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Comparison of different mass transport calculation methods for wind erosion quantification purposes

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ABSTRACT: Quantitative estimation of the material transported by the wind under field conditions is essential for the study and control of wind erosion. A critical step of this calculation is the integration of the curve that relates the variation of the amount of the material carried by the wind with height. Several mathematical procedures have been proposed for this calculation, but results are scarce and controversial. One objective of this study was to assess the efficiency of three mathematical models (a rational, an exponential, and a simplified Gaussian function) for the calculation of the mass transport, as compared to the linear spline interpolation. Another objective of this study was to compare the mass transport calculated from field measurements obtained from a minimum of three discrete sampling heights with measurements of nine sampling heights. With this purpose, wind erosion was measured under low surface roughness conditions on an Entic Haplustoll during 25 events. The rational function was found to be mathematically limited for the estimation of wind eroded sediment mass flux. The simplified Gaussian model did not fit to the vertical mass flux profile data. Linear spline interpolation generally produced higher mass transport estimates than the exponential equation, and it proved to be a very flexible and robust method. Using different sampling arrangements and different mass flux models can produce differences of more than 45% in mass transport estimates, even under similar field conditions. Under the conditions of this study, at least three points between the soil surface and 1·5 m high, including one point as closest as possible to the surface, should be sampled in order to obtain accurate mass transport estimates. Additionally, the linear spline interpolation and the non-linear regression using an exponential model, proved to be mathematically reliable methods for calculating the mass transport. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: wind erosion; mass transport; mass flux profile

Introduction

Quantitative estimation of the material transported by the wind is essential in the study and control of wind erosion. The amount of transported material, the so called mass transport Q (in kg/m), is generally obtained by vertically sampling the transport at discrete heights, fitting a simplified equation that describes the vertical mass flux profile to the data, and integrating this equation from the soil surface to a height. This method is widely accepted; however, results obtained with different sampling devices, placed at different heights from the surface and using different flux profile models make the interpretation and the comparison between studies difficult. Information related to the effects of applying different mathematical procedures for mass transport estimations is scarce. Although this may not always be possible, standard or comparable quantification methods are needed. Some of these facts led Stroosnijder (2005) to outline the existence of a crisis in erosion measurement.

During the past 60 years, considerable effort has been made to adequately describe the vertical mass flux profile. The horizontal mass flux profile is determined by complex relations between wind, soil, and field properties, and there is no one model for all circumstances. Numerous researchers empirically found that the height profile can be generally described by potential, exponential or logarithmic equations (Table I). In general, it has been considered that the mass flux decreases as the height increases; however, this fact is still being questioned by empirical evidence (Butterfield, 1999; Dong *et al.*, 2004a, 2004b). Although not very widespread, Gaussian peak functions have also been considered for mathematical description of the saltation layer (Zheng *et al.*, 2004; Shao, 2005; Li *et al.*, 2008). A thorough discussion about the saltation mass flux profile is provided by Li *et al.* (2008).

High sampling costs, mass flux profile variability, and difficulties in converting discrete measurements into an integrated total flux led to the use of different wind erosion quantification methods. However, assuming that the major

Table I. Empiric expressions used to describe the vertical mass flux profile

Expression[a]	Reference
$q = q_0(z/\sigma + 1)^{-\rho}$	Zingg (1953)
$q = q_0\exp(-az)$	Williams (1964)
$Q = q_0\exp(-a_1z - a_2z^2)$	Shao and Raupach (1992)
$q = q_0\exp(-az)$	Fryrear and Saleh (1993)
$q = f_0(z/\sigma + 1)^{-2}$	Stout and Zobeck (1996)
$Q = q_0\exp(-a_1z - a_2z^2)$	Gillette *et al.* (1997)
$q = q_0\exp(-z/b)$	Ni *et al.* (2002)
$q = q_0\exp(bz)$	Namikas (2003)

[a] q, mass flux at height z (in kg/m^2); q_0 and f_0, mass flux at height zero (in kg/m^2); z, height from soil surface (in meters); a, b, σ and ρ are regression coefficients.

Table II. Monthly preponderance of prevailing wind erosion direction (north-south)

J	F	M	A	M	J	J	A	S	O	N	D
2·4	4·4	2·1	1·7	3·1	2·8	5·4	6·2	3·7	2·6	3·3	2·3

part of the mass flux occurs near the soil surface and assuming isokinetic and stable sampling efficiency, using fewer samplers placed at higher sampling points should lead to lower mass transport estimations. Additionally, despite their goodness-of-fit when applied to measured data, some models are not easily used in combination with field measurements or there can be mathematical problems when trying to solve their integrals. For example, a power function causes sediment mass to go to infinity near to the soil surface (Vories and Fyrear, 1991), producing improper integrals when integrated from a height equal to zero. A consequence of this problem is that power functions are very sensitive to sampling heights near the surface (Buschiazzo and Zobeck, 2005). This analysis can also be applied, to a lesser extent, to logarithmic functions. These problems could be solved by using more complex equations, but models with many parameters require several sampling heights to be adequately fitted (Sterk and Raats, 1996), therefore requiring much sampling effort. Although methods may vary according to the aim of the study (Zobeck *et al.*, 2003), from a practical point of view, quantification methods should be robust enough to be applicable under a wide range of conditions, cost effective, simple to perform; and easy to interpret.

