Air flow and sediment transport dynamics on a foredune with contrasting vegetation cover.

ABSTRACT

Wind flow and sediment transport across a northern California beach-foredune system with two adjacent vegetation types are examined for the same incident wind conditions. The invasive *Ammophila arenaria* was taller (~1 m) with denser coverage than the neighbouring *Elymus mollis* alliance canopy (~0.65 m), which consisted of a variety of interspersed native plants. Wind flow was measured with rotating cup and sonic anemometry, while sediment transport was measured using laser particle counters. Wind speed profiles over the two canopies were significantly different because of differing vegetation height, coverage density, and stem stiffness. In both cases, there was a lower zone of semi-stagnant air (below about 0.3 m) that transitioned upward to a shear zone comprising the upper part of the canopy and immediately above. The shear zone above the *Elymus* canopy was relatively thin (confined to 0.3-0.5 m above ground) whereas the shear zone in *Ammophila* canopy was thicker extending from a height of about 0.5h (h is average plant height) to about 1.5h. Vertical profiles of Reynolds Shear Stress (***RSS***) and Turbulence Kinetic Energy (***TKE***) are consistent with the shear layer structure over these two contrasting vegetation canopies. The degree of topographically-forced and vegetation-enhanced flow steering was significant, with *Ammophila* strongly shifting the highly oblique (55^{o}) incident wind to essentially shore-perpendicular trajectories. In comparison, the shore-perpendicular steering effect was not as pronounced for the *Elymus* canopy. Sediment transport intensity on the beach was continuous, but decreased progressively to the dune toe, and then dropped to essentially zero once the vegetation canopy was encountered (on the stoss slope). Overall, the study illustrates the significant differences in wind flow and turbulence conditions that may occur in contrasting plant canopies on foredunes, suggesting that greater attention needs to be placed on vegetation roughness characteristics in models of foredune morphodynamics and sediment transport potential.

Keywords: vegetated foredunes, wind speed profiles, canopy turbulence, wind steering, sediment transport, dune morphodynamics.

Introduction

The dynamics of wind flow and sediment transport across coastal dunes and similar ridge morphologies are influenced by many factors such as: incident wind speed and direction (Arens et al., 1995; Chapman et al., 2012; Bauer et al., 2009, 2012, 2015; Walker et al., 2009a, 2009b; de Vries et al., 2012; Hesp et al., 2009, 2013, 2015; Hesp and Smyth, 2016, 2017; Finnigan et al., 2020; Robin et al., 2021); foredune morphology (Davidson-Arnott and Law, 1990, 1996; Arens et al., 2001; Hesp, 2002; Ruz et al., 2017; Walker et al., 2017; Davidson-Arnott et al., 2012, 2018); as well as density, height, and patchiness of vegetation assemblages (e.g., Raupach, 1992; Aylor et al., 1993; Raupach et al., 1996; Finnigan, 2000; Gillies et al., 2000; Järvelä, 2002; Neumeier, 2005; Leonard and Croft, 2006; Walter et al., 2012; Youssef et al., 2012; Nepf, 2012; Marjoribanks et al., 2014; Keijsers et al., 2014, 2016; Hong et al., 2016; Hesp et al., 2019; Charbonneau et al., 2021; Innocenti et al., 2021).

Foredunes vary from scattered discrete nebkha (Mountney and Russell, 2006; Hernandez-Cordero et al., 2015; Hernandez-Calvento et al., 2017; Ruz et al., 2017) to continuous ridges (Hesp, 2002; Garcia Romero et al., 2019; Hesp et al., 2021). While some studies have been conducted on nebkha flow dynamics and their attendant shadow dunes (e.g. Mayaud et al., 2016a, 2016b, Hesp and Smyth, 2017), and several studies have been conducted on flow over foredune ridges with one dominant species (Sarre, 1987; Buckley, 1987; Hesp, 1989; Arens et al., 1995; Davidson-Arnott and Law, 1996; Nordstrom et al., 2006; Walker et al., 2009; Delgado-Fernandez et al., 2011; Hart et al., 2012; Hesp et al., 2013, 2015; Jackson et al., 2013; Bauer and Davidson-Arnott., 2014; Hilton et al., 2016; Keijsers et al., 2016; Grilliot et al., 2018; Wakes et al., 2010, 2021; Schwarz et al., 2021), there are few studies on the stoss slope of a natural foredune where there are neighbouring zones of significantly different vegetation cover. Information on the effects of vegetation on modifying near-surface boundary layer flows and sediment transport potential has traditionally been obtained from wind-tunnel experiments carried out on various artificial and natural plants (e.g. Molina-Aiz et al., 2006; Burri et al, 2011; Walter et al., 2012; Youssef et al., 2012; Suter-Burri et al., 2013; Hong et al., 2016; Miri et al., 2017, 2018, 2019; Cheng et al., 2018; Charbonneau et al., 2021) and there is limited recent field research on natural plant covers (see Finnigan, 2007; Hilton et al., 2009; Hesp et al., 2019, Delgado-Fernandez et al., 2019; and Walker et al., 2021 for reviews). We are aware of no field experiment in which flow dynamics and sediment transport have been measured simultaneously across two contrasting, but adjacent, vegetation covers.

This study examines the nature of wind flow and sediment transport across a single foredune with two contrasting vegetation types--one dominated by *Ammophila arenaria*, an invasive plant, and one characterised by the *Elymus* alliance, dominated by *Elymus molli*s but also comprising several other native plant species common to the northern California coast. The main objective of the study was to quantify flow dynamics and sand transport within these contrasting plant canopies in order to inform the debate about the morphodynamics and resilience of foredunes dominated by native species versus those with invasive or introduced non-native species. The close proximity of the two neighbouring vegetation types at the study area permitted simultaneous measurements of wind flow and sediment transport over both plant canopies on the stoss slope of the foredune under essentially the same conditions of incident wind flow and sediment supply from the upper beach and backshore.

Study Site

The study site is located on the northern portion of a coastal barrier complex on Humboldt Bay, Northern California, USA (Figure 1), known locally as the "North Spit". The historical evolution of the Lanphere-Ma-le'l Dunes complex has been described by Pickart and Hesp (2019), and it comprises a foredune or foredune-blowout complex (depending on location), parabolic dunes, deflation plain and a transgressive dunefield system that is, in places, geomorphologically stable or active. The experimental site is fronted by a wide dissipative beach with significant wave heights up to 3 m in winter, and mixed, semi-diurnal tides with average range of 1.3 m (National Ocean Service, 1988). At low tide, the beach is approximately 100 m wide, and the foredune is continuous alongshore (Figure 2).

FIGURE 1 HERE
FIGURE 2 HERE

The climate classification is Csb in the Köppen-Geiger system with moderate temperatures year-round and a strongly seasonal precipitation regime. Summers are relatively dry with average monthly rainfall of 4.6 mm in July and August, and much wetter winters with 205.7 mm of rain in December (https://www.weather.gov/wrh/Climate?wfo=eka "Monthly Climate Normals (1991-2020) – Eureka Area, CA"). The prevailing wind direction is from the north to northwest from spring through autumn. Wind direction shifts to a southerly approach in winter with slightly stronger average wind speeds (National Weather Service, 2018; Pickart and Hesp, 2019). Most precipitation falls between November and April, which reduces the sediment transport potential because of surface moisture effects. Thus, the most effective aeolian transport season is late spring when winds are generally strongest onshore with daily averages of 3.6 m s^{-1} and peak gusts of up to 28 m s^{-1} during April and early May. The inset in Figure 1 illustrates a sand rose for the region following methods in Fryberger and Dean (1979) and Miot da Silva and Hesp (2010). The resultant drift potential is 44.6 v.u., and the resultant drift direction (RDD) indicates net transport to the SSE.

The foredune was invaded by *Ammophila arenaria* after its introduction to the area ca. 1901 (Pickart and Hesp, 2019). In 1992, the US Fish and Wildlife Service began to remove *Ammophila* in the dune area adjacent to, and south of, the study site, and the native *Elymus mollis* alliance propagated into those cleared sites (Pickart, 2013; Pickart and Sawyer, 1998). The *Elymus* herbaceous alliance (Sawyer et al.

