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THE FETCH EFFECT ON AEOLIAN SEDIMENT TRANSPORT ON A SANDY BEACH: A CASE STUDY FROM MAGILLIGAN STRAND, NORTHERN IRELAND

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Abstract

Experiments were conducted on Magilligan Strand, Northern Ireland, to assess the influence of the Fetch Effect on aeolian sediment transport. During each experiment surface sediments were uniformly dry and unhindered by vegetation or debris. The leading edge of erodible material was well defined, with the limit of wave up-rush demarcating the wet-dry boundary; the work was conducted during low tides. A number of electronic and integrating traps were utilised, with two ultrasonic anemometers used to measure wind direction and velocity at 1 Hz. The combination of 1^{o} direction data and trap locations resulted in a range of fetch distances, from 2 – 26 m. Data integrated over 15-minute intervals (corresponding to the integrating trap data) revealed a distinct trend for all the experiments. An initial rapid increase in the transport rate occurred over a short distance (4–9 m). This maximum transport rate was maintained for a further 5-6 m before a steady decay in the flux followed, as fetch distance increased. A measured reduction in wind speed (6-8%) across the beach suggests a negative feedback mechanism may be responsible for the diminishing transport rate: the saltating grains induce energy dissipation, thus reducing the capability of the wind to maintain transport. For one experiment, the presence of compact sediment patches may also have contributed to the reduction of the transport rate. The decay trend calls into question the utility of the fetch effect as an important parameter in aeolian studies that seek to understand sediment budgets of the foredune-beach zone.

Introduction

A variety of parameters affect aeolian sediment transport, such as wind speed and direction, grain size, bed slope or bedform geometry (Sherman, 1995). Although the mechanics of aeolian sediment transport are quite well understood, applying this understanding to complex natural settings remains a major challenge. One reason for this may be the existence of rarely considered system ‘effects’, such as self-organised criticality (McMenamin *et al.*, 2002), inertial effects (Jackson, 1996b), or the fetch effect (Gillette *et al.*, 1996).

The fetch effect is generally attributed to downwind saltation avalanching. After initial particle entrainment, each grain in motion dislodges more grains as it returns to and strikes the surface, resulting in an exponential growth in the sediment flux and eventually a saturated transport condition arises (Anderson and Haff, 1991, Gillette *et al.*, 1996). The distance required to achieve a saturated condition for a given wind velocity and sediment size, has been termed the ‘critical fetch’ (Bauer and Davidson-Arnott, 2002) at which point the transport system is considered to be operating at its maximum capacity. This rate of transport does not persist downwind as the grains in motion extract momentum from the wind, with near-surface wind speed slowing, which in turn reduces the transport capacity of the system (Neuman and Nickling, 1995, Walker and Nickling, 2002). Bauer *et al.* (2009) describe the reduction of near surface wind speed downwind as the ‘internal boundary layer effect’, where the total shear is distributed across a vertically expanding internal boundary layer rather than near to the surface. Gillette *et al*. (1996) argue that saltation avalanching only explains the fetch effect on a spatial scale of tens of metres, proposing two mechanisms by which the effect may be extended over greater spatial scales. The first is through the Owens effect - an aerodynamic feedback mechanism - whereby saltating grains increase the aerodynamic roughness height, resulting in greater momentum transfer back to the surface, increasing the sediment flux and consequently raising of the roughness height. The second is through a reduction in the threshold friction velocity with distance downwind, due to a change in sediment resistance to erosion (i.e., sandblasting of surface crusting). Gillette *et al.* (1996) were

investigating factors controlling soil erosion on a dry lake bed. Bauer and Davidson-Arnott (2002) postulate that these two mechanisms are likely to be less important on beaches. Delgado-Fernandez (2010), in a review of the fetch effect, cautions that the role of the fetch effect may be difficult to isolate on beaches where other important variables may exert a more dominant role in controlling aeolian sediment transport. Moisture content in particular is considered important in extending critical fetch distances (Bauer *et al.*, 2009, Davidson-Arnott *et al.*, 2005, Davidson-Arnott *et al.*, 2008). Topographic variation on beach surfaces that induce secondary airflow patterns and non-homogenous sediments will also add to the complexity in beach settings (Anthony *et al.*, 2006, Bauer, 1991, Van Der Wal, 2000, Walker *et al.*, 2006). In certain settings it may be argued that variables controlling sediment supply may govern the role of the fetch effect, thus limiting the utility of the critical fetch concept .

