A review of the application of the fetch effect to modelling sand supply to coastal foredunes

Irene Delgado-Fernandez

•

Department of Geography, University of Guelph, Guelph, Ont., Canada

Abstract

The fetch effect is an increase of the aeolian sediment transport rate with distance downwind over an erodible surface. The first observations of the fetch effect go back 70 years and the concept has been widely used in a variety of landscapes. This paper reviews the present state of knowledge of the fetch effect, with particular reference to its application in coastal areas, and compares findings from theoretical, wind tunnel, and fieldwork experiments. While wind tunnel experiments tend to show critical fetch distances of a few metres, studies in natural areas show that measured critical fetch distance can exceed one hundred metres. There is supporting evidence pointing to the role of soil clods/crusts and moisture content in increasing critical fetch distances in agricultural and coastal areas, respectively. In coastal areas tradeoffs imposed by the geometry of the beach over which the wind is blowing and wind direction determine the available fetch distance and thus the sediment transport rate downwind. A major challenge which needs to be addressed is the development of robust equations for predicting both the critical fetch length and the increase in the sediment transport rate with distance on beaches. There is also a need to obtain field data on the combined effect of

moisture, angle of wind approach, beach width, and fetch length. Long-term monitoring using remote sensing techniques may provide valuable data to analyze the effect of fetch distances on the nature of transport events that deliver sediment from the beach to the foredune.

Keywords

Saltation; Equilibrium; Disequilibrium; Sediment transport predictions; Meso-scale

Abbreviations

α - angle of deviation of prevailing wind direction from right angle to the dune line or to the field strip (e.g., $\alpha = 0$ during onshore winds)

ρ - air density (1.22 kg m^{-3})

s- distance from the upwind margin of an erodible surface to the area where transport reaches 63.2% of the maximum transport (common definition of critical fetch distance or critical field length in agricultural areas

c - perpendicular distance separating two parallel streamlines of the wind field

C - proportionality coefficient that varies with the fetch length (F) in Dong et al. (2004)

COG - combined residue factor in RWEQ

Δx - increase in transport quantity across wind in RWEQ

EF - erodible fraction in RWEQ

F - fetch length; distance from the upwind margin of an erodible surface to a point of interest

F_c - critical fetch length; distance from the upwind margin of an erodible surface to the point where transport reaches a maximum value.

Researchers working in agricultural soils define the critical fetch distance as s

F_m - maximum fetch length; maximum distance of erodible surface over which the wind is blowing, determined by the angle of wind approach and the beach width (coastal areas) or the field length (agricultural soils)

g - acceleration due to gravity

KN - soil roughness factor in RWEQ

l - unit alongshore length at the dune line mapped out by two parallel streamlines of the wind field

L - beach length

Q - sediment transport rate for a given wind speed

Q_c - sediment transport rate at the end of the maximum fetch length (along cline)

Q_m - maximum sediment transport rate for a given wind speed

Q_l - sediment deposition per unit length of dune (along l)

Q_i - transport quantity upwind in RWEQ

Q_{i+1} - quantity of soil transported at a point × downwind from the upwind boundary in RWEQ

RWEQ - revised wind erosion equation

SCF - soil crust factor in RWEQ

SLR - single-lens reflex

U - wind velocity

U_t - threshold wind velocity

WEQ - wind erosion equation

WF - weather factor in RWEQ

W_b - beach width

W_f - agricultural field width

x - distance along profile

1. Introduction

The fetch effect is an increase in the sediment transport rate (Q) with distance downwind from a boundary marking the transition from a non-erodible to an erodible surface (Chepil, 1957, Davidson-Arnott and Law, 1990, Stout, 1990, Gillette et al., 1996, Fryrear et al., 2000 and Dong et al., 2004). Under ideal scenarios (steady wind, large sediment availability) the number of saltating particles within the saltation cascade increases exponentially to a maximum condition (Bauer and Davidson-Arnott, 2003). This maximum condition reflects saturation of the system where sand movement carries all the vertical momentum flux of the wind (Gillette et al., 1996) and when the transport rateQ becomes independent of distance x (Shao and Raupach, 1992). The distance from the upwind boundary to a point of interest is the fetch distance, F, and the maximum length of erodible surface over which the wind is blowing is the maximum fetch distance, F_m. The distance necessary to achieve the maximum transport rate (Q_m) associated with a particular wind speed is the critical fetch distance, F_c (Davidson-Arnott and Dawson, 2001).[1]

The significance of the fetch effect has been explored in relation to wind erosion in agricultural soils (e.g., Fryrear and Saleh, 1996), particle emission in arid and semi-arid environments with patch vegetation (streets – see Okin et al., 2006), and aeolian transport of sand from beaches to coastal dunes (e.g., Davidson-Arnott and Law, 1990). In these areas, if $F_m < F_c$ for a given wind speed and surface characteristics, then the amount of erosion will be less than predicted and the transport rate at the downwind margin field boundary, street, or beach will be less than that calculated by standard aeolian transport formulae. Thus, restricted beach width, agricultural field dimension, or wind tunnel length have been identified as potentially limiting our ability to observe the true maximum sediment transport with strong winds, because critical fetch distances often exceed the available fetch distance (Section 2).

In coastal areas, prediction of aeolian sediment transport remains unsolved at a variety of temporal and spatial scales. Field measurements do not generally correspond with predicted rates of sand flux or net deposition into the foredunes (Davidson-Arnott and Law, 1996 and Arens, 1997). Most of the attention over the last decades has focused on identifying supply-limiting factors (Nickling and Davidson-Arnott, 1990) because they decrease the number of grains that become part of the saltation system and thus reduce the equilibrium transport rate. Many excellent reviews exist on the effects of moisture, particle size and sorting, surface crusts, or other supply-limiting conditions (Pye, 1983,Horikawa et al., 1986, Nickling, 1994, Namikas and Sherman, 1995 and Cornelis and Gabriels, 2003; etc.). However, the disequilibrium between the wind flow and sediment transport rate characteristic of most field situations introduces significant problems when applying deterministic formulae to predicting sediment movement. Disequilibrium may occur in time (e.g., due to wind unsteadiness), in space (e.g., influence of topographic form), or, as is the case of the majority of transport systems, both in time and in space (Table 1). The fetch effect is a particular case of a disequilibrium situation with only spatial controls. In the simplest case of a steady wind blowing over an ideal surface, the fetch effect introduces disequilibrium between the transport rate and the wind field up to a distance (F_c) where maximum transport is achieved. In general terms, formulae developed to predict sediment transport are applicable to the equilibrium situation that exists beyond this distance. As wind speed or the effect of supply-limiting factors increase so do corresponding critical fetch distances (Section 3.2), and thus the area where traditional formulae will overpredict the actual transport rate.

Table 1.Contextualization of the fetch effect and other factors causing temporal and spatial equilibrium and disequilibrium in transport systems (only a few examples of publications are including here for practical purposes).