2009) is dominated by *Elymus mollis,* with lesser cover of *Abronia latifolia, Ambrosia chamissonis, Calystegia soldanella, Poa macrantha* and *Lathyrus littoralis*. This alliance is restricted to the foredune and is characterized by variable cover, with considerable patchiness in some cases. The *Ammophila arenaria* cover is characterized by a more densely packed, monotypic stand that covers the foredune and extends into the landward dunes. The mean height of *Ammophila arenaria* plants is 1.01 m (standard error 2.9 cm), whereas the mean height of *Elymus mollis* is 0.65 m (standard error 3.2 cm) (Sawyer et al., 2009). At the time of this study, there was a distinct separation between the *Ammophila* dominated foredune section and the *Elymus* alliance section.

Methods

Dune Morphology and Vegetation Surveys

Topographic profile lines were surveyed across the upper beach to the foredune crest using an inclinometer and tape with measurements at 0.5 m intervals. Two lines were perpendicular to the shoreline following Line A (the *Ammophila* dominated line) and Line E (the *Elymus* dominated line). Two additional profiles were taken obliquely to the shoreline and parallel to the incident wind direction during the experiment period. Detailed 3D mapping of the entire site was conducted using a Riegl VZ400 terrestrial laser scanner to produce a georeferenced digital terrain model (DTM) with survey lines and instrument locations extracted and represented in Figure 3A. Vegetation surveys were conducted along the profile lines using a standard visual estimation method to determine percent cover (Mueller-Dombois and Ellenberg, 1974). On the *Elymus* alliance line, species presence-absence and the percent cover of each of the native species were also estimated using the same visual method.

FIGURE 3 HERE

Wind Instrumentation

Three shore-normal instrument lines were set up. One central line, referred to as "Line B" extended from a tall instrument mast positioned on the beach (Beach Tower or BT) to three additional stations (labelled B3, B2, and B1 in the landward direction) located part-way up the dune ramp to the dune toe, aligned perpendicular to the shoreline, as shown in Figure 3A. The other two instrument lines, one to the north (Line A) and the other to the south (Line B) separated by approximately 16 m, were also shore-perpendicular extending from the dune toe, up the foredune stoss slope, to the crest.

All anemometers were oriented to magnetic north, which corresponded to the approximate orientation of the dune crest locally (about 6.5^o to east of magnetic north). As such, onshore winds (from the west) approach the foredune from 276.5 degrees magnetic, while obliquely (45^o) onshore winds from the northwest approach from 321.5 degrees magnetic. In addition, most anemometers were slope-aligned to the local dune surface gradient, with the exception of a few of the sonic anemometers located on the upper beach and all the cup anemometers, which were levelled horizontally. Corrections for magnetic declination (14.5^o to the east of True North) were performed during data reduction and analysis when necessary to position the instruments on the DTM, but magnetic north was retained as the primary reference orientation throughout.

Incident wind conditions were measured by anemometers fixed to the Beach Tower located on the backbeach upwind of, and centrally between, instrument Lines A and Line E (Figure 3A). The Beach Tower had six logarithmically spaced instruments at 0.15 m, 0.3 m, 0.62 m, 1.27 m, 2.61 m, and 5.35 m with the lower five locations measuring wind speed and direction from co-located cup anemometers and wind vanes (NRG Systems #40-H and #200P, respectively) and the upper location consisting of an RM Young Wind Monitor (model 05103) propeller anemometer. The beach stations (B3, B2, B1) consisted of Gill Instruments Wind Master (3D) sonic anemometers positioned at 0.5 m at B3, 0.75 m at B2, and 0.5 m at B1. In addition, Gill Instruments WindSonic (2D) anemometers were located at a height of 0.15 m at each of B2 and B1.

Line A and Line E both consisted of three instrument stations positioned on the dune ramp or toe area (A1, E1), the mid stoss slope (A2, E2), and the foredune crest (A3, E3). Anemometer heights were 0.15 m, 0.5 m and 1.6 m on each of the six stations, but the instrument manufacturer differed. The sonics on Line A consisted of RM Young 2D model 85000 (2D) at the lower positions and RM Young 3D model 81000 for the middle and upper positions. On Line E the lower instruments were Gill Instruments WindSonic (2D) and the middle and upper instruments were Gill Instruments WindMaster (3D).

Two smaller instrument masts were installed at the foredune crest adjacent to both Line A and Line E, approximately 3-5 m toward the centre between these lines (Figure 3A). These towers, referred to as "CTA" (north, closest to Line A) and "CTE" (south, closest to line E), had 7 RM Young cup anemometers each, positioned nominally at 0.25 m, 0.35 m, 0.5 m, 0.65 m, 0.9 m, 1.2 m, and 1.65 m above a reference line etched into the base of each tower. During the day of the experiment the lowermost anemometer on CTE failed, so only six instruments are shown in the corresponding speed profiles.

Wind Data Analysis and Turbulence Quantities

Wind data were collected on 6 May 2014 between 1130 and 1800h PDT. Prior to the experiment, all anemometers were cross-calibrated for a one-hour period (Figure 4) during onshore flow with slightly varying wind speed. Voltage-to-speed coefficients for cup anemometers were calculated by regression analysis against a time series obtained from a new sonic anemometer, used as a standard, that was co-deployed alongside all other anemometers. The 2D sonics were configured internally to yield time series of horizontal wind speed (s) and azimuth (θ) at a sampling rate of 1 Hz, from which the two horizontal velocity vectors (u, v) were calculated for every 1-second time interval. Most of the 3D sonics were configured to record the three horizontal velocity vectors (u, v, w) directly, but if they were set to record speed and azimuth along with the vertical velocity vector (w) then the u-v-w time series were calculated during post-processing. All sonic anemometers were deployed with their main orientation spurs pointing to magnetic north. The cup anemometers have no directional information and provide only wind speed (s) directly. All instruments were sampled at 1 Hz.

FIGURE 4 HERE

The large number of anemometers used in this study and their wide spacing required the use of several independent data loggers. Accurate time stamps (to within 1 second for all of the time series) were facilitated by the use of a common laptop to launch all data loggers using the same software. Nevertheless, start and finish times for data records throughout the day varied due to intermittent servicing of equipment, so only those periods when the majority of instruments were operative were selected for further analysis. The continuous 1 Hz time series were block-averaged at 5-minute intervals beginning on the hour with 5-minute statistics reported at the half-way mark (i.e., 12:02:29, 12:07:29, 12:12:29, and so on).

The 5-minute block-averaged velocity vectors (U, V, W) were used to calculate fluctuating velocity components (u', v', w') for consecutive 5-minute data blocks (where u' = u – U; v' = v – V; and w' = w – W). The fluctuating components were then used to calculate Reynolds Shear Stress (RSS) on a 5-minute block basis using:

$$\mathrm{RSS} = -\rho\,\overline{s'w'} \qquad (1)$$

where ρ is air density (taken as 1.225 kg m^{-3} for sea-level pressure and 15 ^{o}C), w' is the fluctuating velocity component in the vertical direction as defined by the primary axes of the anemometer, and s' is the fluctuating component of horizontal wind speed (s' = s – S; where $s = \sqrt{u^2 + v^2}$ and S is the 5-minute block average of s), with all velocity vectors reported in the unrotated (instrument aligned) reference frame. Quantities such as $\overline{s'w'}$ are interpreted statistically as the covariance between the fluctuating components. Similarly, quantities involving the products of the same fluctuating component (i.e., $\overline{u'^2}$, $\overline{v'^2}$, $\overline{w'^2}$) are interpreted as variances, which are used to calculate TKE as follows:

$$\mathrm{TKE} = \frac{1}{2}\left[\left(\overline{u'^2}\right) + \left(\overline{v'^2}\right) + \left(\overline{w'^2}\right)\right] \qquad (2)$$

RSS and TKE include the fluctuating vertical velocity (w'), which can vary in magnitude and direction depending on the precise orientation of the anemometer. Thus, it is standard protocol to rotate the frame of reference for each instrument independently (Van Boxel et al., 2004; Walker, 2005). In a few instances, the anemometers were deployed horizontally whereas in most other cases (e.g., on the stoss slope of the dune) they were deployed parallel to the local ground slope. In order to accommodate differences in instrument deployment, a series of rotation procedures were applied to consecutive 5-minute block intervals, as outlined below.

The first step was to perform a rotation of the horizontal velocity vectors to account for yaw using:

$$\boldsymbol{u_1} = \mathrm{u}\cos\alpha + \mathrm{v}\sin\alpha \qquad (3)$$

$$\boldsymbol{v_c} = -\mathrm{u}\sin\alpha + \mathrm{v}\cos\alpha \qquad (4)$$

$$\alpha = \tan^{-1}\left(\frac{\mathrm{V}}{\mathrm{U}}\right) \qquad (5)$$

where bold italics are used to indicate a rotated parameter, $\boldsymbol{u_1}$ and $\boldsymbol{v_c}$ are yaw-adjusted values, and alpha (α) is the wind approach angle calculated using the 5-minute, block-averaged horizontal wind speeds, U and V. As a consequence of the yaw rotation, the following conditions apply: $\overline{u_1}$ = S, $\overline{\boldsymbol{v_c}}$ = 0, and by definition, $\bar{\boldsymbol{v}}'$ = 0.

