Vegetation controls on maximum coastal foredune 'hummockiness' and annealing time

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10   **Abstract.** Coastal foredunes serve as a primary defence against storms and high water events. Dune morphology can
determine how a dune functions as a barrier to storm impacts. Hummocky foredunes — those with alongshore variability in
dune crest elevation —may have a greater potential for breaching during storm events compared to continuous foredune
ridges. Initially scattered dune-building plants and species that grow slowly in the lateral direction have been implicated as
causes of foredune hummockiness. Our goal in this work is to understand the causes and dynamics of hummocky foredunes
15   by examining vegetation characteristics. Using a numerical model, we explore how the initial configuration of vegetation
and vegetation growth characteristics set the development and evolution of hummocky coastal dunes including the
'maximum hummockiness' of a given dune field. We find that given sufficient time and absent external forcing, hummocky
foredunes anneal to form continuous dune ridges. We develop a predictive rule for the timescale of annealing that depends
on initial plant dispersal and two parameters that control the lateral and vertical growth of vegetation, respectively. Our
20   findings suggest that whether or not hummockiness will be maintained depends on the time scale of annealing relative to the
recurrence interval of high water events that reset dune-building in the low areas between hummocks. This relation explains
the tendency for foredunes to be hummocky along the southeast coast of the U.S. where lateral vegetation growth rates, and
thus annealing times, are likely longer.

1 Introduction

25   Coastal foredunes display various morphologies in the alongshore direction, ranging on a spectrum from continuous
to hummocky (i.e., varying in dune crest elevation). Examples of hummocky foredunes from Fort Fisher State Recreation
Area, NC, U.S. are shown in Figure 1. As described below, three explanations have been used (separately and in
conjunction) to explain the existence of hummocky foredunes at a given site — initial configuration (i.e., spatial distribution)
of plants, the rate of plant lateral expansion, and forcing or boundary conditions that control the pace and style of the
30   biophysical feedback that gives rise to coastal dune growth.
        New coastal dunes can be initiated when there is sufficient cross-shore width seaward of the existing foredune for
plants to colonize (e.g., Hesp, 2002). The presence of plants causes the deposition of sand (e.g., Hesp, 1989; Arens 1996;

Kuriyama et al. 2005), leading to the formation of small dunes (Hesp, 1981; Pye, 1983). These incipient dunes have a typology that depends on the mechanism (plant, seed, rhizome, flotsam, etc.) and alongshore continuity of plant establishment (Hesp, 1989; Hesp 2002; Hesp and Walker 2013), and variability in the location where plants initially grow can cause the formation of hummocky dunes. For example, Godfrey (1977) noted that in some settings vegetation initializes

5   from drift lines (wrack), so discontinuous drift lines would cause an initially discontinuous or patchy development of dune plants (and therefore discontinuous dunes). Therefore continuous or discontinuous plant initialization (in the alongshore) can control the initial alongshore continuity of the foredune (continuous or hummocky).

Given a discontinuous initial plant configuration, the spaces between plant sites infill through the establishment of new plants, and/or the lateral expansion of existing plants via rhizomes (e.g., Keijsers et al., 2015). In this way, plant

10   dynamics can also control the existence of hummocky dunes. Some plants grow laterally faster than others — Godfrey and coworkers (Godfrey 1977; Godfrey and Godfrey, 1973) found that dunes of the northeastern U.S. had more continuous ridges than the hummocky isolated dunes of the southeastern U.S., which they attributed to differences in plant lateral growth rates for the dominant species in each region.

Geological and geomorphic templates have also been used to explain variability in dune height. Low areas without

15   dunes can remain low because of shell or coarse grained lags or a high water table that causes plant stress (e.g., Mountney and Russell, 2006; 2009; Wolner et al., 2012). Sediment supply has also been implicated in causing alongshore dune height variability — specifically that geomorphic and geologic framework influences the morphology of bars, beaches, and sediment supply, therefore controlling the height of coastal dunes (Houser et al 2008; Houser and Mathew, 2011).