Investigations of the fetch effect on beaches follow two approaches; 1. comparing fetch distance (the stretch of beach over which wind has travelled, from a leading edge of erodible material, to any general point downwind) to transport rates (Anthony *et al.*, 2006, Bauer *et al.*, 2009, Davidson-Arnott and Law, 1990, Nordstrom and Jackson, 1992, 1993) and 2. comparing beach widths to foredune deposition rates (Davidson-Arnott and Law, 1996, de Vries *et al.*, 2012, Delgado-Fernandez, 2011, Delgado-Fernandez and Davidson-Arnott, 2011, Keijsers *et al.*, 2014, Lynch *et al.*, 2008). These studies have found that firstly, the fetch effect is observable on sandy beach systems, with the critical fetch increasing with wind speed or with less than optimal surface conditions, and secondly, in a more general context, that wider beach width results in increased sediment supply to the foredunes. The interactions between the two variables, critical fetch and beach width, are of course important in attempting to understand the influence of the fetch effect on aeolian sediment supply to coastal foredunes. During shore-normal winds, a short critical fetch in relation to beach width, increases the area of maximum potential transport across the beach, while a

longer critical fetch helps limits potential supply to the foredunes. In the extreme condition critical fetch may exceed beach width and the transport system never reaches its full potential.

This paper aims to investigate the fetch effect under a constrained set of environmental conditions within a natural beach setting in order to decouple the fetch effect from other controlling factors. To constrain the set of variable under consideration, a case study methodology is employed limiting the research to one site. One objective of the study was to obtain sediment flux measurements at sufficient spatial resolution to adequately measure the fetch effect, recording the avalanching growth and downwind saturated transport conditions. This builds on earlier work by some of the authors (Jackson and Cooper, 1999) who found that fetch distance was unimportant when sediment supply was abundant and the system had already reached saturation levels of transport.

Study Area

The study site was located on Magilligan Strand, Northern Ireland (Fig. 1). The beach is approximately 6 km in length and extends from Magilligan Point, at its north-western extremity, to Benone Strand to the southeast. It faces northeast on the margin of the Atlantic Ocean, and forms the seaward edge of a large Holocene foreland (Wilson *et al.*, 2004). The beach is flat and dissipative, up to 100 m wide during low tide, and has a mean spring tidal range of 1.6 m (Jackson *et al.*, 2005). Beach sediments consist of well-sorted quartz sands with a mean grain size of 0.17 mm. At the time of the experiments the area of beach under investigation was unvegetated with little debris or shell content. No bedforms larger than ripples (<2 cm in height) were present and the surface sediments were loose and dry. For the 17 August 2006 study, an area consisting of patches of more compact sediment was evident, extending from the mid-beach to the dune foot. The slopes over which transport took place ranged from -1^{o} to 3^{o}. While the predominant wind for the site is from the southwest, all the experiments described here were conducted under northerly winds (onshore winds), which ranged from approximately 3 to 8 m s^{-1}. The research was part of a larger

field study into beach-dune dynamics at the site (Lynch *et al.*, 2006, 2008, 2009, 2010). As the fetch experiments here required northerly winds and a dry upper beach, suitable conditions were very limited; three separate datasets were gathered.

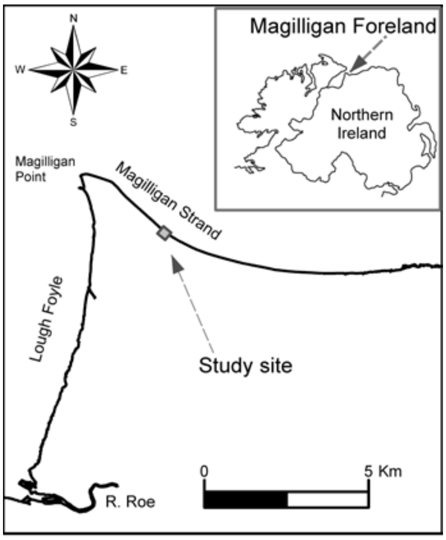


Figure 1. Study site location.

