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INFLUENCE OF REED STEM DENSITY ON FOREDUNE DEVELOPMENT

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ABSTRACT

Vegetation density on foredunes exerts an important control on aeolian sediment transport and deposition, and therefore on profile development. In a long-term monitoring field experiment, three plots were planted with regular grids of reed bundles in three different densities: 4, 2 and 1 bundles per m^2. This study reports on the differences in profile development under the range of vegetation densities.

Topographic profiles were measured between May 1996 and April 1997. Results indicate important differences in profile development for the three reed bundle densities: in the highest density plot a distinct, steep dune developed, while in the lowest density a more gradual and smooth sand ramp was deposited. When the stems had been completely buried, differences in profile evolution vanished. After a second planting of reed stems in January 1997 the process was repeated. In May 1997, all plots had gained a sand volume ranging from 11·5 to 12·3 $m^3\ m^{-1}$, indicating that the sediment budget is relatively constant, regardless of the particular profile evolution.

The field evidence is compared with simulations of profile development, generated by the foredune development model SAFE. The model successfully reproduces the overall profile development, but in general, the equations used for vegetation–transport interaction overestimate the effect of vegetation. This causes some deviations between field and model results. Several reasons for this are discussed. Based on the experiments reported here, recommendations are given for further research. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS: vegetation density; aeolian processes; modelling; roughness elements; adaptation length

INTRODUCTION

Vegetation is an important parameter in aeolian environments, because it reduces sediment transport. In coastal and agricultural areas, planting of vegetation is often used as a means for surface stabilization. The presence of even small amounts of vegetation in desert environments may be decisive for dune mobility or stability (Wiggs *et al.*, 1995; Lancaster and Baas, 1998). Wolfe and Nickling (1993) describe the effects of vegetation on sediment transport in three ways: (1) vegetation extracts momentum from the air flow; (2) vegetation elements present an obstacle for saltating sand grains; (3) the part of the surface that is covered with vegetation is withdrawn from the sediment supply system.

Two basic approaches are distinguished to quantify the effect of vegetation. The first approach estimates the reduction of shear stress near the surface due to the presence of the vegetation canopy (for example Raupach, 1992). The second approach estimates the increase of threshold shear velocity (above the vegetation) of the

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vegetated surface in comparison with a bare surface (for example Stockton and Gillette, 1990; Musick and Gillette, 1990; Musick *et al*., 1996).

Studies on the effects of vegetation are often performed in wind tunnels. In order to avoid problems with heterogeneity of natural vegetation, usually non-erodible roughness elements are deployed. These elements can be constructed in any form and can be arranged in any specific setting in order to study effects of, amongst other things, density, height, diameter and patterns.

Most field studies in natural vegetation focus on the large-scale effects of vegetation cover on average sediment transport (e.g. Fryrear, 1985; Wasson and Nanninga, 1986; Buckley, 1987; Leys, 1991; Wiggs *et al*., 1995). More detailed studies on roughness parameters are often performed in agricultural crops (e.g. Jacobs and Van Boxel, 1988; Hagen and Armbrust, 1994). These studies are difficult to perform in natural dune systems, because of the complex patterns of natural vegetation. Besides the complicated morphology of plants, heterogeneous clustering in vegetation also contributes to the complexity of the system (e.g. Lancaster and Baas, 1998).

This paper reports on a field experiment studying the effects of different densities of roughness elements on sediment transport and foredune profile development. Reed stems are planted as a surrogate for vegetation at the frontal side of the foredune. Plots are covered with a regular pattern of bundles of reed stems, in three different densities. Profiles through the plots are monitored weekly over a period of nearly one year. The purpose of the experiment is to study profile development for several vegetation densities and to provide validation data for the foredune development model SAFE (Van Dijk *et al*., 1999). In this paper, we present a comparison between field and model results.

STUDY SITE

The study site is located near the village of ‘s-Gravenzande on the Dutch North Sea coast of South Holland, about 5 km north of Hook of Holland, The Netherlands (Figure 1). The beach was nourished in 1995. The

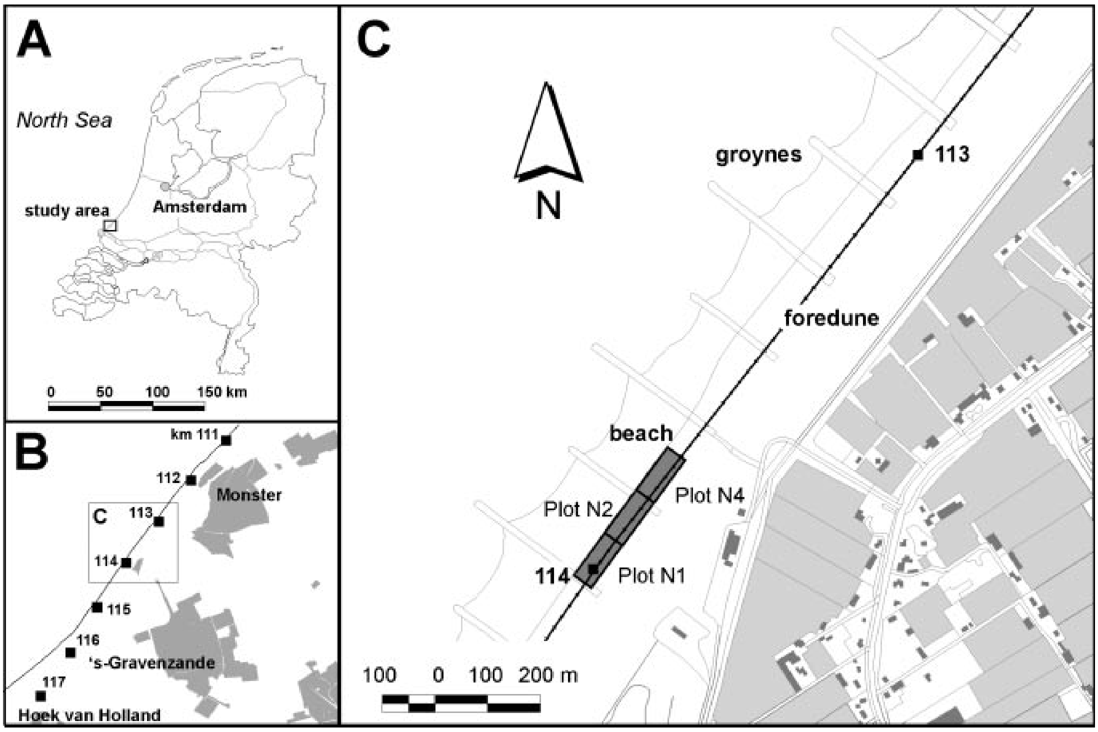

Figure 1. Location of the site

Figure 2. Photograph of the site

Table I. Characteristics of reed bundle roughness elements

	No. stems per bundle, n_s	Height, h (m)	Bundle diameter, d (m)	Stem diameter, d_s (m)
Average	55·4	0·53	0·17	0·006
St. dev.	16·8	0·062	0·053	0·003
Maximum	78	0·62	0·25	0·010
Minimum	31	0·40	0·10	0·003