Transport systems		Time	Space	Example of studies
Equilibrium (transport rate in equilibrium with applied stress)	Transport-limited (surface provides unlimited grains)	Steady flow	Dry, non-cohesive and uniform sediment; flat surface	Bagnold, 1941, Kawamura, 1951 and Lettau and Lettau, 1977
	Supply-limited (surface ability to supply grains is limited)	Steady flow	Homogeneous moisture, bounding agents, roughness elements, particle size and sorting, slope, etc.	Horikawa et al., 1986,Iversen and Rasmussen, 1994, Lancaster, 1981,Logie, 1982 and Nickling and Ecclestone, 1981
Disequilibrium	Transport-	Unsteady	Fetch effect,	Butterfield, 1999, Dong

Transport systems		Time	Space	Example of studies
(transport rate variable and in disequilibrium with wind field)	limited (surface has the potential to provide unlimited grains)	flow, wind ramp-up/down	boundary layer development	et al., 2004, Spies and McEwan, 2000 and Stout and Zobeck, 1997
	Supply-limited (surface ability to supply grains is limited)	Spatial and temporal variations of supply-limiting factors (moisture, crusts, topography, etc.), flow, and fetch		Bauer et al., 2009,Davidson-Arnott and Bauer, 2009 and Walker et al., 2006

This paper critically reviews the evidence for the fetch effect, the mechanisms that may produce it, and the problems that remain to be resolved in incorporating it into models predicting aeolian sediment transport in complex environments. While the focus of attention is directed towards aeolian transport on beaches, it also draws on material from agricultural soils and semi-arid environments. Theoretical, wind tunnel, and fieldwork studies are analyzed to determine the physics of aeolian entrainment and transport processes that could provide an explanation for long fetch distances (Section 3). The linkage between the fetch effect and supply-limiting factors such as moisture content is examined in light of recent findings suggesting the interaction between both as a primary control of sand transport on beaches (Davidson-Arnott et al., 2008 and Bauer et al., 2009). The abundant literature on agricultural fields provides a background to develop deterministic equations that include the fetch effect in coastal areas, together with the results of wind tunnel (e.g., Dong et al., 2004) and field experiments (Davidson-Arnott et al., 2008). However, a major challenge remains on how to incorporate knowledge of the fetch effect into a model that could be used to predict sediment input to the foredunes at the meso-scale (Section 5). Remote sensing techniques provide effective tools for measuring the combined effect of important key variables such as moisture, beach width, and fetch distances over a number of transport events through the year (Lynch et al., 2006, Darke et al., 2009 and Delgado-Fernandez and Davidson-Arnott, 2009) (Section6). Theoretical frameworks (Bauer and Davidson-Arnott, 2003) can be implemented to analyze assumptions surrounding the geomorphological impacts of these events. If the fetch effect plays an important role in controlling the magnitude of transport toward the foredunes, then its incorporation into modelling will improve predictions of aeolian transport rates and sediment budget calculations in coastal areas.

2. Evidence for the existence of the fetch effect

2.1. Wind tunnel experiments and numerical simulations

Wind tunnel studies differ from fieldwork results in the numerical characterization of the fetch effect, and suggest shorter critical fetch distances (a few metres) than those reported in natural areas (from tens of metres to over hundreds of metres). However, a number of authors have reported on critical fetch distances longer than the length of the wind tunnel. Bagnold (1941) suggested the need for a minimum length of 9 m to attain equilibrium between the wind flow and saltation. Shao and Raupach (1992) found that their 10 m long wind tunnel did not allow the stabilization of saltation and they built a second wind tunnel of 17 m, which was still too short to observe the final equilibrium state of transport with high wind velocities. Laboratory analysis by Dong et al., 2002 and Dong et al., 2004 confirmed the positive relationship between increasing wind velocity, fetch distance, saltation height, and both vertical and horizontal flux. They found that as wind speed increases more grains travel at a greater height and further downwind with the distance required to achieve equilibrium also increasing (a phenomena previously observed in agricultural soils – Section 2.2). Similar to Shao and Raupach (1992), equilibrium transport was not reached for strong winds within the 16 m long wind tunnel ofDong et al. (2004). That is, even under ideal transport-limited conditions in laboratory settings, critical fetch distances may be larger than tens of metres. Additionally, wind tunnel experiments may be in fact substantially underestimating critical fetch distances. The small vertical dimension characteristic of most wind tunnels interferes with the flow and constrains the full vertical development of an internal boundary layer seeking its natural equilibrium at some distance downstream. The vertical distribution of shear within the profile is artificially "forced", which anticipates the adjustment of saltation (Bauer et al., 2004). Numerical simulations on the length required to achieve a steady state by Spies and McEwan (2000) suggest that critical fetch distances can reach up to 50 m or more (depending on wind speed) when the effects of gusts and wind turbulence are included.

Fig. 1 and Table 2 compare results by (A) Shao and Raupach (1992) (wind tunnel) andDavidson-Arnott and Law (1990) (field experiment), and (B) Dong et al. (2004) (wind tunnel) and Spies and McEwan (2000) (numerical simulation). Note that the maximum wind speed reported by Shao and Raupach (Fig. 1A) is 12.5 m s^{-1}, which is one of the lowest wind speeds considered by Dong et al. (Fig. 1B). Fig. 1 is solely used here to analyze in general terms the differences in curve shape and distances and not for transport magnitudes. Curves are reproduced from original graphs and tables, and transport flux quantities have been normalized by each of the maximum values reported in the corresponding publications. Caution is required regarding the true maximum transport value because critical fetch distances may be greater than those reported here. Shao and Raupach's experiments show an overshoot centred at 5–7 m. The overshoot is characterised by a rapid increase of Q with distance to a maximum condition followed by a decrease to a lower equilibrium value (Shao and Raupach, 1992). The overshoot is also predicted by Spies and McEwan, but their simulations suggest that increases in wind speed produce longer distances for both maximum and equilibrium transport values. The overshoot is not evident in other wind tunnel studies (e.g., Dong et al., 2004) nor has it been observed in field measurements in agricultural fields and on beaches (e.g., Stout, 1990, Davidson-Arnott and Law, 1990 and Davidson-Arnott et al., 2008). The experiments by Davidson-Arnott and Law and Dong et al. confirm the presence of longer critical fetch distances with higher wind speeds. While the F_c associated with winds less than 12 m s^{-1} are negligible in the study by Dong et al., Davidson-Arnott and Law report on F_c up to 30 m at much lower wind speeds of 8.3 m s^{-1}.

Table 2. Summary of numerical values reported by authors listed in Fig. 2. Wind speeds for Spies and McEwan (2000) have been calculated from effective friction velocities reported by the authors following the Law of the Wall ($U = \ln(z/z_0)\, U_*/k$), and assuming a grain size of 0.25 mm.

Publication	Wind speed range (m s^{-1})	Fetch distances range (m)	Sediment size (mm)
Davidson-Arnott and Law (1990)	5.9–13.8	10–15 to > 35	0.2–0.33
Shao and Raupach (1992)	8.5–12.5	Length to overshoot = 5	0.2
		Length to equilibrium >17	
		Minimum distance for equilibrium = 15	
Dong et al. (2004)	8–22	Negligible to >16	0.18
Spies and McEwan (2000)	7.9–26.9	Length to overshoot = 5 to 30	0.25

2.2. Field experiments

2.2.1. Agricultural soils

The fetch effect was identified early in the twentieth century as a primary control for wind erosion in agricultural fields (Chepil and Milne, 1939), and gained major attention especially after environmental issues associated with the Dust Bowl of the 1930s in the Great Plains of North America (Hansen and Libecap, 2004). The number of publications dedicated to soil erosion in agricultural fields is rather extensive, and a considerable number of them include the role of field dimensions (e.g., Chepil et al., 1964, Lyles, 1977,Fryrear and Saleh, 1996 and Fryrear et al., 2000). Critical fetch distances of up to 150 m during wind erosion episodes have been observed (Fryrear and Saleh, 1996 and Gillette et al., 1996) and even more than 300 m (Stout, 1990). The critical fetch distance has also been found to vary with height above the bed. Horizontal lengths needed to attain maximum transport were larger at 1 and 1.65 m than at 0.15 and 0.25 m heights in experiments carried out by Stout, 1990 and Stout and Zobeck, 1996, respectively.

