ARTICLE IN PRESS

Aeolian Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

UAV-imaging to model growth response of marram grass to sand burial: Implications for coastal dune development

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ARTICLE INFO

Keywords:
Ammophila arenaria
Coastal aeolian dynamics
Plant-sand interaction
Gaussian response model
Unmanned Aerial Vehicle (UAV)

ABSTRACT

Vegetated coastal dunes have the capacity to keep up with sea-level rise by accumulating and stabilizing wind-blown sand. In Europe, this is attributed to marram grass (*Ammophila arenaria*), a coastal grass species that combines two unique advantages for dune-building: (1) a very high tolerance to burial by wind-blown sand, and (2) more vigorous growth due to positive feedback to sand burial. However, while these vegetation characteristics have been demonstrated, observational data has not been used to model a function to describe the growth response of *Ammophila* to sand burial. Studies that model coastal dune development by incorporating positive feedback, as a result, may be hampered by growth functions that are unvalidated against field data. Therefore, this study aims to parameterize an empirical relationship to model the growth response of *Ammophila* to burial by wind-blown sand.

A coastal foredune along a nourished beach in the Netherlands was monitored from April 2015 to April 2016. High-resolution geospatial data was acquired using an Unmanned Aerial Vehicle (UAV). Growth response of *Ammophila*, expressed by changes in Normalized Difference Vegetation Index (Δ NDVI) and vegetation cover (Δ Cover), is related to a sand burial gradient by fitting a Gaussian function using nonlinear quantile regression. The regression curves indicate an optimal burial rate for *Ammophila* of 0.31 m of sand per growing season, and suggest (by extrapolation of the data) a maximum burial tolerance for *Ammophila* between 0.78 (for Δ Cover) and 0.96 m (for Δ NDVI) of sand per growing season. These findings are advantageous to coastal management: maximizing the potential of *Ammophila* to develop dunes maximizes the potential of coastal dunes to provide coastal safety.

1. Introduction

Coastal dunes are prominent features along many of the world's sandy shorelines, covering about 34% of the world's ice-free coasts (Hardisty, 1994). They are the result of complex interactions between wind, waves, sand and vegetation (Hesp, 1989; Keijsers et al., 2016) and have the capacity (1) to reduce hydrodynamic impact from storm surges and (2) to keep up with sea-level rise by accumulating and stabilizing wind-blown sand (Temmerman et al., 2013). As a result, coastal dunes are often essential for flood protection and ensuring coastal safety (De Jong et al., 2014; Keijsers et al., 2015; Poortinga et al., 2015).

The capacity of coastal dunes to keep up with sea-level rise is attributed to the specialized morphology of coastal grass species covering the dunes. Especially European and American marram grass, *Ammophila arenaria* and *Ammophila breviligulata*, combine two unique advantages for dune-building, namely (1) very high tolerance to burial by wind-blown sand, reportedly up to 1 m (Ranwell, 1972) or even 2 m of sand per year (Baas and Nield, 2010), and (2) more vigorous growth under the right conditions of sand burial (e.g., Huiskes, 1979; Disraeli, 1984; Maun and Lapierre, 1984; Hesp, 1991; Van der Putten et al., 1988). This introduces a reinforcing feedback essential to dune development: adequate levels of wind-blown sand encourages *Ammophila* to grow, which in turn enhances *Ammophila's* capacity to accumulate and stabilize wind-blown sand (Maun, 1998; Zarnetske et al., 2012). As a result, dune development is directly related to the growth response of marram grass to sand burial (Keijsers et al., 2016), and throughout temperate climate zones in the world *A. arenaria* and *A. breviligulata* helped to create very high vegetated coastal dune landscapes (Ranwell, 1972).