Methodology

The field experiments were carried out at Magilligan Strand on three occasions, 7th and 8th July 2004 and 17th August 2006. Datasets of 2.5 hours, 3 hours and 1 hour respectively were obtained, consisting of 1 Hz wind speed, direction and sediment flux measurements. Tide data from the Portrush tide gauge (OD, Belfast) and temperature data from a weather station at Magilligan Point are used (17.5 km and 2.5 km respectively from the site) (Table 1).

Experiment	Tidal cycle	Experiment start time	Last high tide time / height (m)	Last low tide time / height (m)	Temp (°C) start / end
17 August 2006	Neap tides	17:45	11:15 / 1.42 m	17:00 / 0.58 m	15.3 / 14.3
8 July 2004	Moving from spring to neap tides	13:25	09:45 / 1.06 m	15:30 / 0.60 m	13.1 / 13.7
7 July 2004	Moving from spring to neap tides	13:30	09:15 / 1.27 m	14:45 / 0.60 m	14.3 / 14.1

Table 1 Tidal and temperature variations over the duration of the experiments.

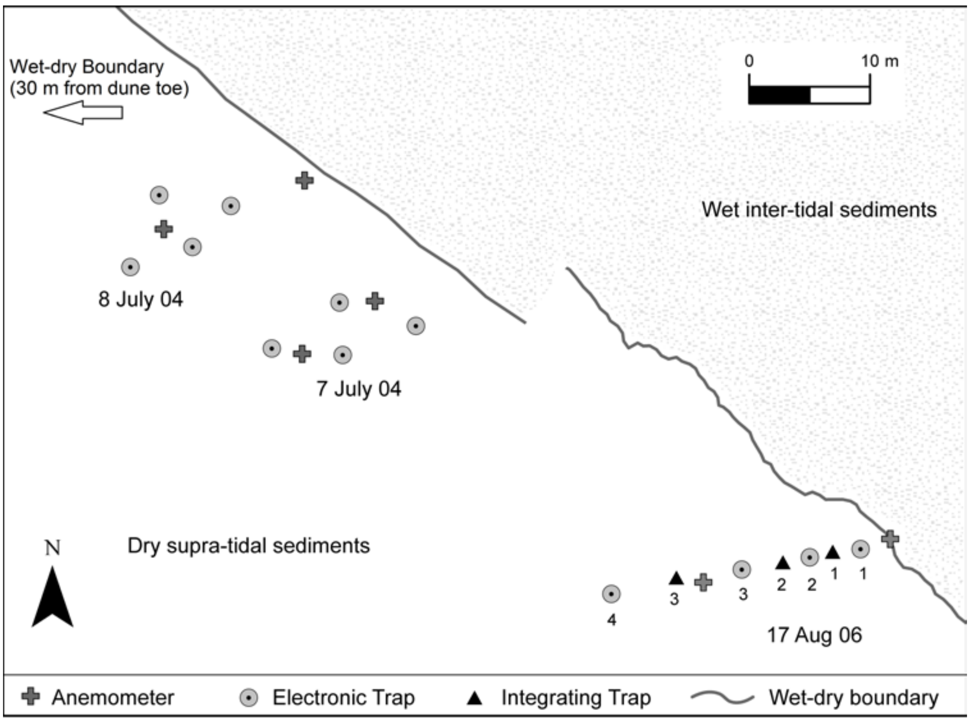


Figure 2. Instrument locations.

Sediment transport

The electronic trap (ET) of Jackson (1996a) was utilised to collect 1 Hz measurement of sand flux. This horizontal trap funnels sediment into a bucket - mounted on a load cell - where it is recorded sediment load at a resolution of 1 g. When a pre-determined weight is reached, the bucket tips and is replaced by an empty bucket. Four of these traps were deployed for each experiment. The earlier fieldwork, in July 2004, employed an irregular array of traps (as a result of uncertain forecast wind directions), while in the August 2006 experiment a linear arrangement of traps was selected (Fig. 2) when a more uniform wind direction was expected. The latter experiment also made use of three integrating horizontal traps (IT). These traps are essentially the outer shell of the electronic traps with the tipping bucket mechanism replaced by a plastic container. This container was replaced once every 15 minutes, with the content double bagged for sediment analysis and weighing the following day.

