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Field wind erosion measurements with Big Spring Number Eight (BSNE) and Modified Wilson and Cook (MWAC) samplers

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A B S T R A C T

The aim of this study was to compare the horizontal mass flux (HMF) of Aeolian sediment obtained from field wind erosion measurements with the Modified Wilson and Cook (MWAC) and Big Spring Number Eight (BSNE) and to analyze the effectiveness of exponential, power, logarithmic and rational equations to calculate the horizontal mass transport (HMT) for each sampler type. With this purpose wind erosion was measured on fine sandy loam soil in 10 erosion events between December 4, 2008 and July 1, 2009. The relative efficiency of the MWAC related to BSNE ($RE_{W/B}$, quotient between the HMF of MWAC and the HMF of BSNE multiplied by 100) was 247% while $RE_{W/B}$ obtained from the absolute efficiency of the BSNE (85% to 95%) and MWAC (44% to 120%) found in previous studies, was between 51% and 141%. The $RE_{W/B}$ increased with height, as a consequence of the wind speed increase and particle size decrease, which reduces the efficiency of the BSNE while the efficiency of the MWAC remains constant. Depending on the equation used, the HMT of MWAC was from 2.1 to 2.53 times higher than the HMT of BSNE indicating that if the HMF is corrected by the $RE_{W/B}$, found in this study, the HMT obtained with the MWAC and BSNE is similar. The HMT obtained from exponential equations was 16% higher than the power equation and, 62% and 11% lower than logarithmic and rational equations respectively. In spite of this, the HMT obtained with different equations presented a good relationship with each other ($p<0.05$), indicating that the HMT can be corrected and compared between equations. This study shows that the HMF and HMT data obtained from field measurements with the BSNE and MWAC are different. Nevertheless, comparable measurements of wind erosion can be obtained with both samplers taking into account the relative efficiency and the relationship between equations found in this study.

1. Introduction

Accurate estimations of the material transported by the wind are necessary to quantify the wind erosion process, to validate the wind erosion prediction models and to evaluate the mechanisms of wind erosion control (Zobeck et al., 2003). Different sampler types are used to measure the horizontal mass flux (HMF), and different equations have been developed to calculate the horizontal mass transport (HMT). However, little knowledge is available about the relationships between the HMT of different samplers calculated with different equations.

Many samplers have been developed for measuring the material transported by wind (Goossens et al., 2000), though the Big Spring Number Eight (BSNE, Fryrear, 1986) and the Modified Wilson and Cook (MWAC, Wilson and Cooke, 1980; Kuntze et al., 1990) samplers are the most commonly used (Zobeck et al., 2003).

The BSNE samplers are used in many countries like Australia and the USA for the quantification of the material transported by saltation and rolling, while the MWAC samplers are more commonly used in Europe, and in the European Wind Erosion Projects (WELSONS, WEELS, for example) (Goossens et al., 2000).

The BSNE and MWAC samplers have been calibrated for catching sand and dust particles by means of wind tunnel simulations (Fryrear, 1986; Sterk, 1993; Shao et al., 1993; Bakkum, 1994; Pollet, 1995; Goossens et al., 2000; Funk et al., 2004). Some of those studies included few field measurements to confirm the results obtained in wind tunnels. Both sampler types are used for sampling material at different heights in order to calculate the total mass transport associated to soil losses by wind erosion. The sampling efficiency of both traps depends on wind speed and particle sizes (Fryrear, 1986; Shao et al., 1993; Goossens et al., 2000). Sampling efficiency of the MWAC remains constant but BSNE's efficiency decreases with wind speed, due to the higher stagnation pressure in the BSNE at higher

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wind speeds (Goossen et al., 2000). The stagnation pressure effect is higher for small particles, because they have lesser inertia and response time to changes in the air flow. Eddies generated in the inlet edge of the sampler cause small particles to be transported outside the sampler.

As a consequence of the lower efficiency of BSNE in relation to MWAC samplers at higher wind speed and lower particle size, and considering that wind speed increases and the particle size decreases with height, it can be expected that the amount of material collected by MWAC related to BSNE will also increase with height. This should have consequences for calculating the total amount of transported material.

Different equations have been used to describe the vertical distribution of the collected material with height, and their integration makes possible the estimation of the HMT. Such equations are exponential (Greeley et al., 1983; Anderson and Hallet, 1986; Dong et al., 2003), logarithmic (Zingg, 1953; Rasmussen and Mikkelsen, 1998; Namikas, 2003) or power type (Zingg, 1953; Chepil and Woodruff, 1957; Rasmussen and Mikkelsen, 1998). Models that mix potential or potential modified equations with exponential, also known as rational models, have been used by Stout and Zobeck (1996), Sterk and Raats (1996), Hasi (1997) and Butterfield (1999). Equations are generally derived from experiments with pure sand or sandy soils, where saltation is the dominating transport form.