Most wind erosion mass flux studies have been carried out in wind tunnels, and field studies are generally based on a few erosion events or theoretical analysis. Long term, field wind erosion measurements account for intra and inter annual variability, allowing to evaluate the performance of the methods used for the estimation of mass transport rates under variable field conditions, and using a large amount of data. Although different sediment traps have been used for quantifying mass transport, BSNE (Big Spring Number Eight, Fryrear, 1986) samplers are widespread and their efficiency has been discussed (Shao *et al.*, 1993; Goosens and Offer, 2000). One of the aims of this work was to evaluate the effects of using three discrete sampling heights instead of sampling the full profile with six BSNE samplers plus a surface sampler (Zobeck, 2002) on mass transport estimates. A second objective was to test the performance of four simple mathematical approaches for calculating mass transport: two different widely used equations, a two-parameter Gaussian model, and a linear spline interpolation.

Materials and Methods

The study site was located at the Facultad de Agronomía of the Universidad Nacional de La Pampa, Santa Rosa, Argentina (36°30″ S latitude and 64° 30″ W longitude). The soil of the experimental site was a fine sandy loam Entic Haplustoll with an A-AC-C_1-C_{2k} horizon sequence. The organic matter content (Walkley and Black, 1934) of the A-horizon was 1·25%, and the particle size distribution determined with the pipette method was: 2000–246 μm, 15·7%; 246–104 μm, 30·2%; 104–74 μm, 15%; 74–50 μm, 11·7%; 50–20 μm, 9·7%; 20–2 μm, 7·4% and < 2 μm, 10·2%.

Wind erosion was measured in a 1 ha square field surrounded by a non-erodible boundary during 25 high wind events occurring between 2002 and 2007. The field was tilled periodically with a disc harrow in order to keep it bare and with minimum surface roughness during wind erosion measurements. Annual average soil chain roughness (Fryrear and Saleh, 1993) for the field was 1·2%; standard deviation (SD) = 0·45, and visual estimated weed cover varied between 0% and 10%.

Wind eroded material was collected in the field using BSNE aeolian sediment samplers (Fryrear, 1986), which were placed at three different heights (13·5, 50 and 150 cm). Additionally, one surface creep-saltation sampler (Zobeck, 2002) sampled at 0·15, 0·7 and 1·5 cm height, and one modified BSNE sampler (Fryrear, 1986) at 7, 12 and 22·5 cm height. The total sampler arrangement made a total of nine sampling heights. The three sampler clusters were located at the center of the field, working independently of each other and separated by 1·5 m. Different kinds of samplers have to be used because sampling near to the surface can be done only with special devices. A stated by Stout and Zobeck (1996) these samplers are based in the same operating principle. Nevertheless, there can be a difference in trapping efficiency between these samplers, but this difference remains constant through all the wind erosion events, making measurements comparable to each other. Due to the high wind speeds recorded during the analyzed events in combination with the homogeneous field conditions, spatial mass flux variability was assumed to be insignificant within the small sampling area at the center of the field.

The prevailing wind erosion direction (Skidmore, 1965) for this area is north-south during all the year, and its preponderance (ratio of parallel to perpendicular forces in relation to the prevailing wind erosion direction) is shown in Table II. Due to the preponderance of the prevailing wind erosion direction, the fetch effect was considered relatively constant. Minimum mean threshold wind speed at 2 m high for this experimental plot is 4·9 m/s (de Oro and Buschiazzo, 2008). Only events with mean wind speeds equal to or greater than 4·9 m/s were considered. The sampling length, as well as the averaged and maximum wind speed for each event are shown in Table III.

The horizontal mass flux (q, in kg/m^2) at each sampling point was calculated by dividing the amount of material collected by a sampler by the area of the sampler inlet (in kg/m^2). The remaining calculations were done with CurveExpert 1.38 © fitting software with default settings and using the interpolation, fitting and integration functions. Total mass transport (Q, in kg/m) was calculated for each erosion event by integrating a linear spline interpolation model (LI), which represents a set of line segments linking each data point, and by integrating the following equations (symbols are defined in Table I):