However, while stimulated growth of *Ammophila* to sand burial has

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http://dx.doi.org/10.1016/j.aeolia.2017.08.006
Received 21 March 2017; Received in revised form 23 June 2017; Accepted 21 August 2017
1875-9637/

Please cite this article as: nolet, c., Aeolian Research (2017), http://dx.doi.org/10.1016/j.aeolia.2017.08.006

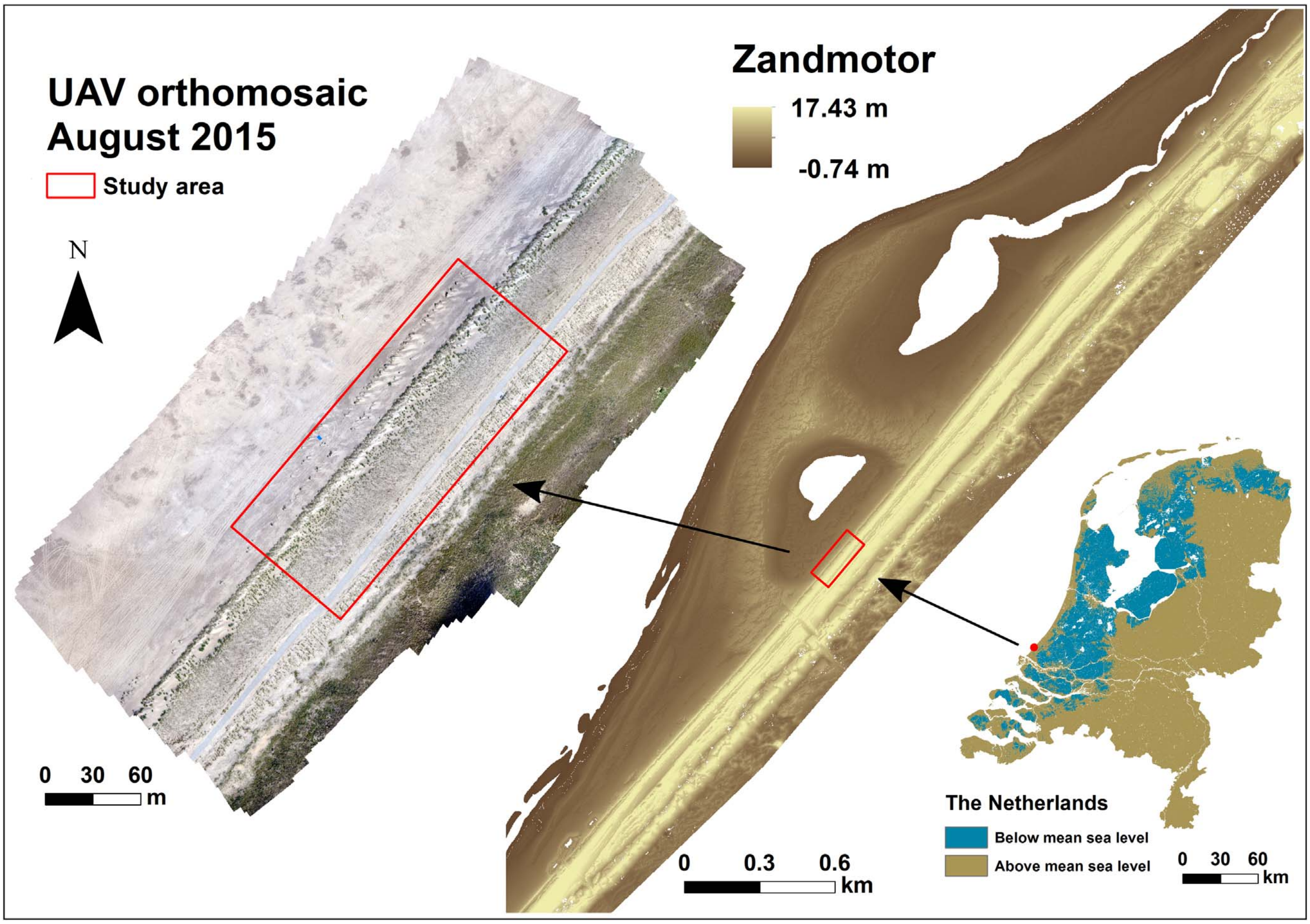

Fig. 1. The study area (red box), a stretch of foredune that was artificially created in 2011 just prior to construction of the Zandmotor, an uniquely large nourishment of sand (21.5 Mm^3) located just south of The Hague along the Dutch coast. The studied foredune has a south-west to north-east orientation, parallel to the dominant south-western wind direction. Just after construction the ~40 m long stoss slope of the foredune (15° at its steepest) was manually planted with marram grass (*Ammophila arenaria*) in a regular grid of about 7–9 small tussocks per m^2. From dune toe to dune crest the stoss slope ranges between 4 and 12 m above mean sea level (MSL) and *Ammophila* grows between 7 and 12 m +MSL. Note the bike path running along the dune crest at 11.5 m +MSL and the incipient dunes in front of the dune toe at 4 m +MSL. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

convincingly been demonstrated by aforementioned studies, the observational data has not been used to model a function to describe this response. Instead, the findings are reported primarily using inferential statistics based on a limited number of plant samples. Moreover, except in Disraeli (1984), results are drawn from experiments that relied on artificial sand burial treatments within a restricted burial range. The reported growth response of *Ammophila* to sand burial, therefore, may not have been fully representative for burial conditions due to natural coastal aeolian dynamics.

As a result, studies that aim to model coastal dune development by explicitly incorporating positive feedback, (i.e., Baas, 2002; Nield and Baas, 2008; Baas and Nield, 2010; Keijsers et al., 2016), may be hampered by an inadequate description of growth response of marram grass to sand burial under natural conditions. While the employed growth functions are deliberately simplistic to reduce model complexity, they are not validated against