Table II. Vegetation structure indices for the three plots

Plot	N (m^{-2})	λ	λ_s	C (%)	P_f
N4	4	0·360	0·705	9·1	0·511
N2	2	0·180	0·352	4·5	0·511
N1	1	0·090	0·176	2·3	0·511

front of the foredune was planted with reed stems every year in order to trap sand and to create a buffer against wave erosion. This is a common management practice in this part of The Netherlands.

The height of the foredune is around 12 m DOD (Dutch Ordnance Datum: approximately mean sea level). The top and the landward side of the foredune are densely covered with marram grass (*Ammophila arenaria*), but the seaward dune front is bare. This is the zone where reed stems are commonly planted. The beach is wide and dissipative, with an average tidal range of 2 m. The beach width between +1 m and −1 m DOD is approximately 100 m. The Netherlands is characterized by a temperate humid climate, with winter storms from the southwest, west and northwest, often accompanied by rain.

For the field study the seaward front of the foredune was partitioned into three neighbouring plots, each 100 m long along the foredune and 10 m wide over the cross-shore. Figure 2 shows a photograph of the site. In the three adjacent plots, bundles of reed stems were planted in a regular pattern with different densities, with approximately 55 stems per bundle. The height of the stems is approximately 0·5 m immediately after planting and gradually decreases due to sand burial. Distance between bundles varied between plots from 0·5 to 0·7 to 1·0 m, with the number of bundles varying from 4 to 1 per m^2. These plots are referred to as Plot N1 (1 bundle per m^2), Plot N2 (2 bundles per m^2) and Plot N4 (4 bundles per m^2). Specifications of the roughness elements are given in Tables I and II. Figure 5 illustrates the difference between plots.

METHODS

Vegetation cover and roughness concentration

When bundles of reed stems are treated as individual roughness elements, the roughness element lateral cover (λ) (also referred to as roughness concentration or as frontal area index, FAI) is calculated from (e.g. Raupach, 1992):

$$\lambda = hd\ N \tag{1}$$

where $h =$ height of roughness element (m), $d =$ diameter of roughness element (m) and $N =$ number of roughness element per surface area (m^{-2}).

Since every bundle consists of a number of stems, it can be argued that each stem contributes to the lateral cover. In that case stem lateral cover (λ_s) as defined by Musick *et al.* (1996) is calculated from:

$$\lambda_s = h_s d_s n_s N \tag{2}$$

where $n_s =$ number of stems per roughness elements, $h_s =$ model stem height (m) and $d_s =$ model stem diameter (m). This, however, is problematic since within a bundle of stems the wakes shed by one stem are directly affected by the next element.

Horizontal cover in percentage (C) is calculated from:

$$C = 100N\pi(0{\cdot}5d)^2 \tag{3}$$

When the bundles are considered as the primary roughness element, the porosity of elements is also of importance. Musick *et al.* (1996) calculate porosity (P_f) from:

$$P_f = \frac{hd}{h_s d_s n_s} \tag{4}$$

Modelling of the effect of vegetation cover on the air flow

In 1992, Raupach published a concept of the reduction of shear stress due to the presence of vegetation. Raupach (1992) relates the friction velocity near the surface under a vegetation cover (U_{*s}) to the friction velocity above that vegetation cover (U_{*v}) with:

$$\frac{U_{*s}}{U_{*v}} = \frac{1}{\sqrt{1+\beta\lambda}} \tag{5}$$

where

$$\beta = \frac{C_r}{C_s} \tag{6}$$

$C_r =$ drag coefficient for roughness elements (0·3 ± 25 per cent; Raupach, 1992) and $C_s =$ drag coefficient for bare surface (0·0033–0·0018; Raupach, 1992; Raupach *et al.*, 1993).

Wolfe and Nickling (1996) describe β as a parameter that depends on the element drag coefficient C_r, determined by roughness element shape, aspect ratio and porosity (Raupach, 1992) and on the surface drag coefficient C_s that is affected by surface roughness. Equation 5 is used in the foredune development model SAFE (Van Dijk *et al.*, 1999; Van Boxel *et al.*, 1999) to calculate the effects of vegetation on friction velocity, the resulting sand transport and finally consequences for foredune development.

In 1993, Raupach *et al.* extended Equation 5 to:

$$\frac{U_{*s}}{U_{*v}} = \frac{1}{\sqrt{(1 - m\sigma\lambda)(1 + m\beta\lambda)}} \tag{7}$$

with

$$\sigma = \frac{\pi d}{4h} \tag{8}$$

for cylindrical elements. The parameter σ corrects for the reduction in surface area on which friction acts, because of the presence of roughness elements, and m is a measure of the spatial variability in friction velocity near the surface (Raupach *et al.*, 1993). A value of 0·5 is proposed for m in the case of an approximately flat, erodible surface (Raupach *et al.*, 1993; Wolfe and Nickling, 1996), or according to Gillies *et al.* (2000) in the case of a homogeneous roughness configuration. However, no clear definition of m, in terms of spatial organization of roughness elements, is given.

Field measurements

In each of the three plots two profiles were monitored, situated 20 m apart in the (long-shore) middle of the plot. Figure 3 indicates the variation in lateral cover λ over the profiles. The figure shows the initial values; λ decreases during the period of observation, because of progressive burial by sand. Erosion pins were established along the profiles with a spacing of 2 m. Absolute heights of the profiles were measured in May 1996 and in January 1997 after placement of the erosion pins, using standard surveying equipment. Relative burial of the pins was recorded weekly, between May 1996 and April 1997. By December 1996 the reed stems were completely covered by sand, so that on 24 January 1997 new bundles were planted over the buried surface in the same pattern, and a new set of erosion pins was established. Between 20 December and 24 January no profiles were measured. Volumetric changes in the profile per metre width were calculated from the recorded changes in profile height.