Wind

Wind speed and direction were recorded at a height of 1 m (during 7th and 8th July 2004) and 0.5 m (during 17th August 2006) with two ultrasonic anemometers (Windsonic by Gill Instruments Ltd.). On each of the experimental days, the surface sediments were dry above the high tide line and very wet below it. An anemometer was placed at this location (wet-dry boundary (WDB)), to assess the wind speed before sediment entrainment was initiated. The second anemometer was placed further up the beach, centred among the sediment traps.

Fetch distance

On 17th August 2006, fetch distances were calculated using a remote-sensing technique (Lynch *et al.*, 2006) employing a digital camera, GPS surveying, and a GIS software package to produce a rectified image of the beach surface. From this, direct measurements of the wet-dry beach boundary can be combined with wind direction measurements to determine fetch distance. The

WDB was also surveyed directly using a GPS during the 2004 experiments because the remote sensing technique was only in the development stages at that time.

Sediment characteristics

Four surface samples (upper 2 mm) were taken before and after the experiment on 17th August 2006, along a cross-shore transect between the WDB and the last electronic trap (ET 4). Moment measures for these samples were obtained using a settling tube (Fromme, 1977). Percent moisture content (w/w) was also assessed. Analysis of the sediment collected by the integrating traps allowed for the characteristics of blown sand to be compared to these surface samples (Table 2).

17:30	Mean grain size (mm)	% Very fine sand	% Moisture
~1 m*	0.15	15	0.9
~7 m*	0.16	11	0.6
~12 m*	0.16	11	0.4
~18 m*	0.18	5	0.6
18:00			
~1 m*	0.16	11	1.5
~7 m*	0.17	7	0.4
~12 m*	0.16	12	0.4
~18 m*	0.17	8	0.5

Table 2 Surface sediments (17 August 2006). At 17:30 a shore-normal mean grain size gradient (0.15 mm – 0.18 mm) is evident. At 18:00 (after the transport event) a more even distribution of grain sizes occurred across the beach. The percentage of very fine sand in the samples show that smaller grain sizes were moved up the beach, with the two samples further up the beach (12 and 18 m) increasing their fraction of very fine sand and the two closer to the WDB (1 and 7 m) seeing a reduction. (*Landward of WDB)