Though these three categories provide potential mechanisms to explain the formation of hummocky dunes,

20   foredunes are dynamic, evolving and growing through time. Even continuous dune ridges may evolve from earlier hummocky dunes. Ritchie and Penland (1988a, 1988b, 1990) developed a conceptual model of coastal foredune development following flattening of foredune topography by a storm, stating that a mature continuous foredune can develop from a washover terrace given sufficient time. The transition from washover terrace (a low surface) to a continuous dune requires individual incipient dunes to grow and merge, eventually developing into a single continuous ridge. (Ritchie and

25   Penland, 1988; 1990; Pye, 1983; Carter and Wilson 1990; Davidson-Arnott and Fisher, 1992; Mathew et al., 2010; Montreuil et al., 2013). Such a conceptual model, consistent with widely observed field conditions, leaves open the question of why some initially hummocky foredunes coalesce to a linear foredune ridge, while others remain hummocky, having variable dune height in the alongshore direction.

In this contribution we develop and explore a model of coastal foredune growth and hummocky dune evolution that

30   is consistent with this previous work to better understand the mechanisms behind the development of hummocky foredunes. Our findings suggest that, given no pre-existing template and sufficient time prior to occurrence of a storm event, hummocky dunes eventually anneal to form a continuous coastal foredune ridge. Results suggest that the initial spatial distribution of dune vegetation (which controls the location of incipient dunes), and the lateral and vertical growth rate of vegetation control the rate at which hummocky dunes anneal.

2 Ecomorphodynamic Model

We use a recently developed model of coastal dunes that includes the lateral propagation of vegetation (Moore et al., 2016). This model is based on the coastal dune model of Durán and Moore (2013), itself based on previous models used to study a variety of dunes (e.g., Parteli et al., 2009; Durán and Hermann 2006; Durán et al., 2010). We briefly summarize

5   the model and the vegetation formulation below.

Given an initial topography $h(x, y)$ and a vegetation field, the model computes the bed shear stress perturbation due to the presence of a non-flat topography (Weng et al. 1991), modified by a separation bubble (when there is flow separation; Kroy et al., 2002) and the subsequent shear stress reduction due to vegetation (Raupach et al., 1993). From the bed shear stress field, the local non-uniform sand flux and sand flux divergence is then computed at every position (Kroy et al 2002;

10   Durán et al 2010) — this determines the temporal change in topography. Sand avalanching occurs down the steepest descent gradient when topography exceeds the angle of repose. After the topography has been updated, the change in the vegetation field is calculated (itself dependent on the local accretion/erosion rate).

We use a simplified version of the vegetation formulation presented in Moore et al. (2016), which is itself a modification of earlier models (Durán and Moore, 2013, 2015; Durán and Hermann 2006). We now present the simplified

15   vegetation model and then discuss the physical interpretation for the two key sensitivity parameters.

The vegetation is parameterized by the cover fraction ρ_{veg}. The growth and propagation of vegetation is modeled by an advection equation of the form:

$$\frac{d\rho_{veg}}{dt} = C|\nabla\rho_{veg}| + G_0\rho_{veg}(1 - \rho_{veg}), \qquad (1)$$

where the first term is the lateral propagation of vegetation at rate C due to rhizome growth, and the second term is the local

20   growth of biomass to maximum cover $\rho_{veg} = 1$. The intrinsic growth rate (G_0) is assumed to increase with the deposition rate $\max\left(\frac{dh}{dt}, 0\right)$ and to vanish near to the shoreline $(x < L_{veg}$, where x is the distance to the shoreline):

$$G_0 = H_v^{-1}\max\left(\frac{dh}{dt}, 0\right)\max(0, x - L_{veg}), \qquad (2)$$

The lateral vegetation propagation rate C is also assumed to increase with the deposition rate and to vanish for steep slopes

25    $(\tan\theta_c < |\nabla h|$; where θ_c is 15 degrees and is based on field observations from Moore et al., (2016):

$$C = \beta\, max\left(\frac{dh}{dt}, 0\right)\max(0, \tan\theta_c - |\nabla h|), \qquad (3)$$

This formulation of vegetation growth has two parameters that reflect the sensitivity of plants to changes in surface topography. First, the intrinsic growth rate (G_0) of vegetation in the logistic model is sensitive to plant burial, to simulate the