Sediment transport measurements were performed over a three-week period in February 1997. Transport rates were measured using the omnidirectional, vertical sand traps described by Arens and Van der Lee (1995), consisting of six to ten trays that are stacked at 5 cm intervals. When placed in the sand cloud, these traps measure the vertical distribution of sand in the air. Results of the traps are used to illustrate transport

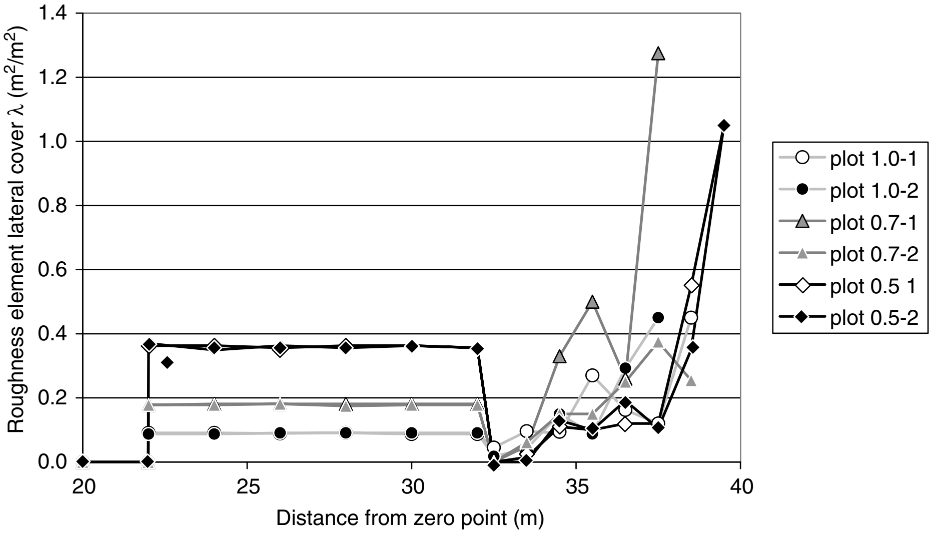

Figure 3. Calculated values of initial lateral cover λ over the profiles

Table III. Parameter values for SAFE

Parameter	Value
Simulation time	3 'days'
Time step	0·01 'day'
Distance step	1·0 m
Average grain size of sediment	200 µm
Roughness length of bare surface, z_0	0·001 m
Friction velocity, U_*	0·4 m s^{-1}
Threshold friction velocity, U_{*t}	0·22 m s^{-1}
Adaptation length with increasing transport, χ_1	20 m
Adaptation length with decreasing transport, χ_2	3 m
β (see Equation 6)	90
Vegetation growth during simulation	Zero growth

gradients between the beach and the plots. Traps were placed on three locations: the beach (1), near the dunefoot (2) and in the plots (3), circa 8 m from the seaward boundary of the plot. The traps on the beach and near the dunefoot were exposed for approximately 10–15 min, those in the plots for 45–60 min, in order to trap enough sand to be weighed. The amounts of trapped sand and the exposure times of the traps were used to calculate transport rates per minute. These sediment fluxes are standardized with respect to transport rates at the dunefoot (trap 2) in order to study the effect of the different bundle densities on the transport gradient.

Modelling of profile development

The model SAFE-HILL predicts the development of a dune profile for given meteorological conditions. HILL (Van Boxel *et al*., 1999) calculates the spatial pattern of friction velocities in response to the presence of a dune and the roughness of the surface, using second-order closure. SAFE (Van Dijk *et al*., 1999) uses the predicted friction velocities to calculate sand transport and, consequently, changes in surface height. Transport at each grid point is determined by friction velocity, vegetation cover, grain size, slope and a parameter called the adaptation length, which describes the length needed for transport to reach equilibrium. Preliminary runs with SAFE indicated that the presence of vegetation resulted in unrealistically low friction velocities below the vegetation. For every setting of reed stems, the model predicted a decrease in friction velocity below the threshold, immediately after the first row of bundles. Therefore we decided to substitute Equation 5 with Equation 7. For the present study, several runs with SAFE were carried out, to compare measured profile changes with profile development as predicted by SAFE. The model takes account of some limiting effects on transport such as air humidity and the occurrence of rainfall. Despite this, predicted transport is overestimated (see for a discussion Van der Wal, 2000). Since in this paper we are only interested in transport gradients, the order of magnitude of predicted transport is not relevant. Therefore we chose to run the model with U_* constant in time (not in space) for an undefined period of time.

The values for some relevant model parameters are specified in Table III. For a discussion on their meaning we refer to Van Dijk *et al.* (1999).

RESULTS

Measurements

Figure 4 shows 40 successive, weekly profiles for the six plots. All changes are due to aeolian activity, as there was no wave erosion in the studied period. Apart from the period 20 December 1996 to 24 January 1997, every profile is at the same height or above the previous profile. The influence of reed stem density is clearly demonstrated. In the highest density plot deposition starts at the first row, and a steep, small dune is developed. The back of this dune gradually migrates upslope over time. Once a row of bundles