Table III. Average wind speeds at 2 m height for 25 wind erosion events

Date (dd/mm/yy)	Sampling period (hours)	Mean wind speed (m/s)	Maximum wind speed (m/s)	LI mass transport (Q9, kg/m)
18/12/2002	25	6·6	11·3	5·02
14/02/2003	47·5	5·3	12·9	1·77
24/02/2003	69	5·3	12·3	26·88
20/03/2003	21	6·4	17·5	59·31
21/02/2005	74·5	4·9	12·8	10·86
28/03/2005	112·5	5·1	–	0·94
28/09/2005	27	8·3	13·6	6·48
24/10/2005	65·5	4·9	15·5	3·86
04/11/2005	16·5	7·8	14·8	0·98
09/11/2005	28	6·1	10·6	0·42
23/11/2005	28·5	5·4	14·5	1·7
02/12/2005	30·5	7·6	17·1	2·22
13/12/2005	90·5	5·1	10·6	0·96
10/01/2006	22	5·8	13·3	16·77
12/01/2006	47	4·9	10·1	3·32
14/01/2006	29·5	6·1	10·3	4·52
18/01/2006	20	5·9	9·9	6·66
19/01/2006	24	7·3	11·6	35·57
19/04/2006	26	6	11·2	8·45
24/05/2006	26	6·7	12·5	5·93
01/06/2006	24	4·9	7·6	0·22
07/07/2006	4·5	7·9	12·1	0·88
30/05/2007	5	8·8	10·7	0·25
31/08/2007	47·5	5	10·7	8·64
04/09/2007	89	5·6	11·2	25·66

Note: LI, linear interpolation model; –, missing data.

$$q = f_0\left(\frac{z}{\sigma+1}\right)^{-2} \tag{1}$$

$$q = ae^{bz} \tag{2}$$

$$q = q_0 e^{-az^2} \tag{3}$$

The equation coefficients were calculated in each case using the Levenberg–Marquardt method (Levenberg, 1944; Marquardt, 1963) for solving non-linear regressions.

According to the definitions given in CurveExpert 1.38 (Copyright © 1995–2003 Daniel Hyams), for regression curve fits, error was assessed using the standard error and correlation coefficient. The standard error of the estimate is defined as follows:

$$S = \sqrt{\frac{\sum_{i=1}^{n_p}(y_i - f(x_i))^2}{n_p - n_{par}}}$$

where y denotes the value calculated from the regression model, y_i denotes the data points, and n_p is the number of parameters in the particular model (so that the denominator is the number of degrees of freedom). The standard error of the estimate quantifies the spread of the data points around the regression curve. As the quality of the data model increases, the standard error approaches zero.

Another measure of the 'goodness-of-fit' is the correlation coefficient. To explain the meaning of this measure, we must return to the data points and define the standard deviation, which quantifies the spread of the data around the mean:

$$S_t = \sum_{i=1}^{n_p}(\bar{y} - y_i)^2$$

where the average of the data points is simply given by

$$\bar{y} = \frac{1}{n_p}\sum_{i=1}^{n_p} y_i$$

The quantity S_t considers the spread around a constant line (the mean) as opposed to the spread around the regression model. This is the uncertainty of the dependent variable prior to regression. We also define the deviation from the fitting curve as

$$S_r = \sum_{i=1}^{n_p}(y_i - f(x_i))^2$$

Note the similarity of this expression to the standard error of the estimate given earlier; this quantity likewise measures the spread of the points around the fitting function. Thus, the improvement (or error reduction) due to describing the data in terms of a regression model can be quantified by subtracting the two quantities. Because the magnitude of the quantity is dependent on the scale of the data, this difference is normalized to yield

$$r = \sqrt{\frac{S_t - S_r}{S_t}}$$

where r is defined as the correlation coefficient. As the regression model better describes the data, the correlation coefficient will approach unity. For a perfect fit, the standard error of the estimate will approach $S_r = 0$ and the correlation coefficient will approach $r = 1$.

Then, integration was performed over the height using Simpson's 1/3 rule coupled with the Romberg integration method (Romberg, 1955). Integration was performed in all cases from 0 to 150 cm height.

Linear spline interpolation is a powerful and undemanding technique used in many sciences. Considering horizontal mass flux variability and fitting procedure limitations, linear spline interpolation was considered as a reference method due to its robustness and simplicity.

In order to test the effect of sampler height and number on the *Q*, Equations 1, 2 and 3 were integrated using data collected from heights of (a) 0·15, 0·7, 1·5, 7, 12, 13·5, 22·5, 50, 150 cm (Q9), and (b) 13·5, 50, 150 cm (Q3).

Models can be fitted to many different combinations of heights. The 13·5 cm height was chosen because it is the lowest mean sampling height at which an ordinary BSNE sampler can be mounted. The 1·5 m height was chosen because it is representative of the upper part of the standard boundary layer (2 m) for wind erosion processes at the agricultural field scale. Mass flux at higher levels is generally neglectable under the experimental plot conditions. The 0·5 m height was chosen because it was considered representative of the upper part of the saltation layer, but any other similar height could have been used for this purpose. Using more than three sampling heights for describing the mass flux profile might be unnecessary, but using only two would provide insufficient information for fitting any model.