30   behavior of dune-building plants that are stimulated by burial (e.g., Maun and Perumal, 1999; Maun, 2004; Gilbert and Ripley, 2010). This sensitivity term H_v, with dimensions of [L], encodes the efficiency of vertical plant growth after burial. Larger H_v result in smaller values of G_0 and therefore slower plant growth, implying that burial is more effective at reducing

plant basal area. Second, the lateral propagation of vegetation is sensitive to burial rate and the spatial gradient of cover density. Here, the dimensionless coefficient β can be interpreted as the efficiency of rhizome propagation after burial. A larger β results in faster plant propagation from place to place. Note that vertical growth rate relies exclusively on H_v, but lateral expansion relies on the spatial gradient of vegetation cover and therefore depends indirectly on H_v. If H_v is large, the

5   vertical growth rate is slower and this will cascade to slowness in lateral growth rate (and vice versa).

The model is integrated in a two dimensional grid (64 m alongshore and 100 m cross-shore with 1 m grid size) with periodic alongshore boundary conditions. The shoreline is set to a fixed location and vegetation is 'seeded' in one band at an identical cross-shore location (40 m from the shoreline). There is a gap in this seeding located near the center of the model domain. The seeded 'line' represents the development of vegetation around a driftline of wrack, and is set at the seaward

10   vegetation limit of plant growth (e.g., Durán and Moore 2013, Kuriyama et al., 2005). As a consequence, vegetation does not propagate seaward in model experiments. We track the evolution of the unplanted gap as a single representative example of an initially unvegetated gap in an alongshore foredune. Beyond the initial 'seeding' we allow plants to establish in unvegetated cells only by lateral propagation.

Forcing conditions (i.e., undisturbed shear velocity $U^* = 0.35\ m/s$) are kept constant for all model experiments,

15   but we vary the characteristics of the model vegetation to mimic variability in vertical and lateral plant growth rates. Experiments are shown for a range of vegetation lateral growth parameter values spanning over an order of magnitude $(10 \geq \beta \geq 0.1)$, vertical growth parameter values spanning an order of magnitude $(0.4\ m \geq H_v \geq 0.04\ m)$, and unvegetated gap sizes $(10 - 20\ m)$.

3 Results

20   From the initial condition, the model domain evolves to fill in the unvegetated gap (Figure 2). Initially the vegetation grows from the planted location in the vertical and lateral direction. Initially planted locations evolve into developed foredunes. Within the unvegetated gap, only minor vertical elevation changes occur prior to the establishment of vegetation (via lateral propagation from the vegetated line). After the establishment of vegetation, the initially unvegetated sites become vegetated and grow vertically into a mature foredune. In the final model state, there is no evidence in the

25   former dune gap to suggest that the site was once unvegetated. All model results yield a consistent maximum dune height of between 3.6 - 3.9 m.

We now focus on the lag in height between the unplanted gap and the surrounding planted dune — we refer to this difference as 'hummockiness', the difference in elevation between the dune under the initially planted area compared to the central location at the initially unvegetated gap. Hummockiness first increases with time as the initially unplanted site lags

30   behind the planted locations in both vegetation cover and vertical elevation. Figure 3 is a partial phase plane for all model results displaying hummockiness plotted against the height at the planted dune site. This partial phase space of the model allows for inspection of the trajectory of model results as they evolve from hummocky dunes to coalesced, annealed dunes.

Initial trajectories all start at the (0.3, 0) mark (the beach is initially at an elevation of 0.3 m, with 0 hummockiness), and evolve in a clockwise fashion as the initially planted sites grow vertically at a faster rate than the unvegetated gap. After the propagation of vegetation into the initially unvegetated gap, the dune in the gap grows vertically at a rate faster than the vegetated sites (which has slowed in vertical growth as it nears the maximum theoretical dune height). This leads all

5   trajectories toward a hummockiness of 0. Note that no time scale is shown in this phase space.