Most of the mentioned studies have been developed under controlled wind tunnel conditions. Few attempts have been made to obtain reliable HMT calculations based on field measurements (Sterk and Raats, 1996; Funk et al., 2004; Stroosnijder, 2005). Buschiazzo and Zobeck (2005) carried out field measurements with the BSNE samplers and found that the HMT calculated with a potential equation is from 40% to 55% lower than those calculated with the rational equation (Stout and Zobeck, 1996). The use of different sampling arrangements and different mass flux models can produce differences of more than 45% in mass transport estimates, even under similar field conditions (Panebianco et al., 2010).

The aim of this study was to compare the HMF obtained from field measurements with the MWAC and BSNE samplers and to analyze the effectiveness of different equations to calculate the HMT for each sampler type.

2. Materials and methods

2.1. Field measurements

This study was carried out on a site of the semiarid Pampas of Argentina placed at 36° 46" S lat. and 64° 16" W long., and 210 m above sea level (a.s.l.). The soil of the study area is an Entic Haplustoll (Aimar, 2002) with a sandy fine loam surface A horizon containing 1.25% organic matter, 13.2% clay, 70.5% sand, 16.3% silt, a pH of 6, and 19 mg kg^{-1} Bray Kurtz I extractable P. The dry grain-size distribution obtained by dry sieving and the mean grain-diameter are in the Table 1.

Erosion was measured on a 1 ha square bare and flat plot during 10 wind erosion events that occurred between December 4, 2008 and July 1, 2009. The MWAC and BSNE samplers were placed in five points along a NE–SW oriented transect within the 1 ha plot at 0, 30, 60, 90 and 120 m distance from NE plot edge. Both sampler models were placed at 12.5, 22, 35, 50 and 150 cm height at each sampling point. The collected material after each storm was weighed with a precision scale (0.0001 g of precision).

To characterize the soil conditions during the measurements, soil samples were taken from the first 2.5 cm, one day before and after each storm for the determination of the gravimetric water content (dried to 105 °C). Soil coverage with weeds and non-erodible aggregates was determined using the frequency method based on the counting of the number of points in which weeds or aggregates overlapped the intersection points of a 4×4 cm grid. Such determination was made on a PC screen from 5 digital photographs which were taken simultaneously with soil moisture.

Wind speed was registered by means of a Davis Vantage Pro automatic meteorological station placed in the middle of the sampling plot. Table 2 shows the main characteristics of the analyzed wind storms.

The horizontal mass flux (HMF), the amount of soil passing by unit area of a vertical plane in each individual sampler, was calculated by dividing the amount of material by the sampler opening. This allowed the calculation of HMF for the MWAC (HMF_M) and the BSNE (HMF_B).

The relative efficiency of MWAC related to BSNE was calculated using the following equation:

$$RE_{W/B} = \left(\frac{HMF_M}{HMF_B}\right) \times 100 \quad (1)$$

where $RE_{W/B}$ is the relative efficiency of the MWAC related to BSNE (%), HMF_M is the horizontal mass flux of the MWACs (g cm^{-2}) and HMF_B the horizontal mass flux of the BSNEs (g cm^{-2}).

The horizontal mass transport (HMT), the amount of soil passing by unit area of a horizontal plane defined between two definite heights, was calculated for each sampling point by integrating the exponential, power, logarithmic and rational equations (Eqs. (1), (2), (3) and (4) respectively) which fit a HMF variation as a function of height, between 12.5 and 150 cm height. The integrations were made between 12.5 and 150 cm height, because little changes in the lower boundary for the vertical integration have different effects on the amount of material calculated with each equation (Funk et al., 2004; Panebianco et al., 2010).

$$f(z) = \sigma e^{-\beta/z} \quad (2)$$

$$f(z) = \sigma z^{-\beta} \quad (3)$$

$$\ln f(z) = f_0 + \sigma \ln z \quad (4)$$

$$f(z) = f_0(1 + z/\sigma)^{-\beta} \quad (5)$$

Table 1
Grain-size distribution and mean grain-diameter of each soil.

	Range in particle size (um)						
	<50	50–75	75–100	100–250	250–500	>500	MGD
	(%)						µm
Wind tunnel soil	0.8	1.2	3.0	56.8	37.4	0.8	165
Field soil	7.1	10.8	15.8	37.1	17.1	12.2	121

MGD, mean grain-diameter.

