storms. However, it is not certain whether the entire volume lost from the dune front is due to erosion by wave attack or if a part of the sediment has been eroded by the wind.

4.4 Estimated sand loss due to wind transport

Calculated wind transport from the dune into the forest amounts to 2.8 m³/m beach length from November 2014 to December 2015. The amounts are estimated for the parts of the dunes where the vegetation was removed completely, including the front dune. It is assumed that the transport is fully developed, meaning that it is not limited by the fetch length, here considered as the distance along the wind direction from the runup limit to the landward end of the dune landscape. No further correction is made for the beach slope, which is fairly steep

in the dune landscape which may lead to an overestimation of the transport rates (Bagnold, 1973).

Equilibrium transport formulas tend to overestimate aeolian transport compared to field observations (e.g. Barchyn et al., 2014; Sherman et al., 1998). To assess if the calculated volumes are reasonable, the amounts are compared to observed sand spreading during the period November 2014 to December 2015. Assuming that half of the sand that had spread into the forest during this period originates from the dunes where vegetation was removed completely, the transported volume corresponds on average to a 5 cm thick sand layer. Although, the actual thickness of the sand layer has not been measured in field, it can be concluded that the calculated transport is in the right order of magnitude.

In summary, during a 13 month period, starting 7 months after the vegetation was removed, about 3 m³ sand per m beach length was estimated to be lost from the beach system in the area where vegetation was removed completely. With time, this transport may decrease, if new vegetation is allowed to establish. In other studies, development of armouring layers on the sand has been observed to develop from e.g. coarser sediment, shells, and salt crust (Hoonhout and de Vries, 2016). However, in this specific case, all the sediment is of aeolian origin and is, thus, available for transport which may explain the observed transport more than half a year after the intervention.

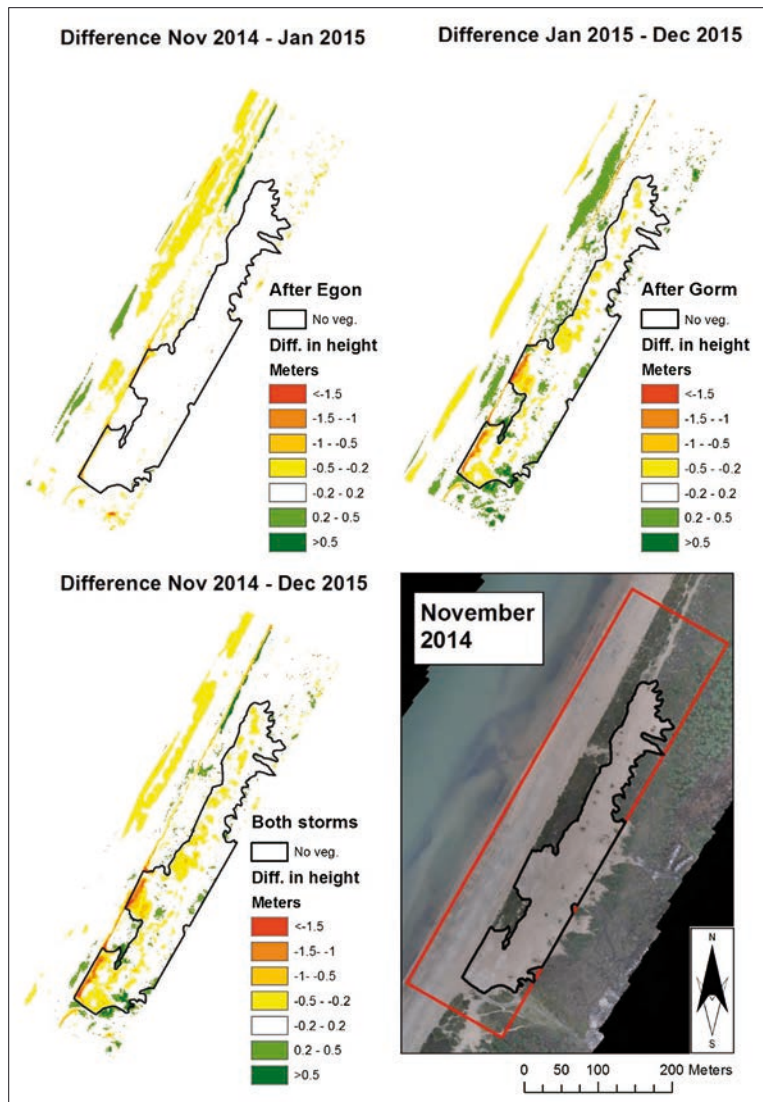


Figure 7. *Difference in ground elevation (height) for November 2014–January 2015, January 2015–December 2015, and November 2014–December 2015. The study area is marked in red and the area that had no vegetation in November 2014 is marked with a black line.*

5 Conclusions

The results from this study show that vegetation removal have had a considerable impact on the development of the dunes in Ängelholms Strandskog. The non-vegetated dunes were subject to 2–4 times larger erosion in the dune front after Egon and Gorm than the vegetated dunes. The non-vegetated dunes have become flattened as sand has blown into the forest behind the beach. This process is explained by the fact that non-vegetated dunes no longer are stabilized by vegetation and, therefore, cannot trap and bind the sand. The removal of beach vegetation has increased wind and wave erosion of the dunes, which makes the dunes more vulnerable to

storm events. The decrease of dune volume and dune height, where the vegetation was removed, has made the area behind the dunes more flood prone.

Calculations of potential aeolian transport shows that the wind drift into the forest could have been foreseen using this methodology. The aeolian transport of sediment into the forest is a sediment sink for the beach that may contribute to beach erosion and a landward retreat of the coast.

Removing dune vegetation may enhance biodiversity, but can also increase beach erosion and coastal flooding. Through a closer cooperation between biologists and engineers, multi-functionality of coastal dunes can be enhanced. In future habitat restoration projects it would

therefore be interesting to test different alternatives of vegetation removal and evaluate their effect on the dunes' morphological evolution. To tackle future challenges due to climate change, a sustainable coastal landscape will require both species richness and protective dunes.

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