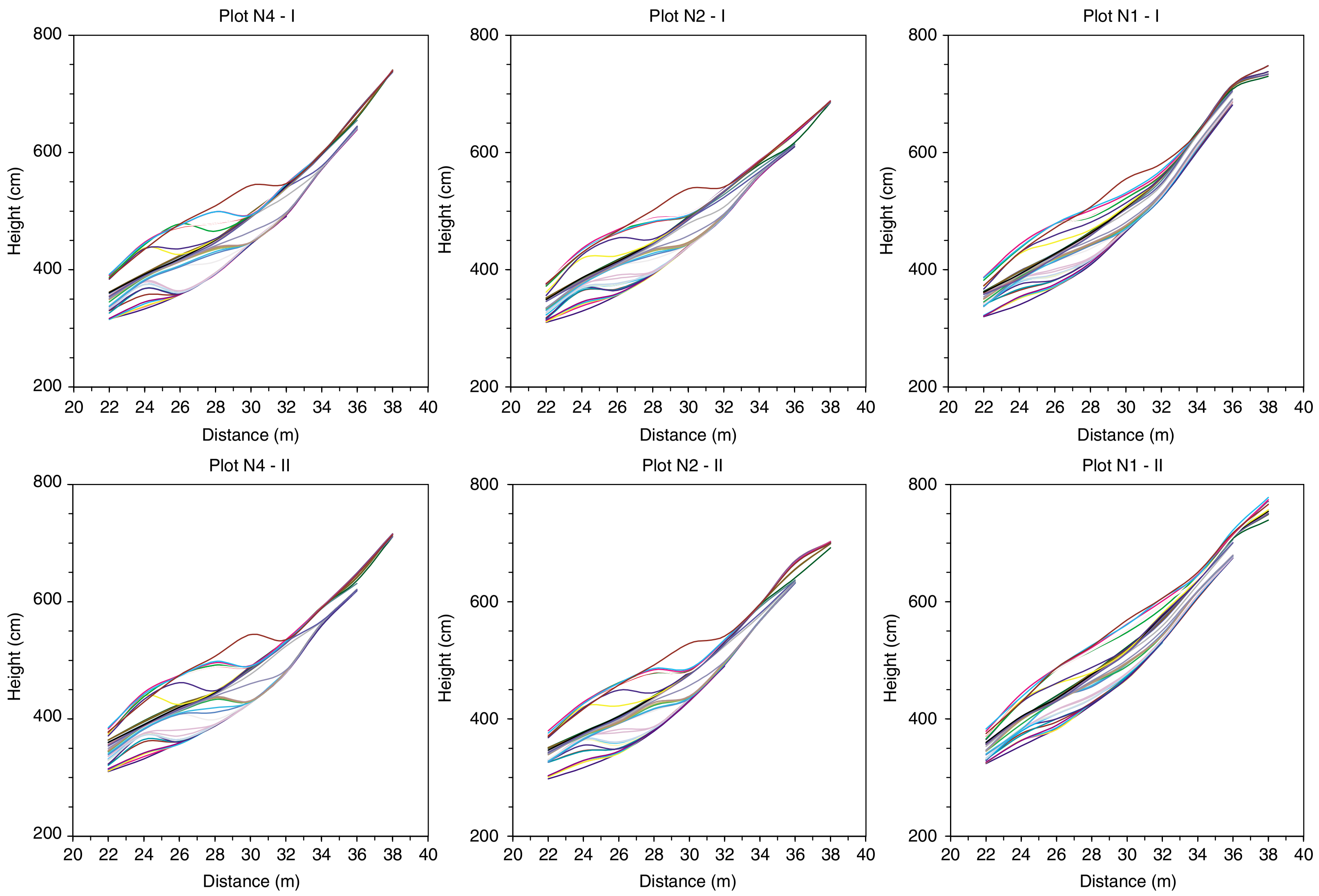

Figure 4. Profile development in three densities between May 1996 and April 1997. The order of the profiles is straightforward: the bottom line is the oldest profile, the top line is the youngest profile

is filled up completely, sand is transported further landward, and deposition starts within the next row. In the lowest density plot, deposition occurs simultaneously over almost the entire depth of the plot. Strongest deposition does not occur at the first row, but at some distance from the seaward boundary of the bundles. In this case a more gentle and wide dune develops and deposition is spread out over a number of rows. Some deposition also occurs behind the zone of reed stems. Plot N2 shows an intermediate type development which, however, resembles Plot N1 more than Plot N4. Figure 5 further illustrates differences in development.

Table IV displays the temporal volumetric changes for all profiles during the two measurement periods. In the intermediate period between 20 December and 24 January a small volume of sand appears to be lost. This could be due to errors in profile height measurement, since new profiles were established in January. However, as this period coincided with strong offshore winds, the losses might be real, as sand might have been blown seaward out of the profiling area. Total deposition ranges from 11·5 to 12·3 m^3 m^{-1} in the period May 1996 to April 1997, which is a common value for moderate accretion along the Dutch coast (Arens and Wiersma, 1994; Van der Wal, in press). Despite short-term spatial variations in accretion, the overall accretion

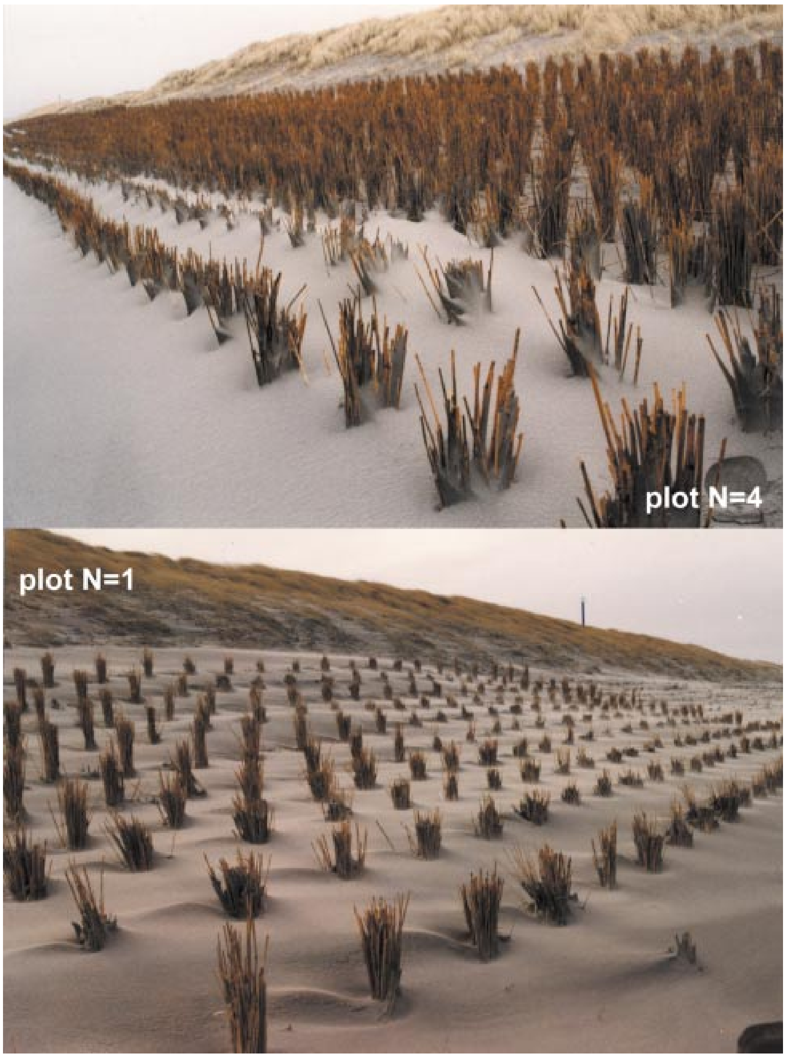

Figure 5. Photographs of deposition in Plots N4 and N1

Table IV. Volume gain for all profiles (in $m^3\ m^{-1}$)