Two trajectories are shown in Figure 3 to illustrate that the maximum hummockiness (the peak) is a function of H_v and β. As the lateral vegetation growth parameter (β) decreases from 10 to 0.1, the lateral growth rate slows down, which increases the variability in alongshore dune crest heights — hummockiness tends to increase (Figure 4A). On the other hand, an increase in the vertical parameter H_v (plants are more sensitive to burial) slows the growth rate of vegetation thereby

10   increasing the maximum hummockiness (Figure 4A). The unvegetated gap width also plays a role in controlling hummockiness as smaller initially unvegetated gap widths result in faster annealing (Figure 4B)

The general behavior of hummockiness and annealing lends itself to heuristic analysis. Since the development of coastal dunes relies on the feedback between vegetation growth and aeolian sediment transport, maximum hummockiness occurs at the moment just before the center of a given gap transitions from unvegetated to vegetated (at which point the

15   surrounding vegetated dunes have grown for some time). Therefore maximum hummockiness is related to gap size and lateral propagation of plants —which from (2) and (3) depends on β and H_v (via the spatial gradient in vegetation cover). For example, small gap size, high β (fast lateral growth of vegetation) and low H_v (fast vertical growth of vegetation) lead to low maximum hummockiness and vice versa. Results from all model simulations conform to this general behavior (Figure 4A and 4B).

20   Gap size, lateral growth rate of vegetation, and vertical plant sensitivity also impact model timescales for the alongshore coalescing of hummocky dunes. Maximum hummockiness occurs later (Figure 5A) and dunes take longer to anneal (Figure 5B) with decreasing lateral growth rate of vegetation, increasing plant sensitivity to burial, and increasing gap size.

The lateral propagation rate (P) of the dune is defined as the time needed to propagate the crest a given lateral

25   (alongshore) distance—the lateral spreading rate of the dune crest. This rate encompasses the spreading rate of the plant, and the biophysical feedbacks that lead to dune growth. Lateral dune propagation rate is defined as $P = (0.5 \times W)/T_a$ where $(0.5 \times W)$ is the half width of the gap (W) and T_a is the time to annealing. The half width of the gap is used since all model experiments include unvegetated gaps that fill in from both sides. Within the limits of the model experiments, results are well described by an equation of the form:

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$$P = K_1\beta + \frac{K_2}{H_v}, \tag{4}$$

where K_1 and K_2 are dimensional parameters (6.5 m/yr and 1.9 m^2/yr). A high β (fast lateral growth of vegetation) and low H_v (fast vertical growth of vegetation) lead to fast lateral propagation of the dune crest. Figure 5 shows the modeled vs. predicted propagation times derived from (4).

Rewriting equation 4, the annealing time can be written as:

$$T_a = \frac{W}{K_1\beta + \frac{K_2}{H_v}} \quad or \quad T_a = \frac{WH_v}{K_1\beta H_v + K_2}, \tag{5}$$

Following Durán and Moore (2013), we assume in the model a constant wind shear velocity ($U* = 0.35\ m/s$) that represents typical wind conditions during dune growth. Because in reality conditions sufficient for transport do not occur all the time, Durán and Moore (2013) suggest that model time can be converted to real time by multiplying model time by a

10   factor (r_t) that varies from 0 to 1 and represents the fraction of time there is no transport. Therefore reduction in the flux of sand from beach to dune, because of low wind speeds, large grain sizes, or narrow beaches, can be encapsulated through variation in r_t and has an effect similar to decreasing β and increasing H_v.

The height of the dune crest at the moment of annealing can be described by:

$$H_a = H_{max}\left(1 - e^{\left(-\frac{T}{T_f}\right)}\right) + Z, \tag{6}$$

15   where H_{max} is maximum dune size, T_f is formation time of the planted sites, and Z is the initial beach elevation at the site of dune nucleation (here 0.3). Both H_{max} and T_f are functions of the seaward vegetation growth limit as well as other relevant parameters, defined in Durán and Moore (2013). Figure 6 is the modeled vs. predicted dune height at annealing calculated from (6).