The second step was to perform a pitch rotation to account for tilt angle of the instrument relative to the incoming streamlines using:

$$\boldsymbol{u_c} = \boldsymbol{u_1}\cos\varphi + \mathrm{w}\sin\varphi \qquad (6)$$

$$\boldsymbol{w_c} = \boldsymbol{u_1}\sin\varphi + \mathrm{w}\cos\varphi \qquad (7)$$

$$\varphi = \tan^{-1}\left(\frac{\mathrm{W}}{\boldsymbol{u_1}}\right) \qquad (8)$$

where $\boldsymbol{u_c}$ and $\boldsymbol{w_c}$ are pitch and yaw adjusted values. Phi (φ) is the angle of the incoming streamline relative to the sensor plane given by the ratio of W (the mean vertical velocity vector from the original time series for each 5-minute data block) over $\overline{u_1}$ = S (the 5-minute mean wind speed or horizontal velocity in the streamwise direction ***after*** yaw rotation).

Fluctuating velocity components for the pitch and yaw adjusted times series ($\boldsymbol{u'}$, $\boldsymbol{v'}$, $\boldsymbol{w'}$) were calculated as follows:

$$\boldsymbol{u'} = \boldsymbol{u_c} - \boldsymbol{U_c} \qquad (9)$$

$$\boldsymbol{v'} = \boldsymbol{v_c} - \boldsymbol{V_c} \qquad (10)$$

$$\boldsymbol{w'} = \boldsymbol{w_c} - \boldsymbol{W_c} \qquad (11)$$

in which $\boldsymbol{U_c}$ **,** $\boldsymbol{V_c}$ **,** $\boldsymbol{W_c}$ are the block-averaged velocity vectors for the yaw and pitch adjusted time series, satisfying the following conditions and definitions: $\boldsymbol{U_c} = \overline{\boldsymbol{u_c}} = \boldsymbol{S}$, where ***S*** is the mean wind speed in the direction of the streamline; $\boldsymbol{V_c} = \overline{\boldsymbol{v_c}} = 0$; $\boldsymbol{W_c} = \overline{\boldsymbol{w_c}} = 0$; and $\overline{\boldsymbol{v'}} = \overline{\boldsymbol{w'}} = 0$.

The fluctuating components from the rotated time series were then used to calculate the rotation-adjusted Reynolds Shear Stress (***RSS***),

$$\boldsymbol{RSS} = -\rho\, \overline{\boldsymbol{u'w'}} \qquad (12)$$

and the rotation-adjusted Turbulence Kinetic Energy (***TKE***),

$$\boldsymbol{TKE} = \frac{1}{2}\left[\left(\overline{\boldsymbol{u'^2}}\right) + \left(\overline{\boldsymbol{v'^2}}\right) + \left(\overline{\boldsymbol{w'^2}}\right)\right] \qquad (13)$$

Sand Transport Intensity

Laser Particle Counters (LPCs), commonly referred to as Wenglor fork sensors (Model # YH08PCT8 - 8 cm path length and Model # YH08PCT5 - 5 cm path length), were used to measure sand transport intensity at various locations over the beach and foredune. Wenglor sensors were first deployed for aeolian research by Davidson-Arnott et al. (2009) and several subsequent studies have evaluated their performance characteristics (see Bauer et al., 2018, and references therein).

Data time series from the LPCs consist of particle counts per second (# s^{-1}) and are referred to as sediment 'particle' flux rather than sediment mass flux (kg s^{-1}) due to uncertainties associated with count-to-mass conversion algorithms (Barchyn et al., 2014). LPCs have proven reliable in many previous deployments although not without challenges in moist, marine air when the laser windows become fouled by sea spray and fine particulate matter.

In total, 24 LPCs were deployed during this study, but only a subset will be used for this paper. Several LPCs were deployed along the Beach Line between BT and B1 at a height of 0.01 m above the sand surface. Due to bed level fluctuations associated with ripple migration as well as prolonged periods of local erosion or deposition, these nominal heights changed slightly throughout the day. The LPCs were periodically adjusted to accommodate these changes. LPCs were also deployed at 0.02 m and 0.8 m at each of the three instrument locations on Line E (E1-E3) to characterize transport activity near the surface and above the plant canopy. Along Line A, an LPC was positioned at a height of 0.8 m at each of the three instrument locations (A1-A3), but due to instrument shortages, only station A1 had a surface LPC deployed at 0.02 m. All LPC sensors were positioned within a horizontal distance of 0.5 m from the co-located sonic anemometers, due to logistical constraints (e.g., cable lengths, mast or tripod locations, plant locations and density). To accommodate differences in the fork widths of the LPCs, the particle count data were divided by their respective beam widths (in cm), then multiplied by 100 cm to yield standardized values of particle counts s^{-1} m^{-1} of width across the transport surface.

Results

Dune topography and vegetation density

Shore-normal topographic profiles with vegetation cover percentages are illustrated in Figure 5A. The two profiles display relatively similar topographic morphologies, but somewhat dissimilar percent vegetation covers. Line A had greater vegetation coverage, especially from mid-slope to the crest. Wind approach angle was obliquely onshore (331.6° magnetic or 55.1° from shore-perpendicular) during the experimental period so, accordingly, apparent dune profiles were generated to align with the incident wind angle. Figure 5B illustrates the wind-aligned topographic profiles and percent vegetation cover, demonstrating that the apparent slope that the oblique wind responds to is less steep. In reality, there will be some topographically induced flow steering as the near-surface streamlines progress up the stoss slope (cf. Arens et al., 1995; Walker et al., 2009b; Bauer et al., 2012; Jackson et al., 2013; Hesp et al., 2015) with the incident wind responding initially to the apparent slope in the lower sections and then transitioning to a more perpendicular approach angle higher up the stoss slope. Given that the general dune topography is virtually identical for Line A and Line E, any differences in flow parameters between Line A and Line E should be due, in large part, to the differences in vegetation cover.

FIGURE 5 HERE

Temporal trends in general wind flow conditions

The uppermost anemometer (5.35 m) on the Beach Tower (BT) provided information on incident wind conditions on the day of the experiment (May 6, 2014). Five-minute average wind speeds (Figure 6A) in the late morning were less than 8 m s^{-1}, peaking to 11.6 m s^{-1} in the early afternoon, and gradually declining for the remainder of the day. Wind direction (Figure 6B) was obliquely onshore from the northwest at around 331° magnetic (or about 55° from shore-perpendicular) remaining steady throughout the day with relatively minor deviations of less than +/-7°.

FIGURE 6 HERE

The anemometers on the dune Crest Towers (CTA, CTE) were positioned approximately 4–9 m higher in the oceanic boundary layer than the uppermost anemometer on BT (at 5.35 m), but closer to the local ground surface (between

0.25 m and 1.65 m) on the crest, leading to wind field modifications by two opposing tendencies. Being situated higher overall within the incident oceanic boundary layer implies faster wind speeds, which is enhanced by flow streamline compression and acceleration up the stoss slope of the dune (e.g., Walker et al., 2009b; Hesp et al., 2015, Hesp and Smyth, 2016). However, because the crest anemometers were located close to the ground surface, there was wind speed reduction due to enhanced frictional resistance imparted by the upwind vegetation canopy. These opposing tendencies produced wind speeds on the dune crest that were slightly faster than the reference wind speeds on the Beach Tower at the same height above the surface, but likely not as fast as they would have been for a similarly profiled unvegetated foredune.

Wind direction was equally influenced by the combination of topographic steering and frictional resistance up the stoss slope. Figure 6B shows that the flow on the crest was directed in a more onshore trajectory than the incident wind, with a 10^o - 12^o shift at the E3 station and a 15^o – 20^o shift at the A3 station, which reflects the greater frictional resistance imparted by the *Ammophila* canopy relative to the *Elymus* alliance cover. These wind steering effects were consistent throughout the day despite minor variations in incident wind direction between 323^o – 336^o, and similar in magnitude to flow steering effects observed in other studies (e.g., Arens et al., 1995; Walker et al., 2009a, b; Bauer et al., 2012; Hesp et al., 2015; Schwarz et al., 2021).