Results and Discussion

Models performance for nine sampling heights (Q9)

The fitting of Equation 1 using nine sampling heights was not possible in 14 from a total of 25 storms. Greater mass flux variability and hence greater error can be expected at lower sampling heights, and too scattered data in this section of the profile can produce model inadequacies during the regression process, meaning that the model did not describe the data correctly. Although applying a weighting scheme could reduce these inadequacies, it was not used in this case in order to simplify the analysis. For the remaining 11 storms the correlation coefficients (*r*) for the relation between height and horizontal flux ranged from 0·73 to 0·99 (mean $r = 0{\cdot}90$) and the SD of *r* was 0·09. The standard error of the estimate (*S*) ranged from 0·23 to 14·8 (mean $S = 2{\cdot}52$; SD = 4·17). Regardless of the goodness of the fit, mathematical problems were detected in two cases (Table IV). Equation 1 is a rational function not defined for $z = (-\sigma)$. When the regression process yields negative values for this parameter, this function cannot be properly integrated between 0 and 1·5 m because the integration interval is discontinuous. Height (*z*) can take positive and negative values because the domain of this function is the set of all real numbers except $(-\sigma)$. Only *z* values > 0 are considered, but when $\sigma < 0$ the model is not defined for every positive height. The integration of this improper integral can cause mass transport to be significantly overestimated because the discontinuity causes mass to go to infinity at $z = (-\sigma)$. Moreover, under certain calculation procedures, this fact can also produce negative mass transport values. An example of this problem for Equation 1, corresponding to a typical wind erosion event that occurred on December 13, 2005, is shown in Figure 1. Consequently, the use of Equation 1 should be restricted to the cases when $\sigma > 0$. Sterk and Raats (1996) used a similar rational function, but they avoided this problem by assuming a constant value for the parameter (σ).

Table IV. Mass transport values calculated with Equation 1 and linear interpolation (LI) for two wind erosion events

Date (dd/mm/yy)	*S*	*r*	f_0	Σ	kg/m (Equation 1)	kg/m (LI)
13/12/2005	1·71	0·78	2·76	–0·04	3528·89	0·96
01/06/2006	0·23	0·98	0·15	–0·02	–1570·41	0·22

Note: *S*, standard error of the estimate; *r*, correlation coefficient.

Similar problems were previously reported by Vories and Fryrear (1991) for a power function. For the power or logarithmic functions, mass flux is infinite close to the soil surface (height zero), so these models will have practical constraints when calculating mass transport at this height. If a minimum integration height is arbitrarily defined or parameters such as roughness length are kept constant in order to force a lower limit for the integration interval, then the absence of mass flux at some point within the vertical profile is assumed. This produces a misrepresentation of the physical process, and could lead to unreal mass transport estimates.

The fitting of the exponential model (Equation 2) was adequate for the 25 studied storms. Its *r* values ranged from 0·50 to 0·99 (mean $r = 0{\cdot}89$, SD = 0·12) and the standard error of the estimate ranged between 0·24 and 144·82 (mean $S = 17{\cdot}45$; SD = 33·70). The predicted exponential curve and the measured mass data for the December 13, 2005 event are shown in Figure 2.

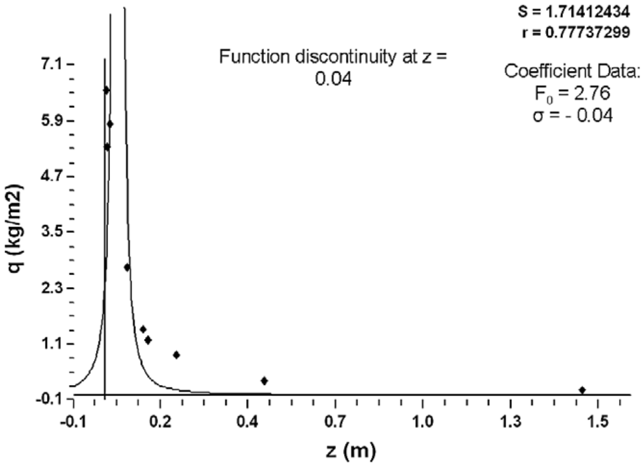

Figure 1. Equation 1 fitted to measured mass data for the December 13, 2005 event, showing discontinuity within integration interval [0, 1·5 m].

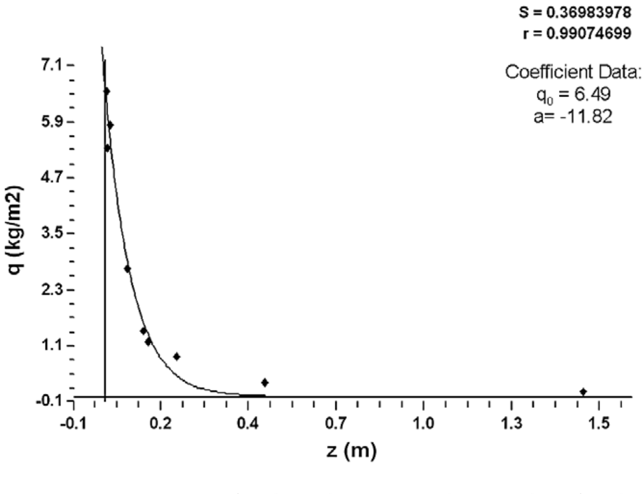

Figure 2. Equation 2 fitted to the measured mass data for the December 13, 2005 event.