4 Discussion and Implications

20   Godfrey (1977) and Godfrey et al. (1979) observed that foredunes change from irregular, 'hummocky' dunes in the southeastern U.S. to contiguous long-crested dunes in the northeastern U.S. This change in observed dune morphology is attributed to changes in foredune species dominance (Godfrey and Godfrey, 1973; van der Valk, 1975; Woodhouse et al., 1977, Godfrey, 1977; Godrey et al., 1979). From Virginia northward, foredunes are dominated by *Ammophila breviligulata* (American Beachgrass) while south of Virginia, *Uniola paniculata* (Sea Oats) dominates foredunes (Wagner, 1964; Godfrey,

25   1977; Duncan and Duncan, 1987; Lonard et al., 2011). On the east coast, *A. breviligulata* and *U. paniculata* exhibit similar rates of vertical growth (including the adapted response of increasing growth rates when buried by moderate amounts of sand; Disraeli, 1984; Maun, 2004, Ehrenfeld 1990, Lonard, et al. 2011; Wagner, 1964). However *A. breviligulata* and *U. paniculata* exhibit differences in rates of lateral growth, 1-3 m/yr and 0.6-1 m/yr respectively (Woodhouse et al., 1977; Ehrenfeld, 1990 Lonard et al., 2011). The slower lateral growth rate of *U. paniculata* provides a potential explanation for the

30   observation of hummocky dunes along the southeastern U.S. coast. This species-specific control on dune morphology likely

arises from differences in growth form, similar to observations that explain species-specific dune morphology along the U.S. West Coast (Hacker et al., 2012; Zarnetske et al., 2012). We can understand these differences in the context of model findings– though *A. breviligulata* and *U. paniculata* may have similar vertical growth characteristics (H_v is identical), their lateral growth rates (encoded here as β) are different, resulting in differences in hummockiness (Figure 4A) and annealing

5 time (Figure 5b). The dominant dune-building plant of the southeastern U.S. has a slower lateral growth rate and therefore a longer annealing time, likely leading to the increased prevalence of hummocky foredunes in this region.

However, the numerical finding that hummocky dunes always anneal if given sufficient time suggests that differences in species-specific lateral growth rates alone are not sufficient to explain hummockiness that persists through time. A more complete explanation likely comes from combining our finding that annealing time lengthens with decreasing

10 lateral growth rate of the dominant dune-building grass, with the suggestion by several studies that low areas (and therefore hummocks) are maintained by overwash during high water events (Godfrey, 1977; Hosier and Cleary, 1977; Ritchie and Penland, 1988). We can understand this using (7)—if the recurrence time for high water events (R) is shorter than the annealing time T_a, existing hummockiness will likely be maintained because low areas are more likely to be overwashed than adjacent higher dunes on either side. When this occurs, the dune-building process in the low areas is reset, increasing

15 hummockiness until vegetation again becomes established in the overwashed zone. Conversely, if $R \gg T_a$, hummockiness will tend to decrease through time because there will be sufficient time between storms for annealing to occur. Along the SE U.S. coast it appears that $R < T_a$ given the previous observations of hummocky dunes and the slow lateral growth rate of *U. paniculata,* Thus, although hummockiness appears to be an intrinsic feature of foredunes along the southeast coast of the U.S., model results suggest that hummockiness is actually a transient characteristic of foredunes that only becomes persistent

20 when annealing time is slow relative to the frequency of storms capable of resetting the dune-building process in the the low areas between hummocks.

In the case of $R > T_a$, environmental conditions may be conducive to bistable dynamics in the alongshore direction—similar to the cross-shore models of Durán Vinent and Moore (2015) and Goldstein and Moore (2016)—with alternating stretches of dunes near the maximum height and lower intervening areas. In addition to storms, other factors such

25 as a high water table, low sediment supply, grain size variability, development of shell lag may also result in suppression of the annealing of coastal foredunes (Mountney and Russell, 2006; 2009; Wolner et al., 2012; Hoonhout and de Vries, 2016). Feedbacks between the wind, dune vegetation and sediment transport that are specific to hummocky dunes may also alter the rates of annealing (Barrineau and Ellis, 2013; Gilles et al., 2014)

There exists a potential for climate change to alter the range of the two dominant species of dune-building grasses

30 along the U.S. East Coast. Plantings of *A. breviligulata* south of VA tend to die as a result of blight, pests, drought intolerance, and intolerance of high temperature (Seneca, 1972; Singer et al., 1973; van der Valk, 1975; Woodhouse et al., 1977; Odum et al., 1987, Seliskar and Huettel, 1993). In addition, a warming climate might lead to further northward expansion of *U. paniculata*, which is currently restricted in northward extent by temperature (Seneca, 1972; Godfrey, 1977)—northern expansion of the range has already been observed (Zinnert et al., 2011; Stalter and Lamont, 1990; 2000)

and is being sought in selective breeding trials (USDA, 2013). Because changes in β between these two dune-buiding species affects variability in alongshore dune height, a change in the dominant dune-building species from *A. breviligulata* to *U. paniculata* has the potential to decrease the protection provided by dunes during high water events. Changes in storminess may also impact the hummockiness of coastal foredunes, with an increase in storm intensity or frequency leading