Figure 6 shows that the incident wind direction changed relatively little throughout the day, whereas wind speed increased progressively to a peak at about 13:30 followed by a gradual decline. Sediment transport across the beach was most intense between 13:00 and 14:00. The remainder of the paper therefore focuses only on the 5-minute peak period centred at 13:27:29, when the majority of instruments were operational and when sediment transport was at a maximum. All other 5-minute intervals showed the same basic trends in terms of flow structure and spatial relationships even though the magnitude of various parameters differed slightly.

Spatial trends in wind speed

Wind speed profiles for the 5-minute interval centred on 13:27:29 are presented in Figure 7 for instrument stations located on the dune crest. The profiles from the cup anemometer tower (CTA)and from station A3 on Line A, both downwind of the *Ammophila* canopy, are compared to the Beach Tower (BT) reference profile in Figure 7A, whereas the equivalent stations (CTE and E3) downwind of the *Elymus* canopy are shown in Figure 7B. The BT reference profile shows that the incident, unmodified boundary layer over the beach has a classic logarithmic form, plotting as a straight line on these log-linear graphs, extending from 0.15 m to over 2 m above the sand surface. The wind speed for the uppermost anemometers at 2.65 m and 5.35 m are not shown, but they also conform to a logarithmic form, indicating that the shear stress is evenly distributed throughout the entire depth of the beach boundary layer. In contrast, the crest profiles differ significantly due to the combined influence of dune topography and differences in vegetation cover on the stoss slope.

FIGURE 7 HERE

The wind speed profiles from the two instrument positions on the crest downwind of the *Ammophila* canopy (CTA and A3) have very similar shapes despite using different sensing technologies and a separation distance of 5-6 m laterally. There is a steeply sloping upper region from about 0.5 m to 2 m (relative to the beach reference profile) and a lower zone below about 0.5 m where air flow was essentially stagnant. The lowermost instruments (below 0.25 m) were positioned deeply within the vegetation canopy, which for the *Ammophila* was about 0.75 m high on average. Even though the 5-minute mean wind speeds were a little more than 1 m s^{-1} in this lower zone, visual observation of the cup anemometers on CTA indicated that the cups only turned during wind gusts and sometimes reversed direction due to eddying within the canopy. The uppermost anemometers above 1 m height show the expected wind enhancement due to flow acceleration effects induced by streamline compression, which amounts to about a 3 m s^{-1} enhancement relative to the BT reference at a height of about 1.6 m above the surface. The speed profiles between about 0.5 m to 1.6 m are log-linear, which indicates that the distribution of shear stress is evenly distributed with height, but of a magnitude that is much greater than on the beach for the same heights above the ground. The primary reason is that the beach profile is responding to a relatively smooth frictional surface (i.e., sand) whereas the crest profiles are strongly influenced by the much greater roughness induced by the vegetation canopy as well as by flow acceleration up the stoss slope. The segmented nature of the crest profiles, however, indicates that the shear is not conveyed to the sand surface with most of the flow momentum from above being absorbed by the vegetation canopy. Thus, the log-profile is displaced upward and away from the sand surface due to the presence of the tall *Ammophila* canopy.

The wind speed profiles downwind of the *Elymus* alliance canopy (CTE and E3) have a much different form (Figure 7B). The upper region generally follows the same sloping trend as the reference tower, but the wind speeds are uniformly greater by approximately 3 m s^{-1} down to a height of about 0.5 m. This is consistent with the shorter height of the *Elymus* relative to *Ammophila*, such that only the lowermost anemometer at station E3 showed a marked reduction in wind speed, although the influence was apparent at about 0.35 m height. Unfortunately, the cup anemometer deployed at 0.25 m on CTE failed to provide data on this day so the downward trend in wind speed cannot be extended lower into the near-surface boundary layer at CTE. Nevertheless, it is evident that the frictional resistance imparted by the *Elymus* canopy does not extend as high as in the taller *Ammophila*, and its influence is not as strong in modifying the upper parts of the boundary layer, as shown by the fast wind speeds above about 0.4 m height. The profile is semi-logarithmic in the upper region but with a much less steeply sloping trend than over the *Ammophila*, which indicates that the strongest shearing action is restricted to the zone below about 0.45 m. There is evidence of a speed bulge in the CTE profile between 0.4 m to 1.2 m.

The influence of the differing vegetation canopies on modifying the near-surface boundary layer flow is also demonstrated by vertical speed profiles measured along Line A and Line E from the dune toe to the dune crest. Figure 8A shows the spatial evolution of the profiles within the *Ammophila* canopy. The speed profile on the dune toe (A1) had the same shape as the profile measured on the beach (BT) with slightly slower speeds close to the surface because of the adverse pressure gradient induced by the presence of the dune. There was no vegetation cover on the dune toe to impede the air flow. On the mid-stoss (A2), where the vegetation cover was 85%, the shape of the speed profile was strongly influenced by the vegetation canopy and had essentially the same form as the profile on the crest (A3). This indicates that the influence of the *Ammophila* vegetation cover is fully effective within only a few metres of the transition from beach sand to plant cover.

FIGURE 8 HERE

The influence of the *Elymus* cover was similarly felt within metres of the sand-to-plant transition (Figure 8B). The profile at the dune toe (E1) was almost identical to the profile on the beach (BT), with only slightly reduced speeds close to the surface. At the mid-stoss location (E2), the speed profile was very different from the toe location (E1) but essentially the same as at the crest (E3). Therefore, both the *Ammophila* and *Elymus* canopies were equally effective in modifying the near-surface boundary layer flow but in slightly different ways. The primary difference is the height at which wind speed-up becomes pronounced. The E2 and E3 profiles demonstrate that the frictional resistance from the shorter *Elymus* canopy only affects the lowermost anemometers (0.15 m). Toward the top of the canopy (at about 0.5 m) the wind speeds were much faster than for the same heights on the dune toe and beach where there was no vegetation. In contrast, the taller *Ammophila* canopy impeded the flow up to about 1 m, and the speed-up zone was located above this height. In both cases, the near-surface wind was slowed due to friction imparted by the plant stems, whereas above some displacement height there was speed-up (relative to the beach profiles) due to flow acceleration because of streamline compression up the foredune.

Spatial trends in wind direction

Wind direction information from the sonic anemometers located on Line A and Line E was derived from the yaw corrections described in the Methods section, which yielded values for wind approach angle relative to magnetic north (360°) for the peak period centred on 13:27:29 (Figure 9). Oblique winds moving across a beach are typically steered toward more onshore (crest perpendicular) orientations across the stoss slope of foredunes (Walker et al., 2009 a,b; Hesp et al., 2015; Walker et al., 2017 and references therein), and this was also evident during this experiment. But, the influence of enhanced frictional resistance due to the different vegetation canopies was particularly striking.

FIGURE 9 HERE

Wind approach angles at the foredune toe upwind of the two vegetation canopies were similar to the incident wind angle of 331.6° measured high above the beach. Shore-perpendicular flow is 276.5° magnetic whereas the dune crest was oriented 6.5° magnetic, indicating that the wind approach angle at this time was approximately 55° from shore-normal (i.e., highly oblique). Both of the instrument stations at the foredune toe were positioned over bare sand (i.e., upwind of any vegetation in the case of A1 and just leeward of a few individual plants at E1), so any steering effects on the dune toe were due predominantly to form drag induced by slight differences in micro-topography upwind of the instrument stations (refer to photos in Figure 3). However, on the stoss slope (A2 and E2), the flows were strongly influenced by the roughness imparted by the presence of a vegetation canopy, especially at heights of 0.15 m, which was well within both canopies. For the *Elymus* alliance cover (Figure 9B), the wind experienced a shore-perpendicular shift of about 35-40° near the surface, which decreased progressively with height, whereas for the *Ammophila* canopy (Figure 9A), in stark contrast, the near-surface wind shifted by 90° such that the approach angle was slightly from the south rather than NW. This extreme steering is likely due to near-surface wind being channeled through gaps in the non-uniform vegetation cover as it approached this instrument position rather than a bulk effect that would apply everywhere. Indeed, higher in the *Ammophila* canopy, at 0.5 m, the deviation from the incident direction was about 30°, and far above the canopy the deviation was only 10°. Nevertheless, as with the wind speed profiles, the influence of the *Ammophila* cover was more pronounced and extended higher above the ground surface than for the *Elymus* alliance cover.