The inclusion of fetch distances in modelling transport rates in agricultural areas dates back to Chepil (1957), who linked the length of the field over which the wind is blowing with the growth of the transport cloud. The Wind Erosion Equation (WEQ) proposed byWoodruff and Siddoway (1965) was adapted to design controls against erosion, where the amount of sediment removed from a given field could be calculated using field length, prevailing wind erosion direction, and soil, vegetation and climatic factors. In an attempt to include new inputs such as sediment transported in suspension, Fryrear et al. (2000)reviewed the WEQ and tested the improved Revised Wind Erosion Equation (RWEQ) computer program against measured erosion from 22 different sites.[2] The quantity of soil transported at a point x downwind (Q_{i+1}) is expressed in RWEQ as:

$$Q_{i+1} = Q_i + \left(\frac{Q_m - Q_i}{s}\right)\frac{2x}{s}\Delta x \tag{1}$$

where Q_i is the transport quantity upwind and Δx stands for an increase in transport quantity across. The distance from the upwind margin of an erodible surface to the area where transport reaches 63.2% of the maximum transport is the critical fetch length s. Q_m is the maximum transport capacity for a given wind over a specific soil and is computed as:

$$Q_m = 109.8 + (WF \times EF \times SCF \times KN \times COG) \tag{2}$$

where WF = weather factor, EF = erodible fraction, SCF = soil crust factor, KN = soil roughness factor, and COG = combined residue factor. Each of these factors is calculated based on a number of surface and environmental variables (for details seeFryrear et al., 2000), and field shape, size, and orientation are included in the management input files.

Based on the assumption that wind erosion-processes are naturally controlled by a self-balancing mechanism, Stout (1990) derived and tested in the field a simple equation to describe the variation of sediment flux with distance:

$$q/Q_m = 1 - e^{(-x/b)} \qquad (3)$$

As described in Section 2.1, both Q_m and s depend on height. Fig. 2 compares the increase of transport with distance for one prediction carried out with RWEQ (extracted from Fryrear et al., 2001) and Stout's theoretical curve. Transport rates and distances reported in the RWEQ original graph have been normalized by Q_m and F_c, respectively. Maximum transport in Fig. 2 in Stout's (1990) original publication occurs around x/s = 4.5 (this is, F_c is roughly 4.5 s). Thus x/s values have been divided by 4.5 to obtain distances normalized by F_c. The agreement between the two curves is significant, but Stout's equation tends to overestimate transport in the area where $F < F_c$ (or vice versa: RWEQ underestimates transport). The equations proposed by Bauer and Davidson-Arnott (2003) are discussed in Section 5.2.

2.2.2. Beaches

Svasek and Terwindt (1974) introduced the first explicit reference to the importance of fetch distances on beaches, and suggested a minimum critical fetch distance of 10–20 m for onshore winds to reach maximum transport. However, they did not distinguish the cause of the observed fetch effect. Experiments by Nordstrom and Jackson (1993) are instructive because of their efforts to analyze the combined effect of variables such as moisture content, mean grain size, beach slope and fetch distances amongst others. They compared aeolian transport during five high-velocity wind events (from 8.5 to 15.9 m s^{-1}) on an estuarine beach in Delaware Bay (New Jersey, US), and demonstrated that short available fetch distances on narrow beaches can counteract the potential of higher wind speeds to transport large amounts of sediment. Sand trapped during periods of oblique winds was over 20 times greater than any day with onshore winds, because oblique winds created an available fetch distance (≈ 37 m) nearly double that for onshore winds (≈ 18 m). Increases in fetch distances were able to partially overcome surface limitations such as higher moisture content or larger mean grain sizes. Independent experiments carried out by Bauer (1991) (Monterey Bay, California, US) and Davidson-Arnott and Law (1990) (Long Point, Lake Erie, Canada) related the increase of sediment transport rates landward from the shoreline with the existence of upwind sand sources and beach width, respectively. At Long Point, winds just above the threshold achieved maximum transport rates at approximately 10–15 m, but saltation did not fully develop over a dry surface with stronger winds of about 14 m s^{-1} because the 35 m wide beach did not provide enough fetch distance.

The fetch effect may be small for low wind events and dry, well-sorted fine sands (Fig. 1).Jackson and Cooper, 1999 and Lynch et al., 2008 report on the insignificant role of the fetch effect with onshore winds around 8 and 10 m s^{-1}, respectively blowing over dry, well sorted sediments (0.17 mm mean grain size). Although the strength of the control exerted by the fetch effect varies both temporally and spatially, there is strong evidence supporting the existence of long critical fetch distances in many common beach situations, specifically in relation to moisture content and other supply-limiting factors (Van der Wal, 1998, Davidson-Arnott and Dawson, 2001, Davidson-Arnott et al., 2005a,Davidson-Arnott et al., 2005b and Davidson-Arnott et al., 2005c). Thus, for example, the measured F_c ranged from 80 to 200 m (Davidson-Arnott et al., 2008) and in another study from 50 to 150 m (Bauer et al., 2009).

3. The physics of the fetch effect

3.1. Evolution of saltation

Numerical models of sand transport by wind have been able to simulate many of the physical processes involved in saltation (Ungar and Haff, 1987, Werner, 1990, McEwan and Willetts, 1993, Shao and Li, 1999 and Lu and Dong, 2007), including the time and length required to achieve a steady state (Anderson and Haff, 1991 and Zeng, 2008).Spies and McEwan (2000) confirmed some of the characteristics of saltation observed by previous researchers (e.g., Bagnold, 1941, Anderson and Haff, 1988 and Shao and Raupach, 1992).

The existence of a critical fetch distance is inherent to the evolution of saltation and can be explained as follows: when wind with a speed greater than the threshold of movement starts blowing over an erodible surface there is an initial rapid increase of Q with distance from the upwind boundary over the first few metres as a consequence of the rapid cascade of particle mobilization and entrainment into the air flow. Aerodynamic entrainment of particles is the most important process when saltation begins. The wind lifts, accelerates, and transmits kinetic energy to the grains, which travel following trajectories of different heights and lengths depending on the wind velocity (Dong et al., 2009). Acceleration of grains is such that their impact velocity is almost equal to the wind velocity at the highest point of the trajectory (Svasek and Terwindt, 1974). The increase in particle momentum allows the impact of saltating grains to eject more particles into the air or roll them along the surface, which quickly shifts the dominant entrainment process to grain impact (Nickling, 1988 and Anderson and Haff, 1991). The number of grains in motion growths exponentially with distance, as in a snow avalanche (Chepil, 1957). As the particle flux increases it modifies the flow, creating an internal boundary layer that grows downwind, and reducing the wind speed near the bed. The result is a self-balancing mechanism responsible for limiting the growth of mass transport to a stable value (Fryrear and Saleh, 1996) in which the particle ejection rate eventually reaches an equilibrium state at some point in distance downwind (Shao and Raupach, 1992 and Fryrear et al., 2000).