5   to a greater tendency for dunes to be hummocky and therefore to provide less protection to habitats behind them. Here, we have focused on the development of hummocky dunes from an initially flat condition, but Lazarus and Armstrong (2014) discuss the potential for storm events to create regularly spaced overwash throats (via self-organization) that could also set up hummocky dune topography.

     Model results shown here should be compared to field observations. We are actively developing several monitoring

10   programs to analyze the coupled evolution of topography and vegetation at spatial scales on the order of 100 m and yearly (or more frequent) temporal scales. Comparisons between model results and field data will provide further insight into the processes that lead to the annealing of hummocky dunes.

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Figure 1: Ground-based photo of 1-2 m hummocky foredunes covered with *Uniola paniculata* at Fort Fisher State Recreation Area, NC, USA. (Note the person in the center left wearing black with a 2 m fixed height survey pole for scale). The hummocky foredunes are seaward of an older continuous dune ridge.
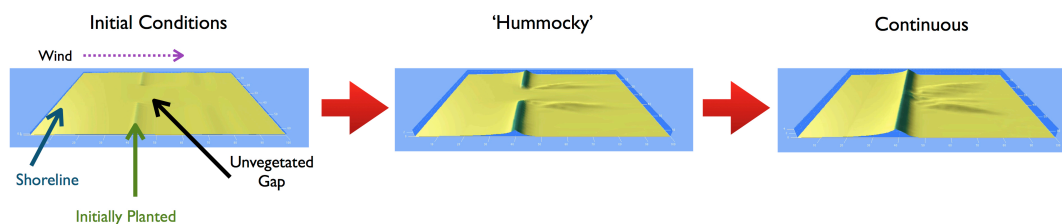
Figure 2: Numerical model definition sketch. A) Initial conditions; B) Formation of foredune and the infilling of the initially unvegetated gap. C) The final continuous foredune ridge at the maximum theoretical dune height.
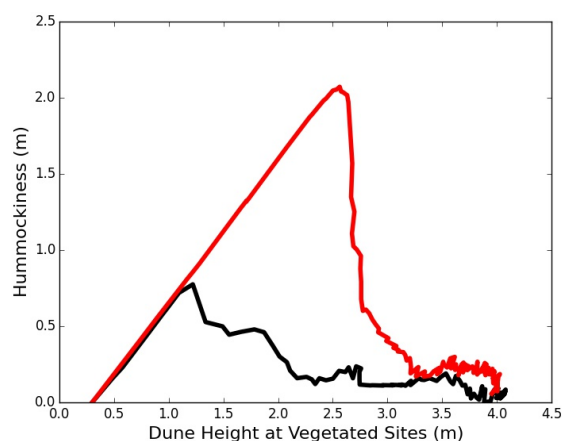
Figure 3: Phase plot of two numerical model experiments — the experiment in black has larger growth parameter (β) and therefore faster lateral growth and lower hummockiness than the red experiment. All model iterations begin at (0.3, 0), reflecting the initial height of the planar sloping surface (0.3 m) at the location of the dune vegetation plantings. As the model iterates, the hummocky dunes develop, as vegetated sites grow in height more than unvegetated sites (which must wait for vegetation to grow