At the foredune crest (A3 and E3), the near-surface anemometers recorded deviations of about 70° for *Ammophila* and 25° for *Elymus.* At heights of 0.5 m, the deviations were only slightly smaller than at the surface, indicating that the influence of both vegetation canopies extended to approximately this level, whereas at 1.6 m, well above the canopy, the deviations were around 25° for *Ammophila* versus 10° for *Elymus*, indicating a slightly stronger shore-perpendicular steering influence for the *Ammophila*.

Spatial trends in Reynolds Shear Stress

After performing yaw and pitch corrections, Reynolds Shear Stresses (***RSS***) were calculated for each of the 3D sonics at each of the three instrument stations along Line A and Line E. The time series from the 2D sonics positioned at 0.15 m cannot be used to calculate Reynolds Shear Stresses because there is no information for vertical velocity. In an ideal boundary layer with a constant stress region, the shear stress ($\tau = \rho u_*^2$) calculated on the basis of shear velocity (u_*) derived from a wind speed profile via regression, should be approximately the same as the Reynolds Shear Stress (***RSS***) calculated using the fluctuating components of velocity (Equation 12) after rotation (Bauer, 2013). Figure 10 shows that this is true for the instrument station positioned at the foredune toe (E1) in front of the *Elymus* canopy (Figure 10B), which duplicates the stress profile derived from the Beach Tower. In front of the *Ammophila* canopy (Figure 10A), the ***RSS*** values at the toe station were larger than τ calculated from the Beach Tower for reasons that may have to do with the undulating backbeach topography upwind of station A1. Such sand surface features give rise to stronger vertical velocity fluctuations that were not apparent at E1, which had smoother upwind topography for these highly oblique wind approach angles.

FIGURE 10 HERE

The ***RSS*** values within the vegetation canopies (0.5 m height) at the mid stoss (A2, E2) and crest (A3, E3) locations were much smaller than those at the foredune toe (A1, E1). Small values of ***RSS*** indicate that the vertical velocity excursions are not correlated well with the horizontal velocity excursions, unlike what would be expected in a classic boundary-layer flow with uniform shearing action where the u′ and w′ motions are closely correlated. The flow within a thick vegetation canopy would typically have smaller mean speeds, smaller velocity excursions, and a generally chaotic directional character. This friction-induced buffering effect leading to flow stagnation deep within the canopy cover was more pronounced in the *Ammophila* canopy, which was taller and denser than the *Elymus*.

Immediately above the canopy top, where the shearing action should be most prevalent, the ***RSS*** values increased, with the exception of the upper anemometer at the mid stoss station above the *Elymus* (E2). The reasons are not clear, but the photo in Figure 3C suggests that with oblique angles of wind approach from the northwest, the uppermost anemometer at the mid stoss station likely measured wind characteristics that were not influenced by vegetation but rather by the smoother sand surface lying upwind. Nevertheless, this does not account for why the ***RSS*** values were not closer to the BT reference shear stress. At the dune crest, the general ***RSS*** patterns were similar for both vegetation types, although the near-surface ***RSS*** values in the *Ammophila* were the smallest measured, as would be expected within a very dense vegetation canopy.

Spatial trends in Turbulence Kinetic Energy

The fluctuating components of velocity (after full rotation) were used to calculate the turbulence kinetic energy (***TKE***) according to Equation 13. The spatial trends shown in Figure 11 indicate that ***TKE*** values above the vegetation canopy (1.6 m) were close to a value of 1 $m^2 s^{-2}$ with slightly greater kinetic energy above the *Ammophila*. There was relatively little difference in ***TKE*** from the dune toe to the dune crest at 1.6 m height. However, the near-surface (0.5 m) ***TKE*** values were distinctly different as a function of vegetation type and position on the foredune. On the beach (station B2), the incident ***TKE*** values were around 0.75 $m^2 s^{-2}$. At the dune toe, the near-surface ***TKE*** values increased to levels that were similar to those measured higher in the profile (at 1.6 m) well above the canopy, suggesting an even distribution with height. As with ***RSS***, the ***TKE*** values at the toe station were greater in front of the *Ammophila*, which is consistent with the explanation that the micro-topography of the sandy surface across the beach in front of the *Ammophila* induced greater velocity fluctuations than for the comparable toe station in front of the *Elymus*.

FIGURE 11 HERE

Farther up the stoss slope of the *Ammophila* dune section (Figure 11A), there was a progressive decrease in ***TKE*** values toward a minimum of 0.23 $m^2 s^{-2}$ at the dune crest. This mimics the trend in ***RSS*** with a pronounced decrease in shear stress to a minimum at the crest. These decreases in ***RSS*** and ***TKE*** reflect the fact that the anemometers positioned at a height of 0.5 m on the mid-stoss and crest were immersed within the stagnation zone at the base of the *Ammophila* canopy. The incident wind moving across the top of the vegetated layer was not able to penetrate down into the *Ammophila* canopy effectively, and the turbulent fluctuations were both reduced in magnitude and became uncorrelated (i.e., chaotic relative to the flow in the shearing zone above the canopy.

The *Elymus* alliance canopy had a very different influence on the ***TKE*** distributions (Figure 11B). Reduced ***TKE*** values less than 1 $m^2 s^{-2}$ at 1.6 m height suggest that the *Elymus* canopy presents a hydrodynamically-smoother surface to the wind than the *Ammophila* canopy, which extends higher into the flow field and generates ***TKE*** values in excess of 1 $m^2 s^{-2}$. However, the near-surface ***TKE*** values at 0.5 m height above the *Elymus* canopy increased progressively with distance up the dune profile to a maximum of 1.58 $m^2 s^{-2}$ at the crest. The likely explanation is that the anemometers positioned at 0.5 m height on Line E were close to the top of the *Elymus* alliance canopy; neither deeply within the canopy nor well above it. The shearing action and turbulence production at this transitional level would be pronounced because the incident wind interacts with the tops of the individual plant stems that are buffeted around. This also explains the reduction in ***RSS*** via the absence of strong correlation between ***u'*** and ***w'***. On Line A, however, the 0.5 m instruments were well within the *Ammophila* canopy and thereby sheltered from the incident wind. The Reynolds Normal Stresses (***RNS***; not shown) closely follow the trends in ***TKE***, indicating that most of the energy associated with the fluctuating velocity components was with the streamwise motions, while the spanwise motions were of secondary importance (approximately 50% of streamwise) and the vertical motions were of least importance (approximately 10-20% of streamwise).

Sediment transport within the vegetation canopies

All LPCs on the beach and at the toe of the foredune (positioned nominally at 0.01-0.02 m above the surface) showed continuous sediment transport entering the foredune system for the 5-minute period of interest (Figure 12) with activity parameter values of AP=1.0 (Davidson-Arnott et al., 2012) greater than other periods during the day. Sand transport intensity on the beach at approximately 2 m downwind of the Beach Tower and 10 m upwind of Line A and Line E, ranged from 5980 to 24,420 counts s^{-1} m^{-1} of beach width with an average of 13,544 counts s^{-1} m^{-1}. At the base of the dune ramp, approximately 5 m downwind of the Beach Tower and just 3 m upwind of the dune toe, transport intensity was slightly less than at the Beach Tower, but still appreciable with counts ranging from 2,500 to 19,180 counts s^{-1} m^{-1} of beach width and an average 8964 counts s^{-1} m^{-1}. At the dune toe locations fronting the *Ammophila* and *Elymus* alliance (A1 and E1, respectively), the sand transport activity dropped considerably (approximately five-fold) with only slightly larger average values at A1 (3477 counts s^{-1} m^{-1}) than at E1 (2673 counts s^{-1} m^{-1}). These differences between the A1 and E1 counting rates are considered to be within measurement uncertainty given slight differences in instrument heights of the LPCs due to fluctuations in the sand surface because of bedform migration and progressive erosion or accretion in the local vicinity of the LPCs.

FIGURE 12 HERE

Near-surface sand transport intensity within the *Elymu*s canopy (along Line E) declined abruptly across the stoss slope of the foredune (Figure 12; lower panel), consistent with the greatly reduced near-surface wind speeds, to levels well below the threshold of motion (Figures 7 and 8). The AP value at E2 (mid-stoss) was 0.237 and at E3 (crest) was 0.007. The maximum transport intensity at E2 was only 50 counts s^{-1} m^{-1} beach width in contrast to about 5,000 counts s^{-1} m^{-1} beach width at E1 on the dune toe and about 24,000 counts s^{-1} m^{-1} beach width at the Beach Tower where there was no vegetation cover to impede transport. Unfortunately, instrument limitations precluded deployment of LPCs at near-surface locations at A2 and A3 within the *Ammophila* canopy, so we are unable to confirm that a cessation of transport occurred on the stoss slope. Nevertheless, given similarly slow near-surface wind speeds and a thicker stagnation zone, it seems reasonable to assume that a substantial (or even greater) reduction in sand transport intensity would have occurred in the *Ammophila* canopy as was observed in the *Elymus* canopy.