3.2. Long fetch distances in field situations

With dry, uniform sand the avalanching process and accompanying self-balancing mechanism occurs within a few metres to a few tens of metres depending on wind speed. Field studies indicate that supply-limiting factors are primarily responsible for increasing the F_c over that measured for dry, uniform sediment. In general terms, a reduced rate of grain ejection from the bed would increase the time/distance needed to accumulate the mass of loose, dry sediment that defines the limit of aeolian transport for a particular wind speed. In the case of agricultural soils, long critical fetch distances relate to the space and time it takes to erode particles from earth clods. In the case of moist sand on the beach surface, the space and time is related to the reduced rate of ejection by saltating particles and the distance needed to accumulate the equilibrium mass of dry sediment downwind.

3.2.1. Agricultural fields and soil conditions

A complete description of the fetch effect should incorporate knowledge of the soil physical state (Gillette et al., 1996) because soil clods and crusts are determinant factors in limiting the quantity of erodible material (Fryrear and Saleh, 1996). The RWEQ requires a large number of ‘soil inputs’. Percentages of sand, silt, organic matter and other variables are introduced to quantify, amongst others, the soil crust factor, which reflects crust development and its influence on soil erosion by wind. Maximum soil loss is often related to smooth, bare, and unprotected dry fields (Fryrear et al., 2000).

Gillette et al. (1996) propose two mechanisms on top of the avalanching processed (Section 3.1) that could explain critical fetch distances up to hundreds of metres. The first mechanism is based on ideas developed by Owen (1964), who described the modification of flow imposed by saltation outside of the region of particle motion as analogous to a solid roughness. The increase in apparent roughness height leads to an increase in friction velocity and momentum transfer to the surface. This in turn increases saltation, which leads the system into a positive “aerodynamic feedback”. This feedback was not found in all locations studied by Gillette et al. (1996), who introduced a third mechanism based on the resistance of soil to erosion. Soil aggregates (including crusts) are destroyed by sandblasting in proportion to the quantity of material being transported by the wind (Fryrear and Saleh, 1996). As sandblasting increases downwind the non-erodible portion of the soil decreases and more wind momentum goes to transporting particles. The same wind stress is able to transport more sediment as distance increases from the leading edge because the decrease in surface area covered by crusts changes the soil resistance to wind erosion. According to Gillette et al. (1996), avalanching dominates at the leading edge of erodible material but it is a residual effect for distances of more than 50–100 m. Threshold friction velocity depends on soil composition and sediment size distribution, while friction velocity is a function of topography, pressure gradients and roughness. The fetch effect is controlled primarily by the “aerodynamic feedback” in non-aggregated homogenous sand surfaces. Non-homogenous size distributions and soil aggregation yield different threshold velocities, and thus soil resistance to erosion becomes the primary control.

3.2.2. Beaches: moisture and other complicating factors

Aerodynamic feedback is probably a second order mechanism in coastal areas, and the effect of crusts may only be occasionally important on beaches (Davidson-Arnott and Dawson, 2001). Small amounts of moisture, on the other hand, are often present on beach sediments, and it seems likely that it plays a significant role in increasing critical fetch distances in these environments. At the time this paper was submitted there were no published results from wind tunnel experiments specifically dealing with the interaction between moisture and fetch distance. Given a tunnel long enough, an experiment with a wet uniform sediment surface would be feasible in order to provide information on the distance needed for a supply-limited environment to achieve equilibrium. Due to the lack of laboratory data, our knowledge relies on the results of fieldwork experiments that describe complex relationships between variable wind speeds and directions, strong spatial and temporal patterns of superficial moisture content, and changing fetch distances (Davidson-Arnott and Dawson, 2001, Davidson-Arnott et al., 2005b, Davidson-Arnott et al., 2005c, Davidson-Arnott et al., 2008, Bauer et al., 2009, Davidson-Arnott and Bauer, 2009 and Walker et al., 2009). Although we can determine the role of the fetch effect in the development of transport under relatively simple conditions, this may be masked or eliminated when complexities such as sharp-crested berms, varying sediment sizes, and non-homogenous moisture add to a system already in disequilibrium. However, there is sufficient evidence suggesting that wet surfaces are indeed responsible for increases on critical fetch distances up to several hundreds of metres.

Moisture increases the threshold of wind speed able to entrain sediment (Cornelis and Gabriels, 2003 and Wiggs et al., 2004b). The reduction of the number of grains ejected by fluid stress decreases the number of grains dislodged by the impact of saltating particles, which slows down the rate of transport increase downwind. Wind gusts may be enough to overcome surface moisture and generate sand streamers with fetch distances close to 30 m and moisture content less than 10% (Davidson-Arnott and Dawson, 2001).

Saltation at the beach is often highly intermittent as a result of fluctuations in wind speed, and wetting and rapid drying of surficial sediments (Bauer et al., 2009). The simple gradual growth in the mean mass flux with distance downwind from the edge of erodible material that is evident in trap data collected over tens of minutes (Fig. 3a) may be produced by an increase in the frequency of instantaneous transport events downwind (Fig. 3b). In this situation the F_c associated with individual transport events may be less than half of that for the integrated time series (Davidson-Arnott et al., 2005c). In the field, a steady state of transport rate on the beach may never be achieved because of additional complexities such as the presence of different sediment sizes (Bauer, 1991), which may make isolation and modelling of the fetch effect more difficult. Boundary layer development downwind produces lower shear-stresses and interacts with the fetch effect to regulate the evolution of transport (Bauer et al., 2009). In addition, as wind approaches the back of the beach the effects of sheltering by vegetation in the embryo dune and stagnation of the flow due to the presence of the foredune (Hesp et al., 2005) commonly reduce transport rates and enhance deposition in the dune toe area (as shown by trap 5 in Fig. 3a).

4. Implications of long critical fetch distances: geometric considerations

The absence of spatial constraints on the angle of wind approach in natural areas gives rise to a series of tradeoffs related to the fetch effect, wind direction, and dimension of the erodible surface over which the wind is blowing. For example, in arid and semi-arid regions with mesquite vegetation flux increases along streets in the windward direction, and the shape and orientation of large gaps created by vegetation distribution are key in controlling aeolian flux (Okin et al., 2006). In the Great Plains, protection of soil from erosion can be achieved by considering simple geometrical relationships amongst field dimensions, wind break height and orientation, and the prevailing wind direction. According to Chepil et al. (1964), the amount of erosion on any field can be determined from the longest distance across the field along the prevailing wind erosion direction, F_m. This can be obtained from the width of the field strip (W_f) and the angle of deviation of the prevailing wind erosion direction from right angles to the field strip (α):

$$F_m = {}^{W_f}\!\big/_{\cos\alpha} \qquad (4)$$

Similarly, the relation between angle of wind approach and beach width determines the available fetch distance between the swash limit and the vegetated surface at the back of the beach. As explained in Section 2.2.2, transport during strong onshore winds can be limited by short fetch distances on narrow beaches. This decreases the amount of sediment delivered to the coastal dune, because sediment eroded from the beach is the primary source of material for foredune building (Psuty, 1988). There are many instances where the beach width may be substantially reduced due to nearshore processes such as wave run up and storm surge (Ruz and Meur-Ferec, 2004 and Bauer et al., 2009) or tidal elevation (Nordstrom and Jackson, 1992). Given that the critical fetch distance increases with wind speed (e.g., Dong et al., 2004) and that the rate of transport is commonly a cubic function of the wind drag (e.g., Bagnold, 1941) or wind velocity (e.g.,Dong et al., 2004), overpredictions of sediment transport rates on many beaches are likely to be related to fetch distance limitations during high energy onshore wind events.