10 **before increasing in height). After vegetation propagates to these sites, a continuous foredune ridge develops and hummockiness reduces to zero. The maximum hummockiness and the trajectory through phase space is set by gap size (w), vertical vegetation growth parameter (Hveg) and lateral vegetation growth parameter (β).**
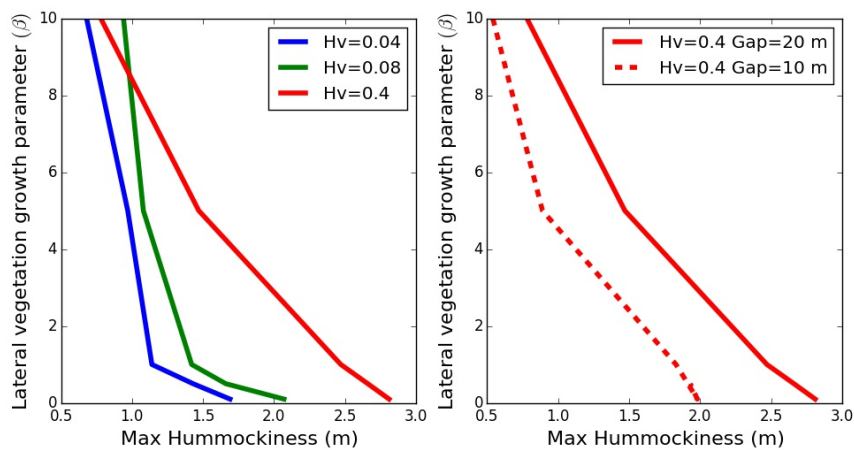
Figure 4: a) Maximum hummockiness (m) as a function of H$_v$ and β; B) Maximum hummockiness (m) as a function of β and unvegetated dune gap size
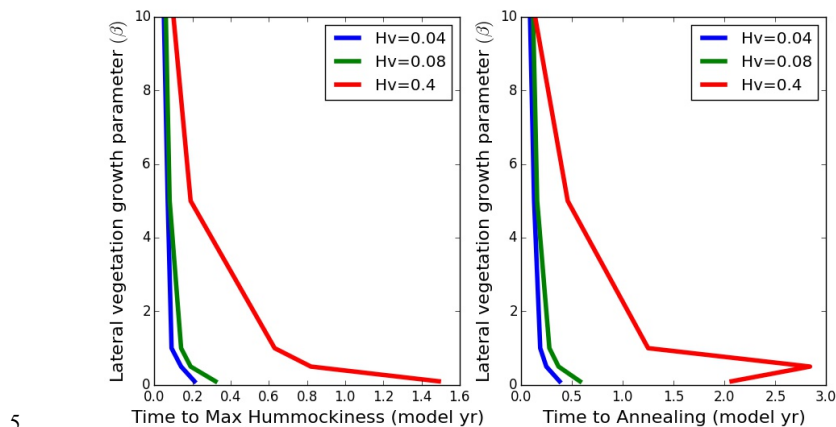
Figure 5: a) The time of maximum hummockiness; b) The time when annealing occurs.
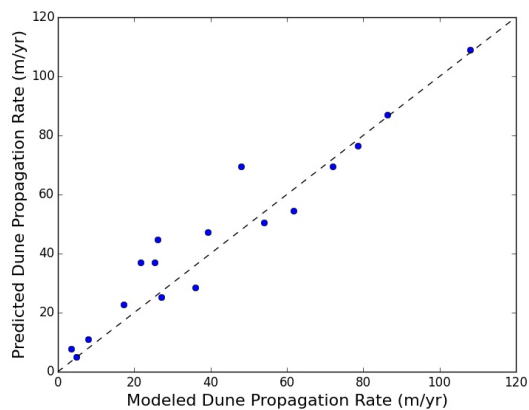
Figure 6: Modeled lateral dune propagation rate vs. predicted propagation rate from (6). Black line is 1:1.
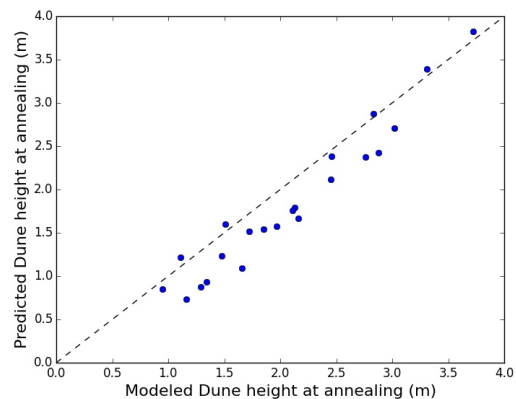
Figure 7: Modeled dune elevation at annealing vs. predicted dune elevation at annealing from (8). Black line is 1:1.