field data but rather based on anecdotal evidence and derived by trial-and-error model runs (Baas and Nield, 2010). Therefore, to help fill that gap, this study aims to parameterize an empirical relationship to model the growth response of *Ammophila* to burial by wind-blown sand. It builds on the conceptual model put forward by Maun, 1998 and Maun and Perumal, 1999, in which a 2nd order polynomial is proposed for describing stimulated growth of *Ammophila* in response to sand burial, up to a maximum burial tolerance beyond which plants start to show a negative response.

To this end, a stretch of coastal foredune, along a nourished beach in the Netherlands, has been extensively monitored over the course of a year using an Unmanned Aerial Vehicle (UAV). Rapid technological advances in platforms, sensors and software have positioned UAV's as a powerful low-cost tool to accurately derive very high-resolution geospatial data, at temporal resolutions defined by the end-user (Westoby et al., 2012; Hugenholtz et al., 2013; Mancini et al., 2013). Processing the aerial images using photogrammetric software is particularly advantageous, for it allows producing high quality digital elevation models and orthomosaics of the same area at the same time. The ability of UAV's to collect topographic and ecological data simultaneously holds invaluable promise for spatial biogeomorphology (Anderson and Gaston, 2013), and may prove to be essential to better quantify the growth response of *Ammophila* to burial by wind-blown sand.

This paper presents the results obtained by aforementioned monitoring study, focusing on a growing season of *Ammophila arenaria* from April 2015 till October 2015. Growth response of marram grass is expressed by temporal changes in Normalized Difference Vegetation Index (Δ NDVI) and spatial–temporal changes in vegetation cover (Δ Cover), while sand burial by wind is derived from changes in dune morphology due to aeolian dynamics (Δ dune height). It has been demonstrated by Disraeli (1984); Maun and Lapierre (1984) and Yuan et al. (1993) that plants subjected to regular burial in sand showed a higher total chlorophyll content and above-ground biomass than plants not subjected to sand burial. This suggests that changes in NDVI and vegetation cover are appropriate indicators for growth of *Ammophila* in