Series	Date	Plot N4		Plot N2		Plot N1	
		Profile 1	Profile 2	Profile 1	Profile 2	Profile 1	Profile 2
1st	30/05/96–20/12/96	7·76	8·22	7·16	7·72	7·14	7·08
	20/12/96–24/01/97	−0·60	−0·58	−0·40	−0·10	−0·56	−0·30
2nd	24/01/97–04/04/97	5·16	4·98	5·00	4·82	4·88	5·52
Total	30/05/96–04/04/97	12·32	12·62	11·76	12·44	11·46	12·30

rates show that net sand input is of the same order in all profiles, although the net accretion in the highest density profiles is slightly higher than in the lower density profiles. This is most likely caused by some loss of sand due to landward transport through the lowest density plots. Because accretion rates are comparable, it is assumed that differences in profile development are related to differences in reed bundle density and not to spatial variability.

During specific wind events, separate data on transport patterns were gathered. Sand traps were placed on the beach and within the plots to measure transport and to study changes in transport rates from beach to the dune. A selection of the results is presented in Figure 6. These data are gathered during oblique winds (35–75° to the normal), with wind speeds varying between 10·0 and 12·4 $m\ s^{-1}$ (measured on the back beach at 5 m height). The figure shows that for most events in the highest density plot transport declines to 0·04–0·12 per cent of the transport near the dunefoot within 10 m. In contrast, transport in the lowest density plot decreases to 2·8–21 per cent. These findings support the results described above. During the highest wind speed event (Figure 6) transport in the lowest density plot does not decrease. In Plot N2 transport only decreases slightly, whereas in the highest density plot, transport still is less than 5 per cent of the transport at the dunefoot.

Modelling

Simulated profile development is presented in Figure 7 for plots N1 and N4. In general, the difference between the three plots seems to be comparable to the field measurements. It is clear that the model succeeds in producing a steeper dune in the highest density plot and a smoother wide dune in the lowest density plot.

Some more details on the modelling results are presented in Figure 8. The figure shows the profile for the first and last time step, and the computed friction velocities above and below the vegetation, for the beginning and the end of the simulation. Some conclusions can be drawn.

- In the simulations deposition starts before the first row with reed bundles, which is mostly visible for Plot N4. Strongest deposition is predicted in the first rows. This is not confirmed by the field results, where the strongest deposition occurs behind the first row of bundles (see also Figure 5).
- After some time the deposited dune starts to influence the airflow. It is remarkable that the friction velocity above the canopy at the back of the plots decreases to much lower values than in the initial situation, although the roughness remains the same. This is most obvious for Plot N4 (Figure 8). Obviously, at this stage, the effects of topography dominate over the effects of roughness.
- In Plot N1 the effective friction velocity increases near the back of the plot. Some sand is transported through the plot and blown further landward. In Plot N4 the effective friction velocity increases just behind the reed bundles.

To gain more insight in the effects of higher friction velocities, some runs were executed with friction velocities of 0·5 (2 ‘days’), 0·6 and 0·7 $m\ s^{-1}$ (1 ‘day’). Figure 9 displays the predicted profiles for Plots N4 and N1. The shape of the profiles seems to be independent of friction velocity. At friction velocity of 0·7 $m\ s^{-1}$ most of the reed stems are buried and the differences between the plots vanish.