Table 2
Main characteristics of the studied storms.

	Moisture (%)	Soil cover (%)	AWS (m s^{-1})	AMWS (m s^{-1})	Duration (minutes)
04/12/2008[a]	4	49.2	6.36	9.4	134
12/10/2008	5.3	25.7	–	–	–
01/04/2009[b]	–	–	2.7	4	1260
06/04/2009[b]	–	–	2.6	4	600
14/04/2009[b]	–	27.8	2.7	4	780
22/04/2009[b]	1.4	–	2.9	4	540
04/06/2009[b]	5.2	29.1	2.6	3.1	360
12/06/2009[b]	3.2	20.2	2.8	4	960
26/06/2009[c]	5	18.3	7.5	10.3	1430
01/07/2009[c]	2.8	15	2.3	4	330

AWS, average wind speed; AMWS, average maximum wind speed; SD, storm duration.
[a] Meteorological station record each 1 min.
[b] Meteorological station record each 60 min.
[c] Meteorological station record each 5 min.

where, $f(z)$ is the horizontal mass flux (HMF), f_0 is the HMF at the soil surface, z is the height and σ and β are equation coefficients.

The integration of HMF_M and HMF_B by means of each equation allowed the estimation of the HMT of the MWAC (HMT_M) and of the BSNE (HMT_B) for each equation.

The HMF_M, HMT_B and the HMT of the used samplers and equations were correlated by the linear regression analysis program of Microsoft Excel.

2.2. Wind tunnel experiment

A wind tunnel was used to measure the HMF_B and HMF_M under controlled conditions. The wind tunnel was 0.5 m wide, 1 m high and 8 m long. No abrasion device was used and the wind profile fitted a power equation. Constructive details of the wind tunnel are given in Fig. 1, and calibration results can be consulted in Mendez et al. (2006). The BSNE and MWAC samplers were installed at the end of the wind tunnel at 0.15, 0.5 and 0.75 m height. The sandy soil used for the simulations remained smooth and loose during the three simulations made with each sampler. The dry grain-size distribution and the mean grain-diameter of the sandy soil are shown in Table 1.

Each wind tunnel simulation lasted 3 min and the mean wind speed at 0.3 m height was 9.5 m s^{-1} when the BSNE was tested and 9.2 m s^{-1} when the MWAC were tested.

The soil trapped by the samplers was weighed on an analytical scale. The $RE_{W/B}$ of the wind tunnel experiments was calculated using Eq. (1). The HMF_B was related to HMF_M using the linear regression program of Microsoft Excel.

3. Results and discussion

The BSNE samplers collected between 0.002 and 28.4 g of sediment and the MWAC between 0.0009 and 2.97 g. The greater amount of material trapped by the BSNE is related to a sampler opening area which is 22.4 times larger in BSNE than in MWAC. This indicates that the BSNE is more suitable for studies where the later quality analysis of the transported soil is the main aim and the amount of sediment transported is scarce. One option to increase the amount of soil collected by the MWAC could be to increase its inlet area and the flask volume, but in this case the performance of MWAC should be tested again.

The horizontal mass flux of BSNE (HMF_B) varied between $2.3\,10^{-4}$ and 2.6 g cm^{-2} while the HMF of MWAC (HMF_M) varied between $2.12\,10^{-4}$ and 6.4 g cm^{-2}. In spite of these differences, the HMF_M correlated well with the HMF_B when all sampling heights were considered together (Fig. 2) or when each sampling height was considered separately (Table 3). When all sampling heights were considered together HMF_M was 2.47 times higher than HMF_B, indicating that the relative efficiency of MWAC related to BSNE