LPCs were also deployed at 0.8 m height along all three stations on Line A and Line E (not shown), and these demonstrated that there was detectable transport at all six stations above the plant canopies. However, typically only a single grain or two passed through the LPC sensing volume at random times spaced tens of seconds apart (or more). AP values at a height of 0.8 m were less than 0.01 across the beach and toward A1 and E1 at the dune toe, across unvegetated surfaces. This is consistent with our understanding of fully developed saltation layers having the bulk of transport within the lower 0.1 m and very little transport above about 0.3 m (e.g., Bauer and Davidson-Arnott, 2014). However, over vegetated surfaces with little to no transport at the ground surface, it is unexpected to measure sediment particles above the canopy. Yet, the AP values at A2 and A3 were 0.13 and 0.14, respectively, for this 5-minute measurement interval. The transport activity at 0.8 m height on the stoss slope was due only to single grains moving through the LPC laser beams at random intervals, but the more persistent activity above the *Ammophila* canopy relative to the *Elymus* alliance canopy suggests that individual sand grains may have bounced off the *Ammophila stems* and rebounded to higher heights than was possible for the shorter and more rigid *Elymus* plants. Project personnel reported feeling sand grains on their faces on the dune crest above the *Ammophila* canopy, but no such effect was noted for the *Elymus* canopy. The source of these grains was evidently not the beach because virtually no grains were sensed at 0.8 m at A1 and E1. We speculate that there may have been local entrainment opportunities presented by sand patches interspersed among areas of semi-continuous plant cover, especially during turbulent wind gusts or alternatively, the particles sensed by the LPCs were not sand grains but bits of organic debris.

Discussion

Influence of plant canopy type on wind flow over foredunes

The results from this study demonstrate how the structure of wind flow across foredunes is strongly influenced by the complex interaction of topographical slope with the type of vegetation cover. The influence of dune topography on wind-field modification has been studied extensively in the field and in wind tunnels, but the effects of dune vegetation are less well understood (see Hesp et al., 2019, Charbonneau et al., 2021, Schwarz et al., 2021, and Walker et al., 2021, and references therein for recent reviews).

In general, when a wind field traverses a sandy beach and encounters a bluff body such as a dune or coastal cliff, an adverse pressure gradient develops in front of the toe or base that leads to flow deceleration and alteration of the turbulence characteristics in the boundary layer (Bauer et al., 2013; Walker et al., 2009a; Hesp et al.,2009, 2013). However, as the streamlines move up the stoss slope, they are compressed leading to flow acceleration toward the crest where a near-surface overspeed region is often found (Walker et al., 2009b; Hesp and Smyth, 2016). The degree of flow acceleration depends on the height of the dune as well as the steepness of the stoss slope, but is most pronounced with shore-perpendicular wind approach angles (Arens et al., 1995; Hesp et al., 2015). When the wind approaches the dune obliquely, the degree of flow acceleration is reduced because the apparent slope angle decreases along with streamline compressional effects. With oblique winds, topographically induced wind steering becomes of greater importance. Near-surface streamlines approaching the toe region tend to be deflected alongshore, especially in front of scarped foredune profiles (Bauer and Wakes, 2022), whereas the higher streamlines are steered toward a more shore-perpendicular trajectory as they traverse the stoss slope and approach the crest (e.g., Bauer et al., 2012; Hesp et al., 2015; Walker et al., 2017; Piscioneri et al., 2019; Hesp and Smyth, 2021; Walker et al., 2021).

Flow acceleration and steering are also strongly influenced by the character of surface roughness on the stoss slope of the foredune, which is why it is important to investigate the influence of different plant canopy types. The dune topography imparts form drag whereas the vegetation dictates surface (skin) friction, and both effects interact on vegetated foredunes, usually in mutually reinforcing ways. The effect of the *Ammophila* versus the *Elymus* alliance canopies on wind steering in this study was particularly evident (Figure 9) with the taller, denser stand of *Ammophila* strongly shifting the obliquely-incident wind approach angles (below about 0.5 m on the stoss and crest) to essentially shore-perpendicular trajectories. This was not as pronounced for the *Elymus* canopy, despite essentially identical apparent dune profiles. Higher in the boundary layer at 1.6 m height, the steering was much less extreme than closer to the surface, but still more evident over the

Ammophila (15°-20°) than over the *Elymus* (10°-12°). These trends indicate that the enhanced frictional resistance due to the vegetation canopy operates in a manner that is complementary to topographic slope in steering wind streamlines across the surface of foredunes, and that the influence is more pronounced for taller and thicker stands of plants such as *Ammophila*. This has clear implications for sediment transport from the beach to the foredune crest because the transport pathways up the stoss slope are mediated in complex ways by the presence, patchiness, morphology and density of vegetation covers as well as topographical irregularities and slope transitions.

The character of plant morphology and stand density also has a pronounced effect on wind speed. The presence of a vegetation canopy imparts frictional resistance to the near-surface flow field, leading to momentum extraction and stagnation within the canopy itself. The height at which flow acceleration due to streamline compression occurs depends on the character of the vegetation canopy. The wind speed profiles shown in Figures 7 and 8 indicate that the effect is rather different for the *Ammophila* canopy than for the *Elymus* canopy. In both instances, the wind speeds measured well above the plant canopy (at 1.6 m) were accelerated relative to the incident reference conditions measured on the beach at the same height due to topographical influences (i.e., there was compression-induced speed-up on the stoss slope that increased to the crest). Over the shorter and more open *Elymus* alliance cover, this flow acceleration or speed-up was apparent at a height of 0.5 m, which is close to the tops of the plants. In contrast, the taller and denser *Ammophila* cover yielded a 50-70% reduction in wind speed at 0.5 m relative to the beach reference profile because these measurements were taken deeper within the canopy cover. Nearer to the ground (at 0.15 m), both vegetation canopies were equally effective in causing near stagnation conditions. Very similar profile differences were found by Hesp et al. (2019) when comparing flow within canopies of differing plant densities.

In order to better illustrate the differences in frictional resistance imparted by the *Ammophila* and *Elymus* canopies, the wind speed profiles from the crest towers

(CTA and CTB) shown in Figure 7 at peak wind were further analysed by deriving estimates of shear velocity (u_*) and roughness length (z_o) following the protocols in Bauer et al. (1992). The values are shown in Table 1. Given that the wind speed profiles from the foredune crest were segmented and non-logarithmic, it is understood that this approach of using the law-of-the-wall to derive values for u_* and z_o is strictly not applicable. Therefore, these values of u_* and z_o must be interpreted with great caution, and they are not presented here as being representative of classic boundary layer flow over a flat, homogenous surface. Rather, they are intended to demonstrate how different the flow conditions are over the two vegetation canopies.

Two regressions were performed: (a) using all the anemometers including those close to the surface (i.e., ignoring the kinked nature of the profiles); and (b) including only the upper five anemometers above the vegetation canopy (i.e., the log-linear segments only, for which the regression approach is more justifiable). The beach reference profile (BT) over the smooth sand surface had a log-linear form, and the regression analysis indicates that the incident wind field had a shear velocity of 0.49 m s^{-1}, which is typical for a moderate wind. This value is slightly above the threshold condition required to sustain transport of medium-size sand. The roughness length at that time was approximately 0.37 mm, consistent with the fact that sediment transport was active and that there were small ripples on the backshore surface.

TABLE 1 HERE

The wind speed profile measured at the foredune crest in the *Elymus* alliance (CTE) had shear velocity and roughness lengths that were not dissimilar to those on the beach (Table 1), despite the vegetation canopy having a much larger characteristic length scale (0.65 m) than sand (0.23 mm). When the lowermost anemometer was included in the regression, the significant reduction in wind speed at that height yielded a slightly larger value of the shear velocity (0.61 m s^{-1} versus 0.49 m s^{-1} on the sandy beach), consistent with the enhanced friction induced by the vegetation canopy. Surprisingly, the roughness lengths were similar. However, when the lowermost anemometer was eliminated from consideration and only the log-linear segment above the canopy was included in the regression, the shear velocity and roughness length values were much smaller. This suggests that much of the induced shear from the vegetation canopy was restricted to a zone below a height of about 0.5 m of the boundary layer, yielding a distinct kink in the profile (as seen in Figure 7B). The zone above approximately 0.45 m follows a log-linear trend that is typical of flow over a hydrodynamically smooth surface, which is contrary to the large relative roughness of the plant canopy itself. Thus, the log-linear shape of the profile is somewhat 'accidental' in the sense that streamline compression and flow acceleration in the region immediately above the canopy yielded local wind speed-up that counter-balanced the expected speed reduction due to surface friction from the *Elymus* canopy. This highlights the interpretive risks associated with applying the law-of-the-wall indiscriminately to wind speed profiles on foredunes.