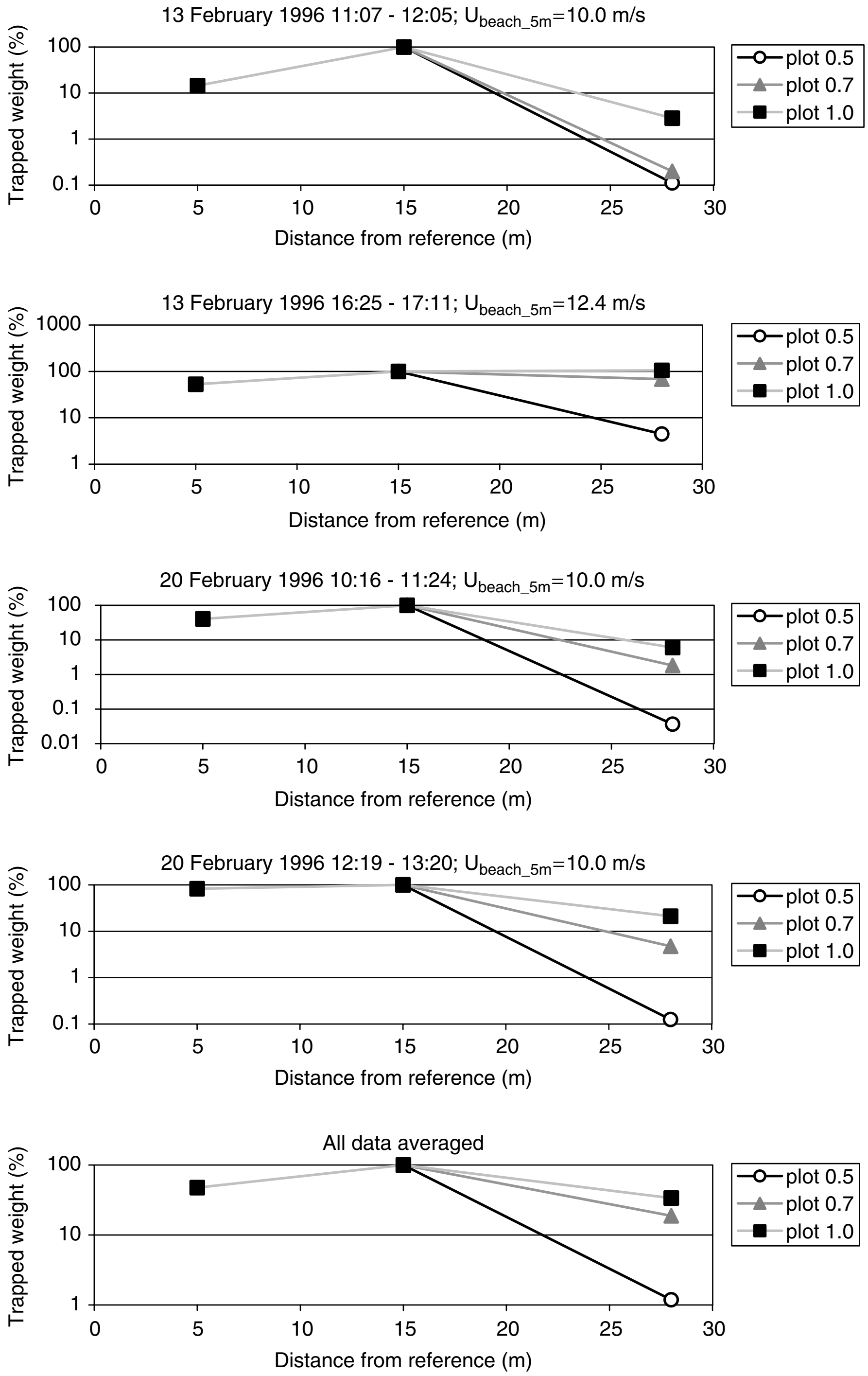

Figure 6. Transport gradients in the different plots as measured with sand traps. For all events, transport is expressed relative to the amount trapped before the dunefoot (which is 100 per cent)

- The model predicts an effective friction velocity near the surface in Plot N4 mostly below threshold, even at an upstream friction velocity of 0·7 m s^{-1}. This is not the case for Plot N1, where the effective friction velocity slightly exceeds the threshold.

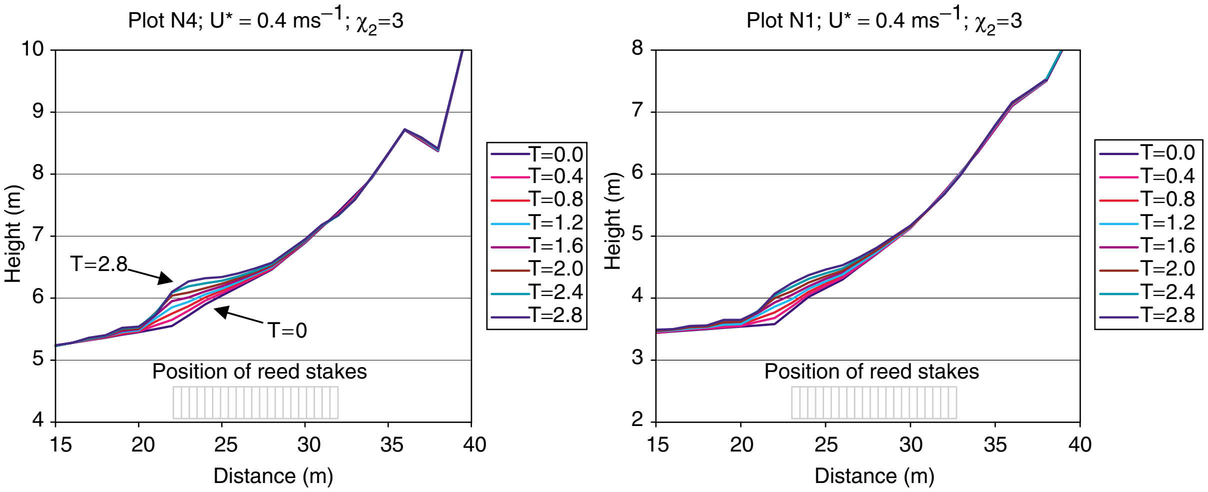

Figure 7. Simulated profile development using SAFE for Plots N4 and N1

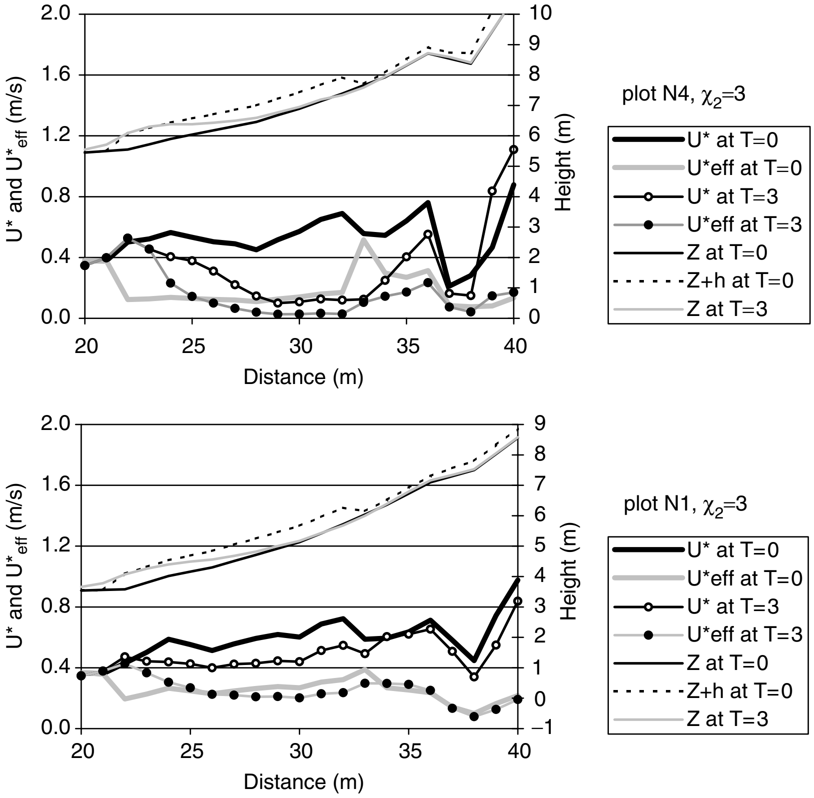

Figure 8. Computed profiles and friction velocities for Plots N4 and N1 at time steps $T = 0$ and $T = 3$. The position of the reed stems is indicated by $Z + h$ at $T = 0$ (Z = profile height; h = roughness element height)

- The back of the dune in all plots is very smooth for all simulations. Especially in Plot N4 the field measurements indicate a more distinct transition at the back than is predicted by the model.