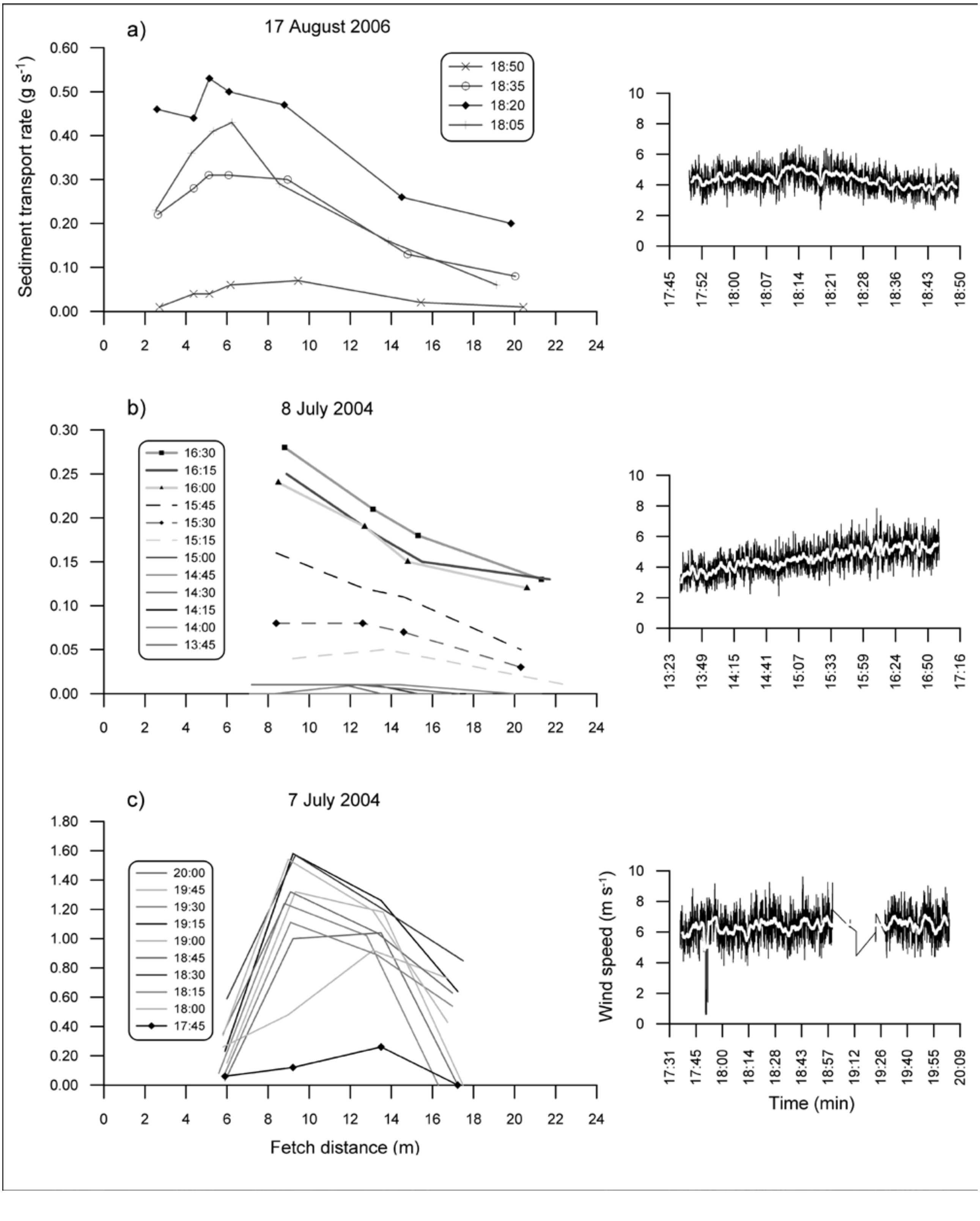
Results and Discussion

17th August 2006

A northerly wind direction during the experiment remained largely steady over the hour duration, ranging from 349^{o} to 45^{o}. This, combined with the trap placements, resulted in fetch distances ranging from 2.4 m to 26.8 m. Total sediment accumulation, over a 15-minute interval, was calculated for each of the four electronic traps. When these totals were graphed alongside the integrating trap results a distinctive trend was evident (Fig. 3). After an initial rapid increase in the transport rate a steady decay followed, as the fetch distance increased. The fetch effect is apparent here, with a maximum condition reached within first 5 to 7 m for the period up to 18:35. This transport capacity is not maintained and declines steadily until the transport rate at 20 m downwind of the wet-dry boundary is less than half that of the maximum reached.

7th 8th July 2004

Although more limited in fetch distance range, the earlier experiments reflect this trend. On 7th July 2004, the flux growth to a maximum was again achieved over a short distance (~ 9 m), with the saturated conditions lasting for approximately 5 m to a position 14 m from the WDB.



a)
17 August 2006
Sediment transport rate (g s-1)
18:50
18:35
18:20
18:05
b)
8 July 2004
16:30
16:15
16:00
15:45
15:30
15:15
15:00
14:45
14:30
14:15
14:00
13:45
c)
7 July 2004
20:00
19:45
19:30
19:15
19:00
18:45
18:30
18:15
18:00
17:45
Fetch distance (m)
Wind speed (m s-1)
Time (min)

A rapid decline in sediment flux followed. The 8th July 2004 experiment captured only the declining transport trend (presumably a maximum had been reached at a shorter fetch distance). The average wind speed for this run was 4.8 m s^{-1}, comparable to the 4.7 m s^{-1} average for the 17th August run. In contrast, a distance of 9 m was required for saturated conditions to be reached for an average wind speed of 6.8 m s^{-1} on 7 July 2004. As expected, the higher wind velocity necessitated a longer fetch distance to reach its full transporting potential. The wind direction during these experiment was from the north, ranging from 350° to 20° on the 7th and 345° to 5° on the 8th.

The relatively high sediment transport rates are attributed to sediment supply from the area between the sediment traps and last high tide line (WDB). An underlying assumption here is that no sediment was supplied from below this WDB. Each experiment was carried out close to the time of the low tide (necessitated by the need for northerly winds), leaving a wide expanse of beach below the WDB (Table 1). While the moisture contents in this area were not monitored, observations on the days of the study noted that the sediments remained wet for the duration of the experiments and no sediment transport was observed in this zone of the beach. The relative lack of drying in the area may have been due to the relatively low summer air temperatures, 13 to 15 °C (Table 1). Notwithstanding this assumption it is possible that the lower beach did contribute some sediment to the transport system.