The wind speed profiles measured at the foredune crest over the *Ammophila* canopy were very different from the *Elymus* (Figures 7 and 8) because the characteristic length scale was greater for *Ammophila* (1.01 m) than for the *Elymus* (0.65 m) and because the plant densities were thicker closer to the ground surface. The induced frictional resistance was therefore more extreme over the *Ammophila* canopy (Table 1), and the influence extended to well above 1 m height. Incorporating only the upper five anemometers in the regression yields exceptionally large values for shear velocity (3.17 m s^{-1}) and roughness length (0.32 m), indicating intense shearing action in the zone between 0.5 m and 1.6 m height. The vertical distribution of wind speed above 0.35 m from the ground follows a log-linear relationship, suggesting that the shear stress is evenly distributed with height, but the constant downward flux of momentum does not extend to the ground surface. The morphology of *Ammophila* is such that it becomes less dense with height and the stems bend and wave easily in the wind, thereby allowing wind to penetrate into the upper portions of the canopy, unlike what occurs in the more rigid *Elymus* canopy. During sustained wind gusts, the *Ammophila* stems bend over thereby presenting a streamlined ‘surface’ to the wind that is akin to skimming flow conditions (Nepf and Ghisalberti, 2008; Marjoribanks et al., 2014; Hesp et al., 2019).

Below about 0.5 m, the *Ammophila* stems are more rigid and densely packed than above, which induces flow stagnation close to the ground. Including the lowermost anemometers in the regression yields only slightly smaller values of shear velocity and roughness length, despite the kinked nature of the speed profile, which strictly invalidates the use of the law of the wall. Incorporating a displacement length in the analysis of these wind speed profiles provided slightly different values for shear velocity and roughness length, but the general outcome was the same with the *Ammophila* canopy yielding much greater overall frictional resistance to the flow than the *Elymus* alliance, and both canopies presenting greater roughness than the native sand on the beach.

In combination, these results suggest that the influence of the taller *Ammophila* canopy on the wind field manifests in two primary ways: (1) a near-surface zone (below about h/2 where h is the average plant height) of essentially stagnant air; and (2) an upper zone extending from h/2 to well above the canopy where there is a log-linear layer characterized by a very steep wind speed profile. The latter suggests that the frictional resistance induced by the plant canopy is focused at a height of about h/2, which acts essentially like a roughness plane because of the increasing plant densities and stem rigidities below that height. In addition, the wind shearing action is evenly distributed from h/2 to the upper parts of the measured profile (1.6 m or 3h/2), implying a relatively thick shear layer with intense shearing action. The measured values of ***RSS*** (Figure 11A) at 0.5 m were very small in comparison to those at 1.6 m, as were the ***TKE*** values (Figure 12A), which reflects the different character of turbulence in the zone below h/2 where the flow is stagnant, and the zone above h/2 where the shearing action takes place.

In contrast, the measurements within and above the *Elymus* alliance canopy, which is characterized by a more rigid morphology but of shorter height and more open structure, suggests that the flow and nature of turbulence were rather different than for the *Ammophila*. The wind speed profiles (Figure 7B and 8B) show that the near-surface wind speed was very small, just as with the *Ammophila*. Similarly, the values of RSS (Figure 11B) were approximately the same, indicating a lower stagnation region with little shearing action. However, the values of ***TKE*** on the stoss (1.2 $m^2 s^{-2}$) and crest (1.6 $m^2 s^{-2}$) within the lower regions of the *Elymus* were much greater than those measured in the *Ammophila*, (0.7 $m^2 s^{-2}$ on the stoss and 0.25 $m^2 s^{-2}$ at the crest), which suggests that wind is able to penetrate the *Elymus* canopy, almost reaching the ground surface, not as a sustained mean wind but in the form of positive and negative fluctuations around a small mean wind. This random gustiness in the near-surface wind has the potential to mobilize sand grains but not to transport them any great distance—it is very much a localized phenomenon that depends on the patchiness of the plant assemblages.

Unfortunately, there was insufficient information from the *Elymus* profiles to indicate at what height the lower stagnation zone begins to transition into the outer zone. The speed profiles in Figure 7B and 8B show that this occurs somewhere between 0.15 m and 0.37 m. Above 0.45 m, the speed profiles are log-linear, likely by accident because of the interaction of topographic speed-up and frictional resistance from the plant canopy. The kink in the profile occurs at about the same height above the ground (about 0.4 m) as with the *Ammophila*, but at a greater relative height of about 3h/2 rather than h/2. Because the slope of the log-linear region above 0.45 m is suggestive of a very smooth hydraulic surface at its base, effectively, the shear distribution is even with height but of relatively small stress values (Table 1). This is corroborated by the ***RSS*** values measured at 1.6 m (Figure 10B, which are particularly small on the stoss slope). The TKE values (Figure 11B) measured at 1.6 m across the *Elymus* canopy are uniformly small across the entire dune profile, indicating that the *Elymus* alliance does not influence the nature of the turbulent fluctuations well above the plant tops. Over the *Ammophila* canopy, however, there was a decrease in TKE values from the dune toe to the crest (Figure 10A), which clearly points to the progressively increasing influence of frictional resistance in transferring some of the mean motion into the fluctuating quantities in the upslope direction.

Influence of plant canopy type on sand transport – implications for dune morphodynamics

The LPC measurements provide insights into how vegetation cover can influence sediment transport potential across the foredune stoss slope. As shown in Figure 12, the sediment transport intensity on the beach by the Beach Tower was continuous (AP=1) with the largest average values (13,544 counts s^{-1} m^{-1}). Transport intensity decreased in the landward direction with average values of 8,964 counts s^{-1} m^{-1} on the dune ramp and about 3,000 counts s^{-1} m^{-1} at the dune toe (A1 and E1). There was no vegetation at any of these instrument stations, so the spatial trends are entirely topographically induced by the slowing of incident wind due to the adverse pressure gradient that builds in front of a large bluff body such as a foredune (Bauer et al., 2009, 2012; Hesp and Smyth, 2021; Bauer and Wakes, 2022). Increasing slope steepness up the foredune ramp also influences the progression of sediment transport in the landward direction.

Up the stoss slope, sand transport declined abruptly within the vegetation canopy, with average near-surface values of only 4 counts s^{-1} m^{-1} and AP = 0.237 at mid-stoss (E2), trending to 0.17 counts s^{-1} m^{-1} and AP = 0.007 at the crest (E3). Despite strong winds on the stoss and crest of about 10-12 m s^{-1} (measured at 1.6 m above ground) and shear velocities in excess of the transport threshold, sand delivery from the beach and onto the stoss slope of the dune was arrested by the presence of the vegetation canopy. Even though surface LPC measurements were not available at A2 and A3, all indications are that *Ammophila* should have had an even more pronounced influence on the reduction of transport within only a short distance of the leading edge of the vegetation canopy, as has been demonstrated by field and wind-tunnel experiments (Hesp et al., 2019).

In relation to the dominant pioneer species present in our study site, namely, *Elymus mollis* and *Ammophila arenaria*, several recent studies have speculated on the effects that these different plant species might have on foredune morphology, resilience, and coastal vulnerability. For example, a wind tunnel experiment by

Zarnetske et al. (2012) found that *Elymus* displayed a greater sand capture efficiency compared to *Ammophila*. However, Hacker et al., (2019) noted that *Ammophila* species have a clumped nature and therefore would trap more sand than vegetation species with lesser degrees of these characteristics. Field observations indicate that *Ammophila arenaria* tends to produce a high density of tillers in response to increasing sand supply, and this, in turn, suggests that *Ammophila* might be more efficient at capturing sand over the long term via a positive feedback mechanism between sand supply and plant growth. According to Hacker et al. (2019: 13), this explains why *Ammophila* foredunes are "inherently taller and wider, and have better coastal protection properties". Hacker et al. (2019) further noted that, when comparing two invasive marram species, *A. arenaria* produced steep, narrow foredunes while *A. breviligulata* (lower density, thicker shoots, greater lateral growth) produced lower, wider foredunes.