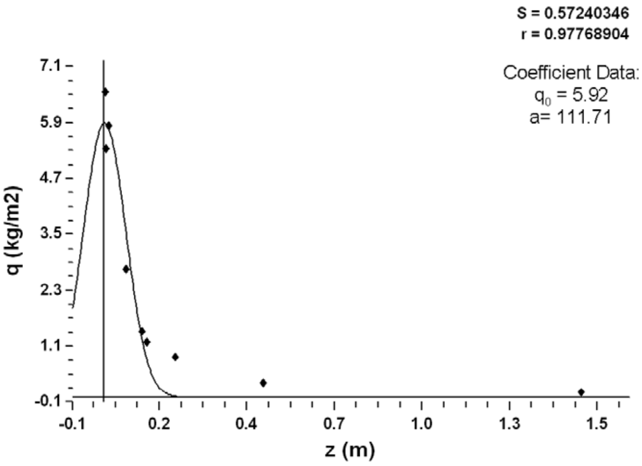

Figure 3. Equation 3 fitted to the measured mass data for the December 13, 2005 event.

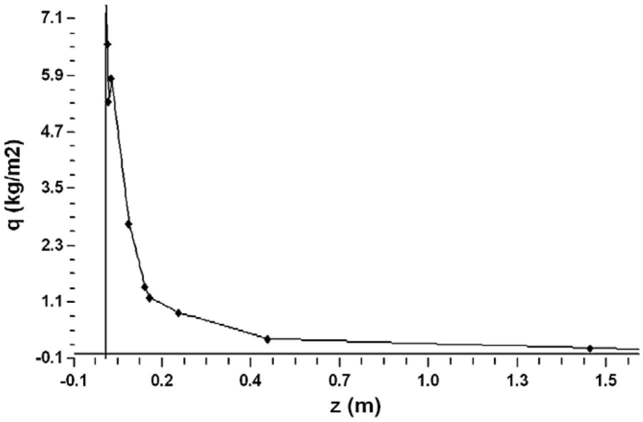

Figure 4. Linear spline interpolation between measured mass data for the December 13, 2005.

The Gaussian curve (Equation 3) did not fit to the nine sampling height data in seven of 25 storms. According to Shao (2005), the mass flux profile tends to be Gaussian as particle size decreases and turbulence increases, and exponential as particle size increases and turbulence decreases. Despite the presence of fine particles in the soil surface layer, under certain field conditions like crusting, high soil humidity, or low roughness length, the mass flux tends to be dominated by the saltation of coarse particles, and hence better described by an exponential model. Mean *r* for the exponential regression for these seven events was 0·93. For the rest of the data sets (18) the *r* values for the Gaussian model ranged from 0·57 to 0·98 (mean *r* = 0·87, SD = 0·11) and the standard error ranged from 0·23 to 28·85 (mean *S* = 7·57; SD = 7·80). Mass data predicted with the Gaussian curve and those measured for the December 13, 2005 event are shown in Figure 3.

The linear spline interpolation model for the December 13, 2005 event is shown in Figure 4. The Q9 mass values computed using the spline interpolation model, generally resulted in higher values than those obtained with Equation 2. Hence, total mass transport calculated with linear spline interpolation model resulted 16·8% higher than with Equation 2 (Figure 5). This result was expectable, because the model that better describes the vertical profile near the soil surface was the spline interpolation model. In addition, straight lines connecting points tend to produce a greater area for integration.

The distribution of the mass with height is frequently highly variable when sampling wind erosion at the field level. Under these conditions the non-linear regression can be difficult to apply. In spite of these difficulties, the exponential model (Equation 2), proposed by numerous authors, was found to be simple and robust enough to be used for field measurements, allowing the identification of two parameters: the mass flux at height zero and the decay rate. Alternatively, linear interpolation allows the analysis of the data 'as is', ensuring that the fitted line passes through every data point. This simple method proved to be very robust and easy to apply to any vertical profile. Although relative efficiencies of each sampler can be questioned, they are supposed to be stable during all the wind erosion events, making comparisons reasonable. Moreover, mass flux profiles found in this study do not differ significantly from wind eroded sediment profiles found in previous studies under field and wind tunnel conditions (Sterk and Raats, 1996; Stout and Zobeck, 1996; Ni *et al.*, 2002; Namikas, 2003; Liu *et al.*, 2005; Dong and Quian, 2007).

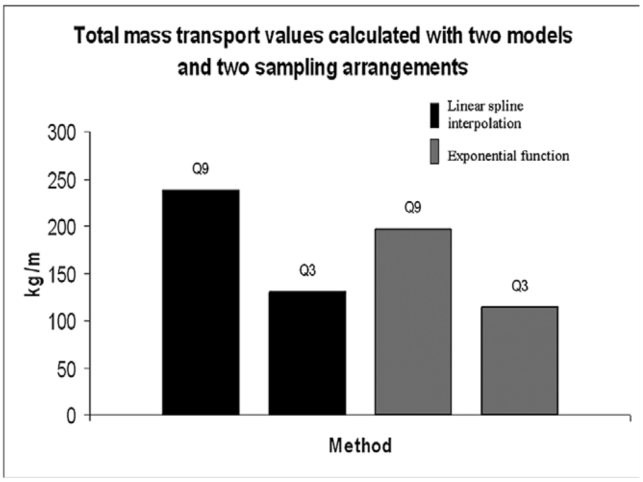

Figure 5. Total mass transport of 25 wind erosion events, calculated with two different models: a linear interpolation and an exponential function (Equation 2), and two different sampling arrangements: nine points (Q9) and three points (Q3).