Where the beach width (W_b) is narrower than F_c for a particular onshore wind an oblique angle of wind approach increases the fetch distance and therefore the potential sediment transport rate. However, beach-dune geometry dictates that the actual deposition in the vegetated foredune per unit distance alongshore decreases as the wind becomes more oblique as a function of the cosine of the wind angle (the cosine effect – see Davidson-Arnott and Dawson, 2001 and Bauer and Davidson-Arnott, 2003). Thus sediment supply to the foredune per unit length of dune (Q_l) is defined as:

$$Q_l = q_c \cos \alpha \tag{5}$$

where Q_c is the sediment transport rate at the top of the beach, and α is the angle of wind to shore perpendicular (Fig. 4). Bauer and Davidson-Arnott (2003) translate this concept into the following distances:

$$c = l \ \cos \alpha \tag{6}$$

where l represents a unit alongshore length at the dune line mapped out by two parallel streamlines of the wind field separated by the perpendicular distance c (Fig. 4). As shown in Fig. 5, during alongshore winds the fetch distance is at its maximum but transport across line c tends to zero. Onshore winds are not subject of the cosine effect (c = l) but short available fetch distances may limit sediment input from the beach to the foredune. Thus, where $W_b < F_c$ there is a complex tradeoff between increasing fetch distance with oblique winds and decreased net transport into the dunes (Bauer and Davidson-Arnott, 2003).

5. Modelling the fetch effect on beaches

While a framework incorporating beach geometry and the fetch effect (Bauer and Davidson-Arnott, 2003) provides a basis for modelling sediment supply to coastal dunes, two factors critical to its implementation are still unresolved: (1) a method for calculatingF_c; and (2) determination of a functional relationship describing the increase in sediment transport with distance when $F < F_c$.

5.1. The critical fetch distance: a new threshold of concern?

The critical fetch distance is a threshold for equilibrium transport conditions (Section 1). If$F > F_c$ then saltation is fully developed and transport rates may be calculated using traditional equations (e.g., Bagnold, 1941). If $F < F_c$ then the fetch effect needs to be considered in the calculations (Bauer and Davidson-Arnott, 2003). Thresholds are highly dynamic with complex interactions that dictate their variability (e.g., Wiggs et al., 2004a and Wiggs et al., 2004b) and transport systems usually require the combination of more than one threshold (Davidson-Arnott and Bauer, 2009). The wind threshold to initiate sand movement can vary over periods as short as tens of seconds in response to drying of the surface by wind and sunshine. In addition, F_c increases with wind speed and moisture content but it is not yet clear whether the maximum transport rate with moist sand is the same as that for dry sand (Davidson-Arnott et al., 2008). Thus, the question is whether future research on the fetch effect should concentrate on associating different wind speeds with particular values of F_c or whether there are alternative ways to include this concept into modelling (e.g., Davidson-Arnott et al., 2008 and Bauer et al., 2009). The determination of F_c may permit isolation of those events where transport-limited equations can be applied, but it is of limited value if not accompanied by a formulae for distance-related transport to be applied to those events when $F < F_c$. One way around this dilemma may be to determine F_c directly from such a formula.

5.2. Transport as a function of distance

Computer simulations by Bauer and Davidson-Arnott (2003) suggest that the particular equation for describing transport rate as a function of fetch distance has significant impacts on the distribution of erosion–deposition processes across the beach and predicted sediment supply to the foredunes. Bauer and Davidson-Arnott (2003) examine four alternative equations (Fig. 2) that are applicable within the area where $F < F_c$:

$$q(F,\alpha) = q_m \sin\left(\frac{\pi}{2}\frac{F}{F_c}\right) \qquad (7)$$

$$q(F,\alpha) = q_m 1/2\left[\sin\left(\pi\left(\frac{F}{F_c} - \frac{1}{2}\right)\right) + 1\right] \tag{8}$$

$$q(F,\alpha) = q_m 4/\pi \tan^{-1}\left(\frac{F}{F_c}\right) \tag{9}$$

$$q(F,\alpha) = q_m 2/\pi \sin^{-1}\left(\frac{F}{F_c}\right) \tag{10}$$

Eq. (7) provides good agreement with findings in agricultural soils. Conceptually, it is also the most consistent with the description of the saltating cascade (a steep initial increase in the transport rate followed by a self-balancing mechanism) and with Davidson-Arnott et al. (2008) who favour an exponential curve, although they do not present any specific equation. However, it can only be applied if F_c is known.

Dong et al. (2004) express the relationship between sand flux and wind velocity (U) as:

$$Q = C\left(1 - {U_t}/{U}\right)^2 U^3 \frac{\rho}{g} \tag{11}$$

where U_t is the threshold velocity measured at the same height as U, ρ is the air density, g is the acceleration due to gravity, and C is a proportionality coefficient that varies with F as follows:

$$C = 0.000306F^{2/3} \tag{12}$$

Dong et al. (2004) found good agreement between observed and calculated sand flux for different velocities, but their equation does not predict the equilibrium stage and has not yet been tested under natural conditions.

Although field data needs to be collected over a variety of wind speeds to verify its suitability, an exponential equation such as the one proposed by Stout (1990 – see Eq. (3)) has several practical advantages: (1) F_c is implicitly defined as the distance at which transport meets the asymptote marking a constant transport rate; (2) considerable variations of F around F_c produce only small differences in calculated transport rates because sediment fluxes are not very sensitive to fetch distances close to the critical fetch.

6. Measuring the fetch effect in the field

Future short-term experiments on the fetch effect over the beach surface should investigate the evolution of transport along the wind line under a variety of field conditions, from ‘simple scenarios’ with dry sand and/or uniform moisture, to ‘complex events’ that could include rapid temporal and spatial variability of moisture or other surface characteristics, and strong winds. Although short-term studies can provide details about physical interactions between fetch and other variables, the relative importance of results obtained from discrete measurements over the long term is unknown (Sherman, 1995). At a temporal scale of months to years tradeoffs between the fetch effect, wind direction and beach width have considerable influence on sediment supply to the foredune (Davidson-Arnott and Stewart, 1987 and Davidson-Arnott and Law, 1996), and challenges remain in developing appropriate instrumentation and ways to store and analyze data over long temporal scales in order to overcome some of the limitations imposed by synoptic observations. Recent advances in remote sensing techniques applied to the study of coastal dunes may provide the means to acquire high spatial and temporal resolution data over periods of time from hours to years, and thus augment the efforts of traditional methods. For example, Lynch et al. (2006) proposed a technique based on the use of digital cameras to measure fetch distances from the wet swash area. Darke et al. (2009) tested the application of video cameras to measure superficial moisture content using calibration curves relating moisture with surface brightness. Delgado-Fernandez et al. (2009) expanded the capabilities of previous systems and tested a remote sensing technique based on digital single-lens reflex (SLR) cameras and ancillary instrumentation to measure key aspects of the aeolian transport system at Greenwich Dunes (Prince Edward Island National Park, Canada). This remote sensing station provides continuous monitoring of surface moisture content, fetch distances, shoreline position, vegetation cover, presence of snow-ice, wind speed and direction, and transport intensity or erosion–deposition of sediment at the back beach. The ability to observe the combined effect of factors driving sediment input to the dunes may allow the characterization of important transport events through the year and thus provide a means of testing models incorporating the fetch effect.