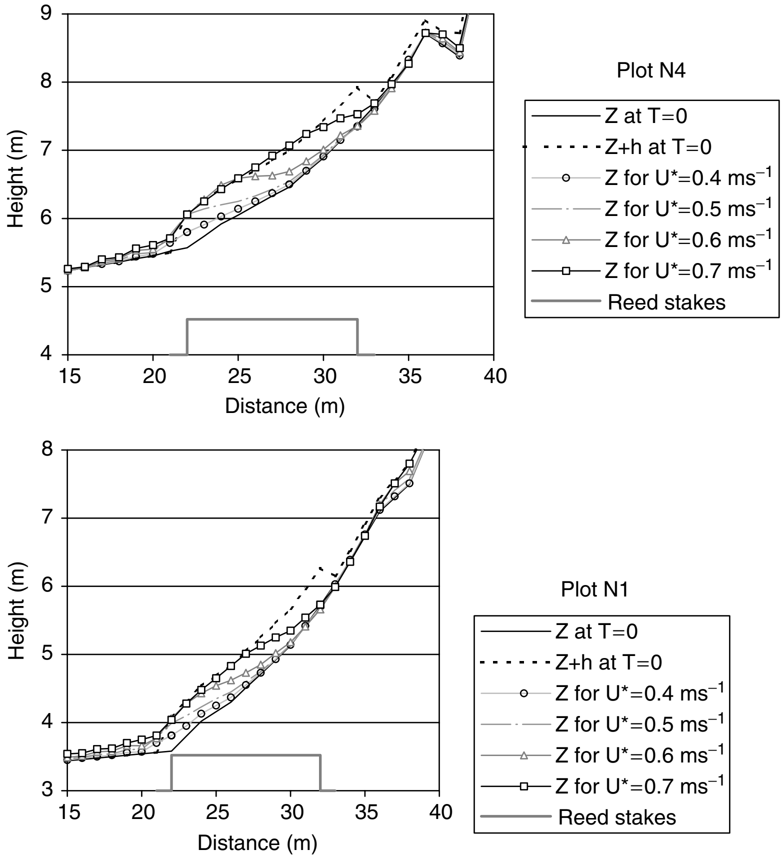

Figure 9. Computed profiles for Plots N4 and N1 for several friction velocities. Profile height Z is computed at time steps $T = 3$ for $U_* = 0{\cdot}4$ m s^{-1}, at $T = 2$ for $U_* = 0{\cdot}5$ m s^{-1} and at $T = 1$ for $U_* = 0{\cdot}6$ m s^{-1} and $U_* = 0{\cdot}7$ m s^{-1}

DISCUSSION

Various authors previously demonstrated the effect of plant density on dune morphology. Hesp (1983) stated that vegetation density and structure influence the form of deposition. Hesp (1989) presented comparable results of profile development in a more natural vegetation of marram grass planted in different densities (compare his Figure 6 to our results). Sarre (1989) showed that vegetation controls deposition and plays an important role in the deposition pattern on the foredune. Arens (1996) measured transport gradients over vegetated foredunes and concluded that the presence of vegetation resulted in a thousand-fold decrease in transport. In this paper, we demonstrate that these observations and measurements can be reproduced reasonably well with the adapted version of SAFE. However, some matters arise for further discussion.

The model is very sensitive to the vegetation density. At densities of approximately 9 per cent (which is the highest cover in our experiments) transport is completely prohibited, even under high friction velocities. It seems that the predicted transport rates for such densities are too low. Numerous studies indicate significant transport on surfaces with vegetation covers of 10 per cent and more. According to figures in their publications, a 10 per cent cover yields a reduction in transport of respectively 20 per cent (Wasson and Nanninga, 1986), 50 per cent (Buckley, 1987) and 60 per cent (Leys, 1991). Wiggs *et al.* (1995) measured surface activity for vegetation covers smaller than 14 per cent. Gillies *et al.* (2000), using the Raupach *et al.* (1993) model, concluded that surface covers of 3 to 4 per cent and 7 to 21 per cent with small and large shrubs respectively of greasewood were sufficient to eliminate wind erosion. They ascribe this to differences in the values of the drag coefficient C_r between plant types and in the distribution of shrubs over the surface.

Several model parameters influence the model's sensitivity to vegetation effects. An appropriate adaptation of these parameters could be justified by the following arguments.

(1) Incorporation of roughness element porosity. Porosity will cause a reduction in the effective diameter of the roughness elements. Their effective diameter will therefore be somewhat smaller than the reported average of 0·168 m. However, the reduction in diameter will be limited to 10–20 per cent (as will the reduction in lateral cover λ), which produces only limited variations in the modelling results. Porosity also affects the drag coefficient (Wyatt and Nickling, 1997; Grant and Nickling, 1998; Gillies *et al.*, 2000).

(2) Adaptation of the β parameter in the calculation of U_{*s}/U_{*v} (Equation 6). Lower values of β result in higher predictions of the near-surface friction velocity under the canopy. Raupach (1992) states that the value of β should vary between 100 and 180, because of values of C_r and C_s of respectively 0·3 and 0·0033 to 0·0018. Wilson and Shaw (1977) report a value of C_r of 0·2, which would imply a value of 66 for β, which would make a considerable difference in the predicted transport. Most of the values of C_r that are presented in the literature are for shrubs growing in desert environments, or for agricultural crops. Apparently different vegetation types have different values of C_r (Gillies *et al.*, 2000). There are no data available for the value of C_r for common vegetation in coastal dunes, such as marram grass (*Ammophila arenaria*).

(3) Adaptation of m. This parameter has an important effect on predicted transport but there is very little evidence for its value. Only two papers give some limited evidence for the value of m. Besides, its interpretation is unclear. Raupach *et al.* (1993) introduce m as a parameter to take account of non-uniform erosion around non-erodible roughness elements. However, in their discussion they explain m in terms of surface characteristics and microtopography.

Our modelling results showed smooth leeward sides for all simulated dunes. In the field, the difference between the leeward slopes was more pronounced. Some runs were executed with varying values of the χ_2 parameter, which is the adaptation length for decreasing transport. Van Dijk *et al.* (1999) state that there is hardly any evidence for the value of χ_2. Based on Anderson (1988) and Hesp (1989), a value of 3 was proposed. Results of some simulations with different values for χ_2 are presented in Figure 10. For lower values of χ_2, the resulting dune in Plot N4 more closely resembles the measured profiles. But also for Plot N1 the back of the dune gets more pronounced. In both cases the deposited dunes rise above the original vegetation, which is not confirmed by the measurements. Best results seem to be obtained when smaller values for χ_2 are used for the highest density plots than for the lowest density plot. This implies that the adaptation length for decreasing transport depends on vegetation properties. During burial of the reed stems, the adaptation length would then increase, due to a decreasing (lateral) cover. Obviously, more research is needed on this matter.