Models performance for three sampling heights (Q3)

As Equations (1) and (3) did not fit adequately for nine sampling heights in most of the studied storms, they were not considered in this analysis.

Results showed that, as expected, the fitting of Equation 2 to three sampling points yielded very good results, with *r* values ranging from 0·71 to 0·99 (mean *r* = 0·98; SD = 0·06). Standard error of the estimate ranged from 0 to 2·08, (mean *S* = 0·32, SD = 0·46). The total mass transport (Q9) obtained using the linear spline interpolation, resulted 12·3% higher than with Equation 2 (Figure 5). Nevertheless, when using three sampling points (Q3), both models described the data in a similar way because the sampling points near the surface were missing (Figure 6).

When fitting Equation 2 to only three sampling heights, near the soil surface (0·007; 0·07 and 13·5 cm), *r* values ranged from 0·27 to 0·99 (mean *r* = 0·89; SD = 0·19). Standard error of the estimate ranged from 0·03 to 29·09, (mean *S* = 5·80, SD = 8·66). Integration of the exponential model between 0 and 13·5 cm yielded a total mass transport of 152·13 kg/m (57% lower than using 13·5, 50 and 150 cm). But when integration was performed between 0 and 1·5 m height, exceedingly high mass transport values were calculated during three (12%) of

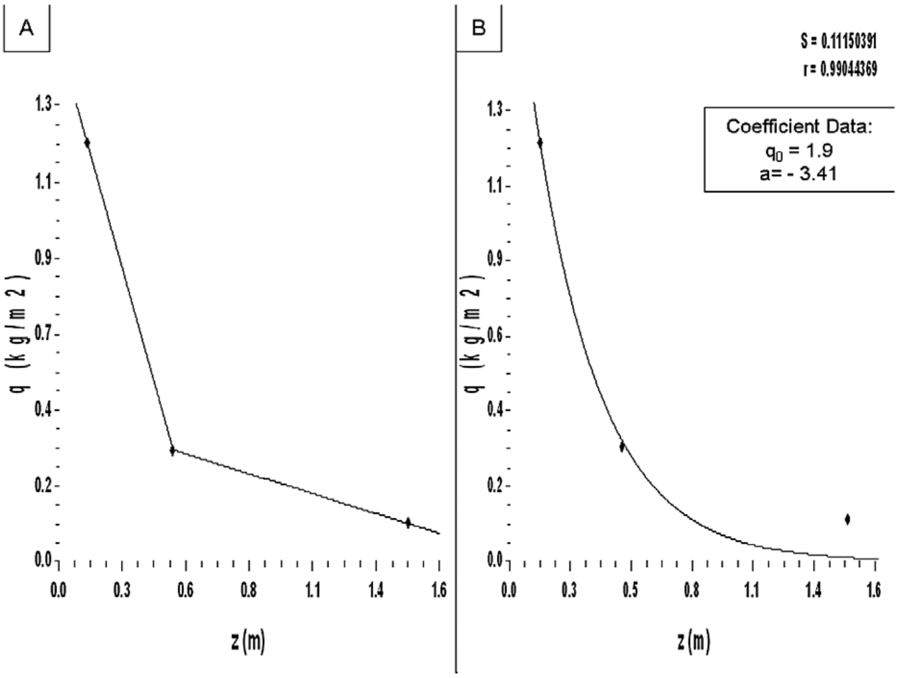

Figure 6. Linear interpolation (A) and Equation 2 (B) fitted to mass data measured with three sampling heights for the December 13, 2005 event.

the analyzed events, and the total mass transport increased to 595·08 kg/m. In these cases, the lowest *r* values were obtained (0·27 < *r* > 0·52), and slightly higher mass flux values were obtained at higher samplers, so the exponential curve resulted positive. Friction velocity, roughness length, and particle size distribution of the wind eroded material affect the shape of the vertical mass flux profile (Shao, 2005), and these factors are highly variable under field conditions. According to Dong and Quian (2007) it is possible that mass flux increases with increasing height in the lowest layer because the velocity of the saltating particles increases rapidly with height within that layer. Hence, as in other research areas, model extrapolation is not convenient when using data from sampling points placed too close to each other. The linear interpolation cannot be extrapolated to 1·5 m in this case (because it crosses the positive *x* axis close to 13·5 cm). Though, it yielded a total mass transport of 165·8 kg/m (8·2% higher than with Equation 2, but 59% lower than using 13·5, 50 and 150 cm). Hence, considering extrapolation constraints, mass transport can be calculated using three near surface sampling heights, but reduction of the integration area will tend to produce low values. Moreover, field sampling near to the soil surface requires special samplers which are expensive and their use very time consuming.