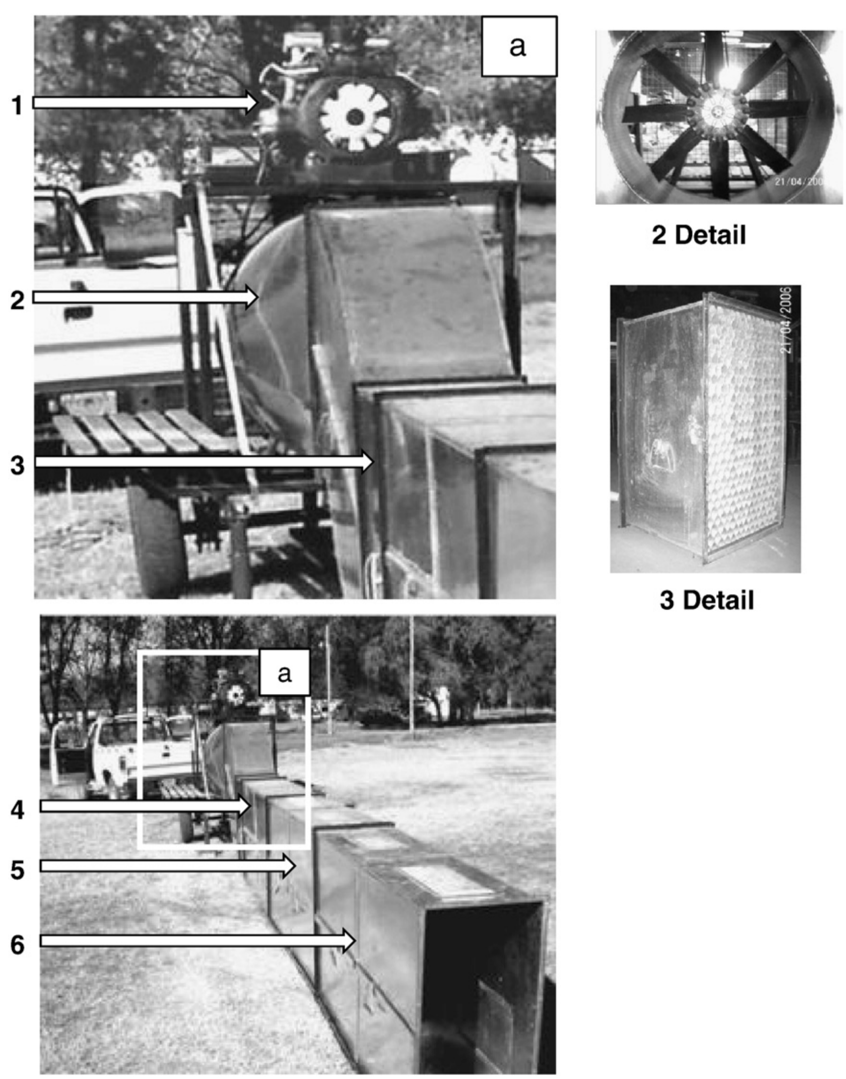

Fig. 1. Wind tunnel: 1) engine, 2) propeller, 3) honeycomb diffusor, 4) stabilization section (2 m long) and 5) and 6) working sections (each one 2 m long).

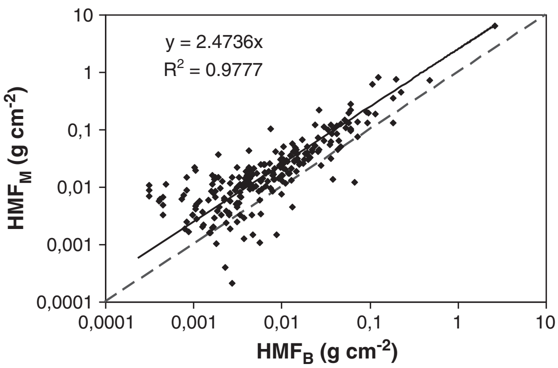

Fig. 2. Relationship between the horizontal mass flux of BSNE (HMFB) and horizontal mass flux of MWAC (HMFM). Dotted line represents the 1:1 fit and solid line represents the regression.

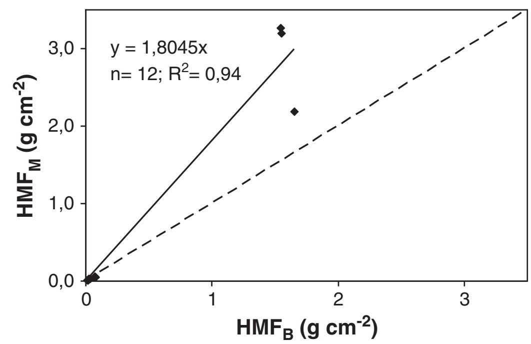

Fig. 3. Relationship between the horizontal mass flux of BSNE (HMFB) and horizontal mass flux of MWAC (HMFM) obtained from wind tunnel measurements. Dotted line represent the 1:1 fit and solid line represent the regression.

($RE_{W/B}$) was 247% (Fig. 2). These results differ from the $RE_{W/B}$ estimated from absolute efficiencies of each sampler found in previous wind tunnel studies, which were between 85% and 95% for the BSNE (Fryrear, 1986; Shao et al., 1993) and between 44% and 78% for the MWAC (Sterk, 1993; Bakkum, 1994; Pollet, 1995). According with these results the $RE_{W/B}$ should vary between 46% and 92%. Differences with our results can be due to an underestimation of MWAC efficiency in the studies of Sterk (1993), Bakkum (1994) and Pollet (1995) because they did not use an isokinetic reference sampler. Goossens et al. (2000), using an isokinetic reference sampler in a wind tunnel study, found that the efficiency of the MWAC varied between 110% and 120% for a mean grain-diameter of 126 µm (131 µm in our study) and wind speeds between 7 and 14 m s^{-1}. According to this result the efficiency of the MWAC is higher than the efficiency of the BSNE (between 85% and 95%), but it cannot explain the $RE_{W/B}$ found in our study (247%). Our results agree with field results of Goossens et al. (2000), who found that $RE_{W/B}$ was 276% when samplers were installed at a height of 12 cm above of a sandy soil.