The observed initial rapid growth in the transport rate for all three of the experiments may be attributed to the downwind cascade effect described by other authors (e.g., Anderson and Haff, 1991, Gillette et al., 1996). The decay in flux requires further consideration. In the controlled environment of a wind tunnel, Shao and Raupach (1992) report a similar growth/decay transport tendency with increasing distance. In the more complex setting of a natural beach, however, there are a greater number of variables at play. Of these a number can be assumed unimportant for these experiments. Temperature, humidity and atmospheric stability should not have varied over the

spatial scales involved; elements that impinge on the airflow dynamics and limit sediment supply to the system were largely absent e.g. vegetation, debris, shells; beach slope was essentially planar (2 to 3^{o} on 7th 8th July and –1 to 2^{o} on 17th August); and moisture content was less than 1% for all three experiments.

Although the sediments at the site were very well sorted, and mean grain size varied little across the beach on 17 August 2006 (Table 2), there is a discernible trend evident from the sediment analysis results. There was a shore-normal mean grain size gradient (0.15 mm – 0.18 mm) before the wind event (17:30), whilst after the event (18:00) a more even distribution of grain sizes occurred across the beach (Table 2). The percentage of very fine sand (0.125 to 0.0625 mm) in the samples show that smaller grain sizes were relocated up the beach, with the two samples further up the beach (12 and 18 m) increasing their fraction of very fine sand and the two closer to the WDB (1 and 7 m) seeing a reduction (Table 2). The samples taken from the integrating traps back up this progression, revealing that for each run the trap with the longest fetch IT3 captures sediment with the largest fines fraction (23%) and the lowest mean grain size (0.14 mm) (Table 3). This may suggest that the energy available to move the larger grains is diminishing at longer fetches as momentum is extracted from the airflow (IT3 and presumably ET4).

	Mean grain size (mm)					% Very fine sand					% Moisture				
	18:05	18:20	18:35	18:50	Avg.	18:05	18:20	18:35	18:50	Avg.	18:05	18:20	18:35	18:50	Avg.
IT1	0.15	0.16	0.15	0.16	0.15	19	12	16	13	15	0.4	0.3	0.4	0.6	0.4
IT2	0.16	0.16	0.15	0.15	0.15	14	16	16	16	16	0.3	0.3	0.3	0.5	0.4
IT3	0.15	0.14	0.15	0.14	0.14	23	22	22	25	23	0.3	0.4	0.3	0.6	0.4

Table 3 Aeolian transported sediments (17 August 2006). Samples taken from the integrating traps replicate the trends evident in Table 1, revealing that for each run the integrating trap with the longest fetch IT3 captures sediment with the largest fines fraction (23%) and the lowest mean grain size (0.14 mm).

This is further supported in the wind data, where the incoming velocity is consistently seen to decelerate by the time it reaches the downwind anemometer (Table 4). The cause of the velocity reduction could be a consequence of energy dissipation, where the incident wind energy is transferred to the saltating grains and in turn is expended in bed deformation due to inelastic collisions (Namikas, 2006). Because the initial fluid energy of the wind is quite low, this negative feedback may have been capable of significantly reducing the transport rate. This explanation is contrary to the 'Owens effect' which purports a positive feedback brought about by the saltating grains. Even in the absence of saltating grains the development of a new internal boundary layer as the fluid flow crosses the beach results in a reduction of shear stress at the surface (Bauer *et al.*, 2009). This 'internal boundary layer effect' offers further explanation for a reduction in transport potential downwind. On 17th August 2006, patches of more compact (less mobile) sediment may also have contributed to the decay in the transport rate. These patches would have reduced sediment supply to the system. There was no such variation in packing for the earlier experiments.