Mass transport calculated at both sampling heights (Q9 and Q3)

Linear regressions comparing Q9 and Q3 values obtained with Equation 2 and with linear spline interpolation fitted well (Table V). The relative underestimation for Q3 in relation to Q9 for the 25 wind erosion events, calculated for each event with the equation [(1 − Q3/Q9) × 100], was 43% when calculated with the linear spline interpolation (SD = 32), and 28% when calculated with Equation 2 (SD = 46). Nevertheless, the accumulated Q3 value was 42% lower than the corresponding Q9 when using Equation 2, and 45% lower when using linear spline inerpolation (Figure 4). These results show that mass transport calculated with Equation 2 was less affected by sampling height near the surface.

Table V. Equations and determination coefficients for linear regressions (*n* = 25) between Q3 and Q9 calculated with Equation 2 (E2) and the linear spline interpolation (LI)

Case	Equation	R^2
Q9(E2) versus Q9(LI)	Q9(LI) = 1·06Q9(E2) + 1·13	0·98
Q3(E2) versus Q3(LI)	Q3(LI) = 1·13Q3(E2) + 0·06	0·99
Q9(LI) versus Q3(LI)	Q3 = 0·69Q9 − 1·39	0·80
Q9(E2) versus Q3(E2)	Q3 = 0·68Q9 − 0·85	0·87

The importance of sampling the first centimeters of the mass flux profile in order to obtain a good estimate is well known. Nevertheless, sampling near the surface is normally difficult due to sampler size and field characteristics. Sampling at higher heights may be also needed for correct model extrapolation. When using the three sampling heights established in this study, the linear spline interpolation allowed better approximation to real (nine height estimated) mass transport rates. Despite this, the exponential model underestimated mass transport to a lesser extent when using three sampling heights and it allowed better linear correlation between the three height and the nine height results to be obtained. Hence, this method resulted in being better for use in combination with higher sampling heights.

As discussed before for Q9 values, the exponential model needs to be fitted to the data, whilst the linear spline interpolation describes the data 'as is', being more influenced by greater mass fluxes near the surface and tending to produce a greater integration area. Mass flux irregularity is a common issue under agricultural field conditions and it can cause the failure of regression procedures, especially in the presence of high surface roughness, vegetation, or residues. Meanwhile, the linear spline interpolation was found to be very robust as well as easy to use, and it could be considered as a feasible method when analyzing field data, especially complex vertical profiles, where ordinary regression may fail. Moreover, due to the higher mass transport values obtained, the linear spline interpolation could be taken into account if soil conservation is the critical target and regression results uncertain. This does not exclude using relative values when comparing conservation practices, but according to the results presented, mass transport and soil loss may well be calculated according to the precautionary principle, which is a way to deal with uncertainty about the potential dangers of activities, and it has been increasingly applied in many sciences during the last 10 years. In this case, the possibility of a greater soil loss than the estimated should be considered.

Conclusions

Results showed that under similar field conditions, mass transport amounts can differ more than 45% if calculated using different sampling heights or mathematical models.

The rational function proposed by Zingg (1953) and modified by Stout and Zobeck (1996) was found to be difficult to use when its σ factor was smaller than zero.

The simplified Gaussian model did not fit the data by means of ordinary non-linear regression. Hence, this model is considered not suitable for soil wind erosion estimates under the conditions of this study.

A simple exponential approach, previously proposed by many authors, proved to be very robust, fitting the field data adequately (mean $r = 0{\cdot}89$, mean $S = 17{\cdot}45$). This method is simple to apply and easy to interpret, showing no discontinuity within the integration interval.

The linear spline interpolation tends to produce higher mass transport values than the exponential model, but results of both models were highly correlated. A disadvantage of the linear interpolation is that it does not allow the estimation of the parameters representing different mass flux profile properties.

Using data from three discrete sampling heights instead of nine generally resulted in lowered mass transport values. Differences obtained between the two sampling clusters in this study are mainly due to mass flux passing below 13·5 cm.

A three height sampling arrangement, one placed at 13·5 cm, one at 50 cm, and the other at 150 cm approximately, could be used in combination with the integration of an exponential model to obtain acceptable mass transport estimates under low surface roughness conditions.

Independently of the mass flux model applied, if the vertical profile is not entirely sampled, mass transport should be corrected using a correction factor accounting for mass transport reduction.

Further research using vertically integrating samplers will allow a better evaluation of benefits and costs of discrete height sampling at the field level.

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References

Buschiazzo DE, Zobeck TM. 2005. Airborne horizontal mass flux calculated with different equations. *Proceedings, Asae Annual International Meeting*, 17–20 July, Florida.