The model that we use relates friction velocity and transport to the lateral cover λ. In our case, we calculated λ by considering the reed bundles as individual roughness elements, consisting of a collection of stems. We could also have used stem lateral cover λ_s as defined by Musick *et al.* (1996), which is much higher than λ. The last method causes errors, because stems overlap; at the back of a bundle stems are in the wake of the frontal stems and hardly contribute to the extraction of momentum. Our impression is that the description of vegetation just in terms of λ is too simple, taking no account of the configuration of the roughness elements (clustering) or of the part of the surface that is actually exposed to wind erosion. Surfaces with comparable values for λ may be very different in the way the vegetation is organized and therefore may respond differently to wind stress. Tentatively we think that the parameter m in Equation 7 should give some measure for clustering and therefore should be defined in terms of vegetation pattern.

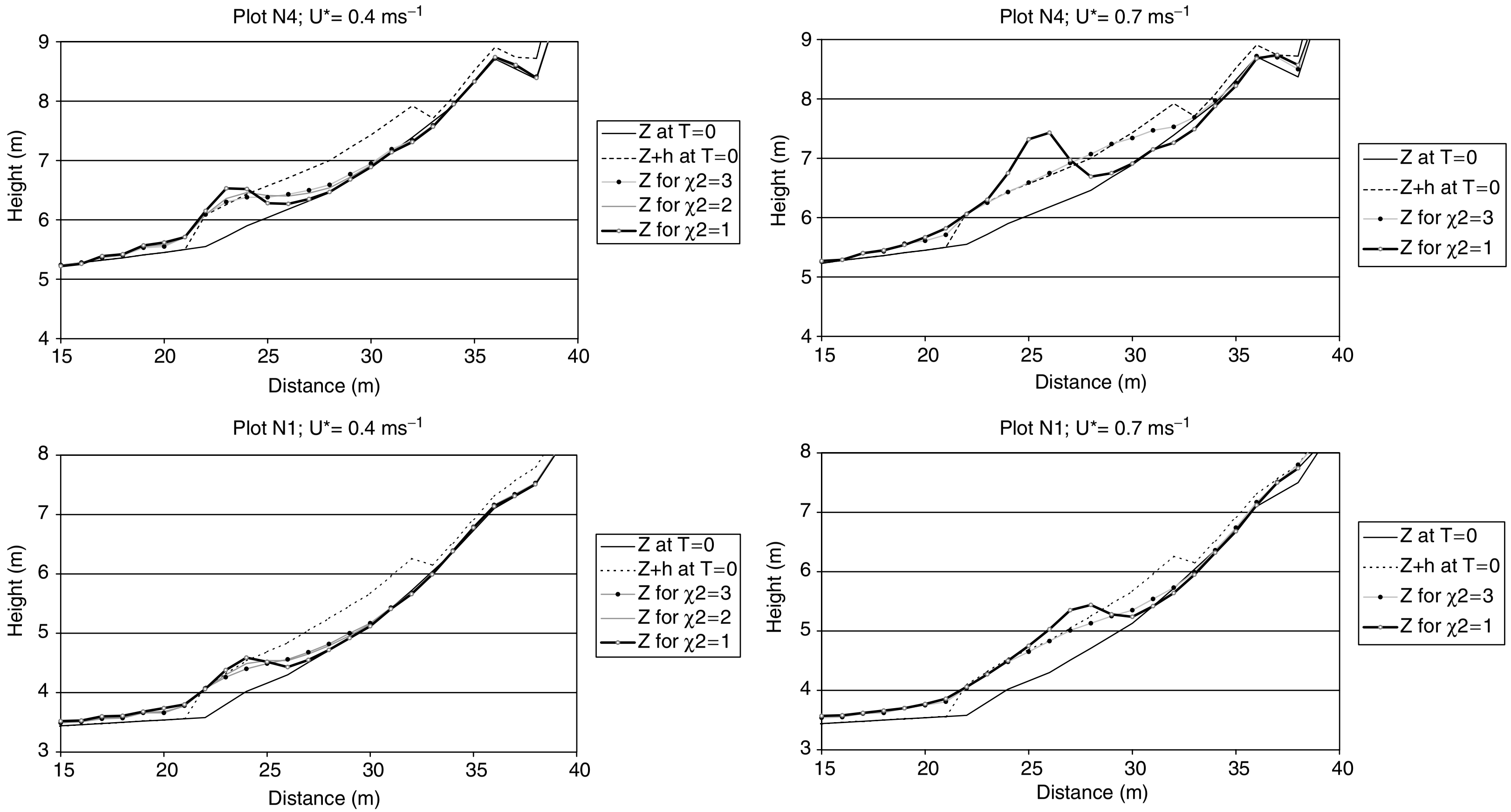

Figure 10. Computed profiles for Plots N4 and N1 for friction velocities of 0·4 and 0·7 m s^{-1} and different values of the adaptation length χ_2

CONCLUSIONS

Field measurements reveal distinct differences in deposited dune morphologies between plots with different densities of bundles of reed stems. In the highest density plot a distinct, steep dune developed, while in the lowest density plot a more gradual and smooth sand ramp was deposited. After burial of the reed stems differences in profile evolution vanished. A second series of measurements after replanting of reed bundles, showed a similar development.

Field results can be reasonably reproduced with an adapted version of SAFE. The model successfully reproduces the overall profile development, but in general, the equations used for vegetation–transport interaction are very sensitive for low vegetation densities. The equation of Raupach *et al.* (1993) predicts a stronger decrease in transport for certain levels of vegetation cover than other models that are based on field evidence (Fryrear, 1985; Wasson and Nanninga, 1986; Buckley, 1987).

Development of the leeward zone of dunes that deposit in vegetation is governed by vegetation density, but also by the adaptation of transport over the vegetated surface. The rate of adaptation in the model SAFE is expressed as the adaptation length. The value of the adaptation length seems to be dependent on vegetation density.

The value of β, the parameter that depends on the element drag coefficient and the surface drag coefficient, needs to be clarified. Some values for β or for the drag coefficients are found in the literature, but these are not consistent. Variation in the value of β has important consequences for the prediction of friction velocities under canopies and consequently on the prediction of transport for certain levels of vegetation cover. Also, there is a need for data on drag coefficients of natural vegetation in coastal dunes.

The meaning of m in the model of Raupach *et al.* (1993), that takes account of spatial variability in stress near the surface due to the presence of roughness elements, needs to be clarified.

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