	Velocity avg. (m s^{-1}) (Wet/dry boundary)	Velocity avg. (m s^{-1}) (mid-beach)	Velocity deceleration
7-Jul-04			
17:45	6.3	6.0	5%
18:00	6.8	6.2	10%
18:15	6.5	6.0	7%
18:30	6.8	6.6	4%
18:45	6.7	6.3	6%
19:00	7.0	6.6	6%
19:15	7.4	7.0	6%
19:30	6.7	6.1	11%
19:45	7.0	6.6	6%
20:00	6.9	6.4	7%
Mean	6.8	6.4	7%
8-Jul-04			
13:45:00	3.8	3.5	6%
14:00:00	3.9	3.6	8%
14:15:00	4.3	4.0	7%
14:30:01	4.5	4.2	7%
14:45:00	4.6	4.3	6%
15:00:00	4.3	4.2	2%
15:15:00	4.8	4.6	4%
15:30:00	5.0	4.6	8%
15:45:01	5.1	4.9	6%
16:00:02	5.3	5.1	5%
16:15:02	5.3	5.2	3%
16:30:01	5.5	5.3	5%
Mean	4.7	4.4	6%
17-Aug-06			
18:05	4.8	4.4	8%
18:20	5.0	4.7	7%
18:35	4.8	4.4	8%
18:50	4.2	3.9	9%
Mean	4.7	4.3	8%

Table 4 Reduction of wind velocity across the beach. Incoming velocity consistently decelerated by the time it reached the downwind anemometer.

	07-Jul-04	17-Aug-06
Critical Fetch	9 m	4 m
Maximum Fetch	30 m	40 m
Beach length that experienced maximum sediment transport - Assuming maximum rate maintained indefinitely past the critical fetch point	21 m	36 m
Beach length that experienced maximum sediment transport - Actual	6 m	5 m
Percentage of over-predicted	350%	720%

Table 5 Fetch as a model parameter. Assuming maximum transport conditions downwind of the critical fetch point will lead to over-prediction of sediment supply to the foredunes.

A synopsis of the results clearly illustrates that assuming maximum transport conditions downwind of the critical fetch point would lead to over-prediction of sediment supply to the foredunes (Table 5). For the experiments reported here this amounted to 350% and 720% for the 7th July 2004 and 17th August 2006 respectively. While each of the three experiments were carried out under constrained conditions with little variability in moisture, slope and sediment size, it is probable that all of these could have played some role in reducing sediment flux in a downwind direction. What is clear from the data is that a downwind reduction in flux occurred, after an initial rapid increase. For the dry part of the beach covered with instrumentation there was no equilibrium transport state. As Bauer *et al.* (2009) noted, transport models assume equilibrium conditions, therefore in studies that seek to test and improve the models it may be appropriate to establish if the fetch effect or the internal boundary layer effect are important variables at the test site. Placement of traps in either of these zones where the system is in disequilibrium would yield less than optimal results.

The results presented here suggest that the while the fetch effect may occur under certain conditions, its influence may be restricted to just a few metres. On fine sandy beaches with abundant sediment supply it might therefore be suggested that it is unimportant (Jackson and Cooper, 1999). It may be that combined 'distance' effects - the fetch effect, the overshoot and the internal boundary layer effect - should be considered when trying to explain transport patterns across sandy beaches. Alternatively, the situation of greater beach width leading to improved sediment supply of the foredunes should simply be addressed as a supply issue (de Vries *et al.*, 2014). Some studies (e.g., Aagaard *et al.*, 2004) have linked the presence of beach-welded sandbars (swash bars) and nearshore sediment supply to increased supply to the foredunes. While this widening of the beach certainly increases fetch distance it is the availability of fresh dry sediment contained within inter- or supra-tidal parcels of sand (Nield *et al.*, 2011) or other depositionary entities that most likely increases the transport rate rather than dominant controls exerted by the fetch effect.

Conclusions

Time-integrated data revealed that fetch distance and sediment flux were inter-related with a distinctive trend evident in each of the experiments. Initial exponential growth of the transport rate to a maximum occurred over distances of 5 to 9 m (for average wind speed of 4.7 m s^{-1} and 6.8 m s^{-1}, respectively). This was followed by decay in the aeolian sediment flux as fetch distance increased. Two possible explanations were put forward for this decay; 1) a negative feedback mechanism whereby the saltating grains induce energy dissipation in the system, reducing the capability of the wind to maintain sediment entrainment and 2) non-ideal surface conditions limiting sediment supply to the system. This paper has highlighted a decay trend in aeolian transport over relatively short distances which may limit the use of critical fetch distance as a useful parameter in understanding aeolian processes on sandy beach systems. As a result, we urge caution in the application of the critical fetch distance, particularly in scenarios where fine sand material is abundant and the system has the potential of introducing feedbacks (fall-offs) in sediment flux. The use of critical fetch without consideration of transport decay may therefore introduce additional errors in aeolian flux predictions in sediment budgets of foredune-beach systems.

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