7. Conclusions and future directions

The fetch effect has been measured in wind tunnel experiments and has long been incorporated in studies of wind erosion of agricultural soils. While field observations of the fetch effect on beaches are not as numerous as for agricultural fields, there is now sufficient evidence of its potential significance for aeolian sediment transport to coastal dunes to warrant its incorporation in long-term modelling. It is clear that there are a number of mechanisms that can produce a fetch effect, but the most significant ones seem to be related to the existence of factors that limit sediment supply to the airstream. In agricultural soils the most significant factor appears to be the presence of fines and the development of clods. On beaches fine particles are generally absent and the fetch effect appears to be related primarily to the presence of surface moisture.

There are a number of promising aspects of the study of the fetch effect that could improve sediment transport calculations in coastal areas. Further research should be carried out to refine the equation describing the increase of transport rate with fetch distance, although the literature seems to favour an exponential function. Studies of agricultural soils open interesting venues for aeolian coastal geomorphologists interested in incorporating the fetch effect into modelling. Although many aspects covered in the literature of agricultural fields are not included in this review, the aim here was to highlight key findings that may apply to beach-dune systems. Some of the physical explanations about long critical fetch distances and the relation between field dimensions and wind erosion can be translated to the coastal realm.

The existence of critical fetch distances that greatly exceed the available source of sediment needs to be taken into consideration when calculating potential sand input to the dunes. Even on very wide beaches, the fetch effect may play a significant role during strong wind events. Storms are usually associated with short available fetch distances due to wave run up and beach inundation, as well as increases in moisture levels on the upper beach (Nordstrom and Jackson, 1992 and Ruz and Meur-Ferec, 2004). Under these conditions, only highly oblique wind angles may be effective in moving sediment into the foredunes (Bauer et al., 2009). Because sediment transport calculations at the meso-scale (e.g., Fryberger and Dean, 1979) are usually based on wind speed to the power of 2 or 3, overprediction is likely to occur during onshore storm events.

Knowledge about the fetch effect at the meso-scale needs to be coupled with measurement of other key factors regulating the dynamics of aeolian transport events delivering sediment to the foredunes. The loss of detail on the study of one factor may be compensated with the advantages of looking at the system holistically. Remote sensing systems allow observations of the frequency and magnitude of events accounting for the majority of sediment moved through the year and permit simultaneous measurements of key factors that can explain about 70–80% of the variability of the system (Delgado-Fernandez and Davidson-Arnott, 2009). The availability of digital cameras and video cameras coupled with improved sensors for measuring sand transport should aid in refining our ability to incorporate the fetch effect in modelling aeolian sediment transport in coastal areas.

Acknowledgements

This manuscript has enormously benefited from critical reviews and numerous conversations with Robin Davidson-Arnott and Bernard Bauer. I am most grateful to Jeff Ollerhead, Ian Walker, and Hosahng Rew for providing challenging questions on the problem of aeolian sediment transport at the beach at meso-scale. Ray Kostaschuk and Bill Nickling thoroughly reviewed the manuscript and gave substantial comments that greatly improved the final version. I am also grateful for the feedback provided by two anonymous reviewers. Financial support was provided by the Ontario Graduate Scholarship Program (Ministry of Training, Canada).

References

Anderson, R.S. and Haff, P.K., 1988. Simulation of eolian saltation, Science, 820-823.

Anderson, R.S. and Haff, P.K., 1991. Wind modification and bed response during saltation of sand in air, Acta Mech. (Suppl.), 21-52.

Arens, S.M., 1997. Transport rates and volume changes in a coastal foredune on a Dutch Wadden island. J. Coast. Conserv. 3, 49-56.

Bagnold, R.A., 1941. The physics of blown sand and desert dunes, London, Methuen, 265 pp.

Bauer, B.O., 1991. Aeolian decoupling of beach sediments. Ann. AAG. 81, 290-303.

Bauer, B.O. and Sherman, D.J., 1999. Coastal dune dynamics: Problems and Prospects. In: Goudie, A.S., Livingstone, I. and Stokes, S. (EdS.), Aeolian

Environments, Sediments and Landforms. John Wiley and Sons, pp. 71-104.

Bauer, B. O. and Davidson-Arnott, R. G. D., 2003. A general framework for modeling sediment supply to coastal dunes including wind angle, beach geometry and fetch effects, Geomorphology 49, 89-108.

Bauer, B.O., Houser, C.A. and Nickling, W.G., 2004. Analysis of velocity profile measurements from wind-tunnel experiments with saltation, Geomorphology 59, 81-98

Bauer, B.O., Davidson-Arnott, R.G.D., Hesp, P.A., Namikas, S.L., Ollerhead, J., Walker, I.J., 2009. Aeolian sediment transport on a beach: Surface moisture, wind fetch, and mean transport. Geomorphology 105, 106-116

Butterfield, G., 1999. Near-bed mass flux profiles in aeolian sand transport: high-resolution measurements in a wind tunnel. Earth Surf. Proc. Land. 24, 393–412.

Cornelis, W.M. and Gabriels, D., 2003. The effect of surface moisture on the entrainment of dune sand by wind: an evaluation of selected models. Sedimentology 50, 771-790.

Chepil, W.S., 1957. Width of field strips to control wind erosion. Kan. AEL Bull. No. 92.

Chepil, W.S. and Milne, R.A., 1939. Comparative study of soil drifting in the field and in a wind tunnel, Sci. Agr. 19, 249-257.

Chepil, W.S., Siddoway, F.H., and Armbrust, D.V., 1964. Prevailing wind erosion direction. J. Soil Water Conserv. 19, 67-71.

Darke, I., Davidson-Arnott, R.G.D. and Ollerhead, J., 2009. Measurement of beach surface moisture using surface brightness. J. Coast. Res. 25, 248-256.

Davidson-Arnott, R.G.D. and Stewart, C.J., 1987. The effects of longshore sand waves on dune Erosion and Accretion, Long Point, Ontario. In: Proc. Can. Coast. Conf., CCSEA, 131-144.

Davidson-Arnott, R.G.D. and Law, M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: Nordstrom, K.F., Psuty, N.P. and Carter, R.W.G. (EdS.), Coastal Dunes: Form and Process. John Wiley & Sons, 177-20.

Davidson-Arnott, R.G.D. and Law, M.N., 1996. Measurement and prediction of long-term sediment supply to coastal foredunes. J. Coast. Res. 12, 654-663.

Davidson-Arnott, R.G.D. and Dawson, J.D., 2001. Moisture and fetch effects on rates of aeolian sediment transport, Skallingen, Denmark. In: Proc. Can. Coast. Conf., CCSEA, 309-321.

Davidson-Arnott, R.G.D., Bauer, B.O., Hesp, P.A., Namikas, S.L., Ollerhead, J., and Walker, I.J., 2005a. Moisture and fetch effects on aeolian sediment transport rates during a fall storm, Greenwich Dunes, Prince Edward Island. In: Proc. Can. Coas. Conf., CCSEA, Compact Disk.

Davidson-Arnott, R.G.D., MacQuarrie, K. and Aagaard, T., 2005b. The effect of wind gusts, moisture content and fetch length on sand transport on a beach. Geomorphology 63, 115-129.

Davidson-Arnott, R.G.D., Ollerhead, J., Hesp, P.A., and Walker, I.J., 2005c. Spatial and temporal variability intensity of Aeolian transport on a beach and foredune. In: Proc. Coastal Sediments 2003. New York, ASCE, 14 p.