Although a taller foredune morphology (especially one with large volume and width) might seemingly reduce coastal vulnerability by providing improved flood protection, the long-term effectiveness of foredunes as barriers depends on their ability to maintain their form in the face of rising water level impacts and increasing severity and frequency of coastal storms (Davidson-Arnott and Bauer, 2021). As such, foredune resilience – or the ability of a foredune to rebuild and recover its morphodynamic shape and function following erosive events – is perhaps a more important consideration than simple dune morphometric attributes controlled by vegetation canopies alone. Although our study results are short-term and do not inform dune recovery, they do indicate that sand deposition occurs preferentially at the dune toe and lower stoss slope when there is vegetation cover on the stoss slope, leading to seaward progradation of the dune form during inter-storm intervals.

Summary and Conclusions

The field measurements described herein demonstrate how two contrasting vegetation canopies (*Ammophila* versus *Elymus* alliance) modify the incident wind field as it traverses the stoss slope of a foredune. The two vegetation types were side-by-side, and the apparent dune morphology was essentially identical on the two instrument lines running through the two canopies. The percent ground cover of both lines was roughly similar on the lower stoss slope, around 50% different in the mid stoss, and 25% different on the upper stoss slope of the foredune with *Ammophila* being generally denser throughout. The *Ammophila* was taller (about 1 m), more flexible, and more densely packed than the *Elymus* alliance which was shorter (about 0.65 m) and had a more open but rigid structure. These differences allowed us to discriminate the influence of the plant covers from that of the topographically-induced, boundary-layer modifications (i.e., steering, streamline compression, flow acceleration), which are generally quite well known. On this basis, we find the following:

1. There was a systematic increase in wind speed measured at 1.6 m (well above plant height) from the toe to the crest for both plant canopies, due mainly to streamline compression and flow acceleration. However, the shapes of the wind speed profiles over the *Ammophila* were substantively different than those over the *Elymus*. The former had a steep gradient that extended from a height of about h/2 (i.e., 0.45 m) upwards in log-linear fashion, which suggests an even distribution of shearing action that begins within the upper portions of the canopy and persists to at least 1.6 m height (i.e., 3h/2). Thus, the shearing zone was quite deep, approximately equal to h. The *Elymus* profiles also had a log-linear upper segment, but it extended from a height of about 3h/4 (i.e., 0.45 m) to 1.6 m and had a much gentler log-linear slope, which indicates that there was relatively little shearing action taking place above the canopy top. The shearing zone in *Elymus* was therefore very thin and confined to the top ¼ of the canopy, which is very different than for *Ammophila* where the shearing zone extended from deeper within the canopy to well above the canopy top. Vertical profiles of ***RSS*** and ***TKE*** are consistent with this interpretation.
2. Under the highly oblique wind approach angles (approximately 55^{o} from shore-normal) during this experiment, the degree of topographically-forced

and vegetation-enhanced flow steering was significant. On the mid-stoss slope, in the *Elymus* canopy there was a shore-perpendicular shift of about 35°-40° near the surface, which decreased progressively with height. At the dune crest, the steering amounted to about 10° at a height of 1.6 m. In contrast, the flow steering in the *Ammophila* canopy was more extreme, turning the wind to shore-perpendicular close to the ground on the mid-stoss and to a deviation of about 25° at 1.6 m on the dune crest. Thus, the taller and denser *Ammophila* canopy had a significantly greater effect on wind steering than the shorter *Elymus*, consistent with differences in aerodynamic roughness that these plant canopies present to the wind field.

3. Deep within both canopies (at 0.15 m) there was a zone of flow stagnation with greatly reduced wind speed. Within the *Ammophila* canopy, this flow stagnation zone is characterized by slow mean wind speed and greatly reduced values of ***RSS*** and ***TKE***. Within the *Elymus* canopy, there are equally slow mean wind speeds and small ***RSS*** values, but ***TKE*** values are much larger. This implies that wind was unable to penetrate to the ground surface through the *Ammophila*, but did so within the *Elymus* canopy in the form of positive and negative velocity fluctuations that counter-balance each other. These enhanced turbulent fluctuations in the *Elymus* canopy may have ramifications for local sediment entrainment potential.
4. Sediment transport intensity, as measured by LPC particle counts, was continuous and energetic on the beach, but decreased progressively to the dune toe due to slope effects and wind speed reductions induced by an adverse pressure gradient in front of the dune. The transport intensity dropped to essentially zero on the mid stoss slope because of near-surface wind stagnation in the lower portions of the plant canopy. Negative flux divergence from the beach to the mid stoss implies significant sediment deposition, leading to sand accumulation on the dune ramp and lower stoss. From the mid stoss to the dune crest, there was virtually no sediment transport.

The results of this study demonstrate how a dense cover of vegetation modifies near-surface boundary layer flows and turbulence characteristics in ways that complement and enhance what occurs by topographical forcing alone. The implications are that sediment transport across the beach leads to deposition at the foredune toe and lower stoss slope, with virtually no sedimentation on the upper stoss or crest, at least for moderate wind speeds similar to those encountered during this experiment. As a consequence, the dune profile can be expected to prograde seaward rather than build vertically under obliquely incident wind conditions, presuming that intervening storms do not yield wave-induced scarping of the toe region.

Given the density, morphology and height differences between the two plant canopies, and consequently their respective aerodynamic properties, one would expect that the *Ammophila* would trap sediment over a shorter distance compared to the *Elymus* canopy in strong wind conditions—those that have the greatest potential to induce morphodynamic changes to the foredune. But this has yet to be tested, and it would be useful to conduct an experiment similar to ours during much more intense wind and transport conditions, especially for more directly onshore wind approach angles. In order to understand foredune maintenance and evolution, it is critically important to capture events that yield sediment delivery to the crest of vegetated foredunes and beyond. But there are several challenges associated with such an objective.

First, our existing technologies are limiting as regards measurement of mass transport at high frequencies. Proxy data from particle counters (e.g., Wenglors, Sensits, Safires, Saltiphones) are useful, but count-to-mass conversions remain problematic. Wind measurements are also challenging within vegetation canopies because current sensors are too bulky and cannot be easily deployed near the ground surface within thick vegetation canopies. Moreover, the cost of instrumentation is often prohibitively expensive, which reduces our capacity to acquire data that is spatially distributed (in three dimensions) and sufficiently representative of complex foredune surfaces.

Second, the methods by which vegetated surfaces are parameterized remain crude, often relying on manual measurements or visual assessments in the field or from photo mosaics. The point clouds derived from terrestrial LiDAR may present an opportunity to characterize the relative flow ‘porosity’ of plant canopies. This is critically important when trying to assess the influence of different types of plant canopies (e.g., species, density, phenology, senescence) on wind modification and sediment transport potential, but current understanding remains limited.

Third, it requires occupying a field site for a considerable length of time so as to capture a broad range of wind events with differing wind speeds and approach angles. This rarely happens, and it remains a challenge to integrate place-and-time specific knowledge derived from intense field experiments such as ours into grand models of foredune evolution and maintenance over periods of years to decades (e.g., Walker et al., 2017). There is great need for long-term monitoring studies across a range of beach-dune environments that are complemented with repetitive field experiments at fixed locations focusing on short-term processes spread across a range of conditions. This combination is essential in understanding the context in which to properly interpret the process results and how they inform foredune evolution. But this is expensive, and funding agencies are reluctant to commit to long-term investments.

It is interesting that, as aeolian process geomorphologists, we tend to devote an inordinate amount of time, energy, and expense to measuring and understanding the wind field (e.g., speed, direction, turbulence) and comparatively little effort to quantifying sediment transport, when in fact, it is the perpetual rearrangement of sand grains that is the central cause of geomorphic change in beach-dune systems. There are, of course, causal linkages between fluid motion and sediment transport, which are of great interest and importance for predictive modeling and natural resource management. But one wonders whether our science might benefit and advance more rapidly from a re-focusing of our primary attention and efforts away from the wind and toward better sediment transport sensing technologies and measurements. In particular, we lack a general understanding, in many cases, of the types of sediment transport events (and their timing) that lead to significant geomorphic change on foredunes (c.f., Delgado-Fernandez and Davidson-Arnott, 2011) even though there is typically detailed information on wind climatologies along most of the world’s coastlines.

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