Butterfield GR. 1999. Near-bed mass flux profiles in aeolian sand transport: high-resolution measurements in a wind-tunnel. *Earth Surface Processes and Landforms* **24**: 393–412.

de Oro LA, Buschiazzo DE. 2008. Threshold wind velocity as an index of soil susceptibility to wind erosion under variable climatic conditions. *Land Degradation and Development* **20**: 14–21. DOI. 101002/ldr.863

Dong Z, Wang H, Liu X, Wang X. 2004a. The blown sand flux over a sandy surface: a wind-tunnel investigation on the fetch effect. *Geomorphology* **57**: 117–127. DOI, 10.1016/S0169-555X(03)00087-4

Dong Z, Wang H, Liu X, Wang X. 2004b. A wind-tunnel investigation of the influences of fetch length on the flux profile of a sand cloud blowing over a gravel surface. *Earth Surface Processes and Landforms* **29**: 1613–1626. DOI. 10.1002/esp.1116

Dong Z, Quian G. 2007. Characterizing the height profile of the flux of wind eroded sediment. *Environmental Geology* **51**: 835845. DOI. 10.1007/s00254006-0363-5

Fryrear DW. 1986. A field dust sampler. *Journal of Soil and Water Conservation* **41**: 117–120.

Fryrear DW, Saleh A. 1993. Field wind erosion: vertical distribution. *Soil Science* **155**: 294–300.

Gillette DA, Fryrear DW, Xiao JB, Stockton PH, Ono D, Helm PJ, Gill TE, Ley T. 1997. Large scale variability of wind erosion mass flux rates at Owens Lake: vertical profiles of horizontal mass fluxes of wind eroded particles with diameter greater than 50 μm. *Journal of Geophysical Research* **102**: 25977–25987.

Goosens D, Offer ZY. 2000. Wind tunnel and field calibration of six aeolian dust samplers. *Atmospheric Environment* **34**, 1043–1057.

Levenberg K. 1944. A method for the solution of certain problems in least squares. *Quarterly of Applied Mathematics* **2**: 164–168.

Li WY, Lü SH, Shen ZB. 2008. Improvement and application of the similarity saltation model: wind-tunnel experimental investigation and numerical simulation of the vertical sand mass flux distribution in the saltation layer. *Boundary Layer Meteorology* **127**: 313–332. DOI. 10.1007/s10546-007-9257-7

Marquardt D. 1963. An algorithm for least squares estimation of nonlinear parameters. *Journal of the Society for Industrial and Applied Mathematics* **11**: 431–441.

Namikas SL. 2003. Field measurement and numerical modelling of aeolian mass flux distributions on a sandy beach. *Sedimentology* **50**: 303–326. DOI. 10.1046/j.1365-3091.2003.00556.x

Ni JR, Li ZS, Mendoza C. 2002. Vertical profiles of aeolian sand mas flux. *Geomorphology* **49**: 205–218.

Romberg W. 1955. Vereinfachte numerische Integration. *Norske Videnskabers Selskab Forhandlinger* **28**: 30–36.

Shao Y. 2005. A similarity theory for saltation and application to aeolian mass flux. *Boundary Layer Meteorology* **115**: 319 – 338. DOI. 10.1007/s10546-004-4632-0

Shao Y, Raupach MR. 1992. The overshoot and equilibration of saltation. *Journal of Geophysical Research* **97**: 20559–20564.

Shao Y, Mctainsh GH, Leys JF, Raupach MR. 1993. Efficiency of sediment samplers for wind erosion measurement. *Australian Journal of Soil Research* **31**: 519–532.

Skidmore EL. 1965. Assessing wind erosion forces: directions and relative magnitudes. *Soil Science Society of America Proceedings* **29**: 602–608.

Sterk G, Raats PAC. 1996. Comparison of models describing the vertical distribution of wind eroded sediment. *Soil Science Society of America Journal* **60**: 1914–1919.

Stout JE, Fryrear DW. 1989. Performance of a windblown particle sampler. *Transactions of the ASAE* **32**: 2041–2045.

Stout JE, Zobeck, TM. 1996. The Wolfforth field experiment: a wind erosion study. *Soil Science* **161**: 616–632.

Stroosnijder L. 2005. Measurement of erosion: is it possible? *Catena* **64**: 162–173. DOI. 10.1016/j.catena.2005.08.004

Vories ED, Fryrear DW. 1991. Vertical distribution of wind eroded soil over a smooth, bare field. *Transactions of the ASAE* **34**: 1763–1768.

Walkley A, Black IA. 1934. An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* **37**: 29–37.

Williams G. 1964. Some aspects of the eolian saltation load. *Sedimentology* **3**: 257–287.

Zheng X, He L, Wu J. 2004. Vertical profiles of mass flux for wind-blown sand movement at steady state. *Journal of Geophysical Research* **109**, B01106. DOI. 10.1029/2003JB002656

Zingg AW. 1953. Wind tunnel studies of the movement of sedimentary material. *Proceedings of the Fifth Hydraulic Conference Bulletin* **34**: 111–135.

Zobeck TM. 2002. Field measurement of erosion by wind. In *Encyclopedia of Soil Science*, Lal R (ed.). Marcel Dekker: New York; 503–507.

Zobeck TM, Sterk G, Funk R, Rajot JL, Stout. JE, Van Pelt RS. 2003. Measurement and data analysis methods for field scale wind erosion studies and model validation. *Earth Surface Processes and Landforms* **28**: 1163–1188. DOI. 10.1002/esp.1033