Davidson-Arnott, R.G.D., Yang, Y., Ollerhead, J., Hesp, P.A. and Walker, I.J., 2008. The effects of surface moisture on aeolian sediment transport threshold and mass flux on a beach. Earth Surf. Proc. Land., 33, 55 - 74

Davidson-Arnott, R.G.D. and Bauer, B.O., 2009. Aeolian sediment transport on a beach: Thresholds, intermittency, and high frequency variability. Geomorphology 105, 117-126

Delgado-Fernandez, I., Davidson-Arnott, R.G.D. and Ollerhead, J., 2009. Application of a remote sensing technique to the study of coastal dunes. J. Coast. Res., 25 (in press)

Dong, Z., Wang, H., Liu, X., Li, F. and Zhao, A., 2002. Velocity profile of a sand cloud blowing over a gravel surface, Geomorphology 45, 277-289.

Dong, Z., Wang, H., Liu, X. and Wang, X., 2004. The blown sand flux over a sandy surface: a wind tunnel investigation on the fetch effect, Geomorphology 57, 117-127.

Dong, Z., Luo, W.Y., Qian, G. and Wang, H., 2009. Momentum profile of aeolian saltation cloud. Sci. Cold Arid Reg. 1, 0025-0029.

Farrell, E.J. and Sherman, D.J., 2004. Process-scaling issues for aeolian transport modelling in field and wind tunnel experiments: roughness length and mass flux distributions. J. Coast. Res., SI 39, 384-389.

Fryberger, S.G. and Dean, G., 1979. Dune forms and wind regime. In: McKee, E.D. (Ed.), Global Sand Seas, 141-151.

Fryrear, D.W. and Saleh, A., 1996. Wind erosion: field length. Soil Sci. 161, 398-404.

Fryrear, D. W., Bilbro, J. D., Saleh, A., Schomberg, H., Stout, J. E., and Zobeck, T. M., 2000. RWEQ: Improved Wind Erosion Technology. J. Soil Water Conserv. 55, p. 183

Fryrear, D.W., Sutherland, P.L., Davis, G., Hardee, G. and Dollar, M., 2001. Wind erosion estimates with RWEQ and WEQ, 760-765, In: Stout, D.E., Mohtar, R.H. and Steinhardt, G.C. (Eds.) Sustaining the Global Farm, p. 1169

Gillette, D.A., Herbert, G., Stockton, P.H. and Owen, P.R., 1996. Causes of the fetch effect in wind erosion, Earth Surf. Proc. Land. 21, 641-659.

Hansen, Z.K. and Libecap, G.D., 2004. Small farms, externalities, and the Dust Bowl of the 1930s. J. Polit. Econ. 112, 665-694.

Hesp, P.A., Davidson-Arnott, R.G.D., Walker, I.J. and Ollerhead, J., 2005. Flow dynamics over a foredune at Prince Edward Island, Canada. Geomorphology 65, 71-84.

Horikawa, K., Hotta, S. and Kraus, N.C., 1986. Literature review of sand transport by wind on a dry sand surface, Coas. Eng. 9, 503-526.

Jackson, D.W.T. and Cooper, J.A.G., 1999. Beach fetch distance and aeolian sediment transport, Sedimentology 46, 517-522.

Lu, P. and Dong, Z., 2007. Numerical simulation of a wind-sand flow. J. Earth Sci. 1, 154-162.

Lyles, L., 1977. Wind erosion: processes and effect on soil productivity. Trans. ASAE, 20, 880-884.

Lynch, K., Jackson, D.W.T. and Cooper, A.G., 2006. A remote-sensing technique for the indentification of aeolian fetch distance. Sedimentology 53, 1381-1390.

Lynch, K., Jackson, D.W.T. and Cooper, A.G., 2008. Aeolian fetch distance and secondary airflow effects: the influence of micro-scale variables on meso-scale foredune development. Earth Surf. Proc. Land. 33, 991-1005.

McEwan, I. K. and B. B. Willetts (1993). Adaption of the near surface wind to the development of sand transport. J. Fluid Mech. 252, 99-115.

Namikas, S.L. and Sherman, D.J., 1995. A review of the effects of surface moisture content on aeolian sand transport. In: V.P. Tchakerian (Ed.), Desert Aeolian Processes. Chapman and Hall Ltd., London, 269-293.

Nickling, W.G., 1988. The initiation of particle movement by wind, Sedimentology 35, 499-511.

Nickling, W.G. and Davidson-Arnott, R.G.D., 1990. Aeolian sediment transport on beaches and coastal sand dunes. In: Davidson-Arnott, R.G.D. (Ed.), Proc. Symposium on Coastal Sand Dunes, National Research Council of Canada, 1-35.

Nickling, W.G., 1994. Aeolian sediment transport and deposition. In: Pye, K. (Ed.), Sediment Transport and Depositional Processes Blackwell Scientific Publications Ltd., 397 pp.

Nordstrom, K. F. and Jackson, N. L., 1993. The role of wind direction in eolian transport on a narrow sand beach, Earth Surf. Proc. Land. 18, 675-685.

Nordstrom, K. F. and Jackson, N. L., 1992. Effect of source width and tidal elevation changes on aeolian transport on an estuarine beach, Sedimentology 39, 769-778.

Okin, G. S., Gillette, D. A. and Herrick, J.E., 2006. Multi-scale controls on and consequences of aeolian processes in landscape change in arid and semi-arid environments, J. Arid Environ. 65, 253-275.

Owen, P.R., 1964. Saltation of uniform grains in air, J. Fluid Mech. 20, 225-242.

Pye, K., 1983. Coastal Dunes. Prog. Phys. Geog. 7, 531-597.

Ruz, M.H. and Meur-Ferec, C., 2004. Influence of high water levels on aeolian sand transport: upper beach/dune evolution on a macrotidal coast, Wissant Bay, northern France. Geomorphology 60, 73-87.

Shao, Y. and Raupach, M.R., 1992. The overshoot and equilibrium of saltation, J. Geophys. Res. 97, 20559-20564.

Shao, Y. and Li, A., 1999. Numerical modelling of saltation in the atmospheric surface layer. Bound.–Lay. Meteorol. 91, 199-225

Spies, P. J. and I. K. McEwan, 2000. Equilibriation of saltation. Earth Surf. Proc. Land. 25, 437-453.

Stout, J.E. 1990. Wind erosion within a simple field. T. ASAE 33, 1597-1600.

Stout, J.E. and Zobeck, T.M., 1996. The Wolfforth field experiment: a wind erosion study, Soil Sci. 161, 616-632

Stout, J.E. and Zobeck, T.M., 1997. Intermittent saltation, Sedimentology 44, 959-970.

Svasek, J.N. and Terwindt, J.H.J., 1974. Measurement of sand transport by wind on a natural beach, Sedimentology 21, 311-322.

Ungar, I. E. and P. K. Haff, 1987. Steady state saltation in air. Sedimentology 34, 289-299.

van der Wal, D., 1998. Effects of fetch and surface texture on aeolian sand transport on two nourished beaches, J. Arid Environ. 39, 533-547.

Van Pelt, R.S., Zobeck, T.M. and Potter, K.N., 2001. Validation of the Wind Erosion Equation (WQE) for discrete periods and of the Wind Erosion Stochastic Simulator (WESS) for single events. In: Ascough, J.C. and Flanagan, D.C. (Eds.), Soil Erosion Research for the 21st Century, Proc. Int. Symp., ASABE, pp. 683-686.

Walker, I. J., Hesp, P.A., Davidson-Arnott, R.G.D., Bauer, B.O., Namikas, S.L., Ollerhead, J., 2009. Responses of three-dimensional flow to variations in the angle of incident wind and profile form of dunes: Greenwich Dunes, Prince Edward Island National Park, Canada. Geomorphology 105, 127-138.

Werner, B. T., 1990. A steady-state model of wind-blown sand transport. J. Geol. 98, 1-17.

Wiggs, G.F.S., Atherton, R.J. and Baird, A.J., 2004a. Thresholds of aeolian sand transport: establishing suitable values. Sedimentology, 51, 95-108.

Wiggs, G.F.S., Baird, A.J. and Atherton, R.J., 2004b. The dynamic effects of moisture on the entrainment and transport of sand by wind, Geomorphology, 59, 13-30.

Woodruff, N.P., Siddoway, F.H., 1965. A wind erosion equation. Soil Sci. Soc. Am. Proc. 29, 602– 608.

Zeng, X.J., 2008. Simulation, prediction and experiment on windblown sand movement and aeolian geomorphology. Proc. 12th Asian Cong. Fluid Mech., Daejeon, Korea.

Table footnotes

[1] Researchers working in agricultural soils define the critical length as the point in distance where 63.2% of the transport capacity for a given wind over a specific soil surface has been reached (e.g., Fryrear and Saleh, 1996; Fryrear et al., 2000; Stout, 1990).

[2] The RWEQ computational models are used by a number of agencies and institutions to model the amount of erosion and soil loss by wind, such as the United States Department of Agriculture or the Natural Resources Conservation Service (Van Pelt, 2001). A detailed comparison between the WEQ and the RWEQ can be found in Fryrear et al. (2001).

List of figures

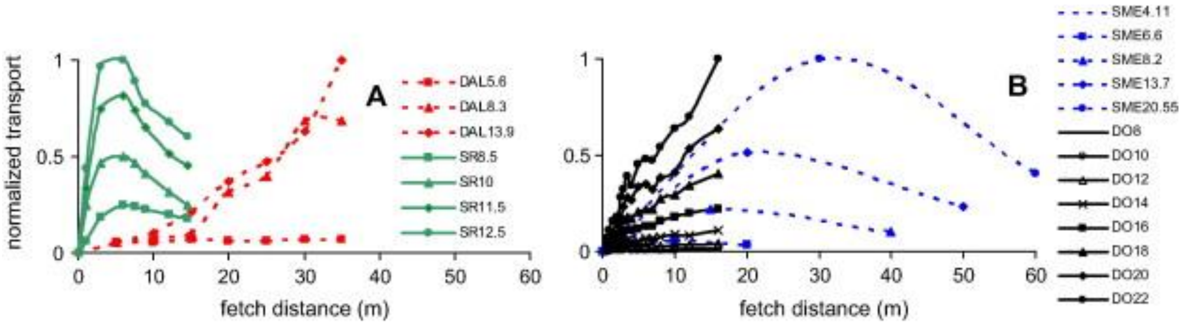

Fig. 1. Evolution of transport downwind from the leading edge of erodible material for different wind velocities. (A) SR: Shao and Raupach (1992); DAL: Davidson-Arnott and Law (1990). (B) DO: Dong et al. (2004); SME:Spies and McEwan (2000). Note that the maximum wind speed in SR (12.5 m s^{-1} – A) is one of the lowest values reported by DO (B).

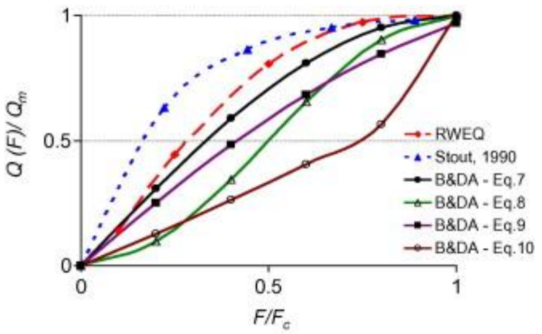

Fig. 2. Comparison of the shape of different transport curves parameterizing the increase of transport rates as a function of increasing fetch distances. Data for the RWEQ has been extracted from Fryrear et al. (2001). B&DA stands for Bauer and Davidson-Arnott (2003).

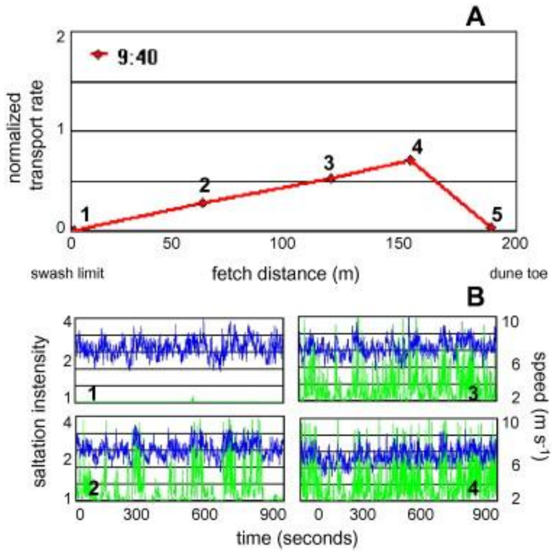

Fig. 3. (A) Evolution of mass flux downwind as recorded by integrating traps (20 min runs); (B) Instantaneous records of safires measuring at trap locations showing an increase in the frequency and magnitude of saltation events downwind (Davidson-Arnott et al., 2008).

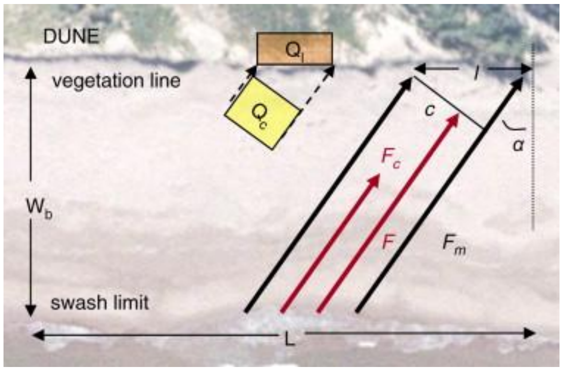

Fig. 4. Terminology associated with the fetch effect at a beach-dune system. F_m: maximum fetch distance; F_c: critical fetch distance; α: angle of wind approach from shore perpendicular; W_b: beach width; L: beach length; l: unit alongshore length at the dune line mapped out by two parallel streamlines of the wind field, separated by the perpendicular distance c; Q_l = sediment deposition per unit length of dune; Q_c = sediment transport rate at the top of the beach (modified from Davidson-Arnott and Dawson, 2001 and Bauer and Davidson-Arnott, 2003).

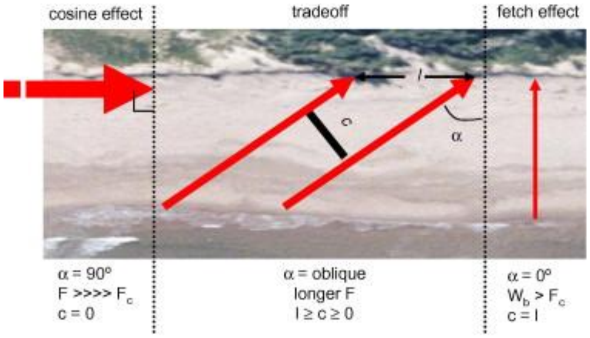

Fig. 5. Effect of wind angle, fetch effect, cosine effect and beach width on narrow beaches. Symbols are defined in Fig. 4.