The $RE_{W/B}$ measured in the wind tunnel experiments was 180%, confirming the result obtained in field conditions (Fig. 3), where HMF_M higher than HMF_B ($RE_{W/B}$ = 247%) was measured. The differences between field and wind tunnel measurements were probably related to the wind speed and the soil mean grain-diameter (Table 1): in the wind tunnel the wind speed was 0.3 m s^{-1} higher in the BSNE experiments than in the MWAC experiments, favoring the greater amount of soil trapped by the BSNE than the MWAC. The soil mean grain-diameter was 44 µm greater in the wind tunnel than in the field, thus explaining lower differences in the amount of soil trapped between the BSNE and the MWAC. Previous studies have shown that the efficiency of BSNE increases while the efficiency of MWAC is constant when the particle size increases, because stagnation pressure on sampler inlet is higher in the BSNE than in the MWAC (Fryrear, 1986; Goossens et al., 2000). Goossens et al. (2000) also found that the differences between the efficiencies of BSNE and MWAC were greater in wind tunnel than in field conditions. However they considered that the differences were a consequence of the following: that in field conditions the airflow is much less steady, the sand transport occurs mainly during gusts of high wind velocity, and the sediment flux differs even when catcher spacing is restricted to few decimeters.

The $RE_{W/B}$ increased with sample height, as shown by the increasing slopes of the regression equations between the HMF_B and HMF_M (see "*a*" coefficient of Table 3). The greater amount of material collected by the MWAC in relation to the BSNE at higher heights has to do with better efficiency of MWAC for smaller particles at higher wind speed. As it is known, wind speed increases with the height and stagnation pressure increases with the wind speed in BSNE and it remains constant in MWAC (Goossens et al., 2000). The higher stagnation pressure is related to the decreasing fluid flux through the sampler opening and with the decrease in the trap efficiency for small particles. In addition, the small particles have lesser inertia energy, being more sensitive to variations in the airflow. This causes them to follow the streamlines of the wind and largely flow around the collector instead of entering to the sampler (Goossens and Offer, 2000). That explains why the MWAC collected greater amounts of material than the BSNE at higher heights. Our field results are in agreement with the wind tunnel results of Goossens et al. (2000) who found that the efficiency of BSNE in relation to the efficiency of MWAC decreased when the wind speed increased and particle size decreased (in our study the wind speed and particle size both changed with height).

The fits of the exponential, power, logarithmic and rational equations to a HMF profile in order to calculate horizontal mass transport (HMT) are shown in Fig. 4 and Table 4. The average fitting and the number of significant fitting of equations were ordered in the

Table 3
Main parameters of the linear regressions between horizontal mass flux calculated for BSNE and MWAC placed at different heights.

Height (cm)	$HMF_M = aHMF_B$		
	a	*n*	R^2
12.5[a]	2.10	49	0.52
22	2.01	50	0.90
35[a]	2.12	45	0.88
50	2.62	50	0.85
150	2.91	50	0.73

HMF_M, horizontal mass flux of MWAC; HMF_B, horizontal mass flux of BSNE; *a*, regression fitting coefficient; *n*, dates number.
[a] Loss of material in some samplers.

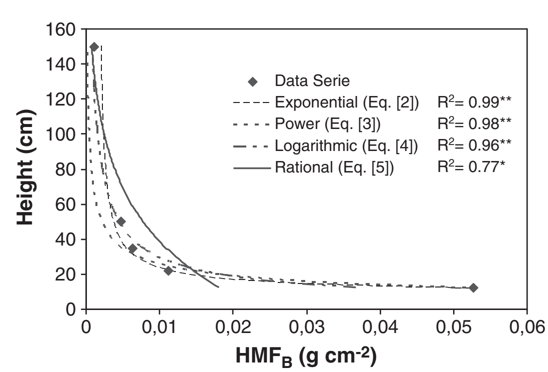

Fig. 4. Fittings of the exponential, power, logarithmic and rational equations to a horizontal mass flux profile. HMFB is the horizontal mass flux of BSNE, *$p<0.05$ and **$p<0.01$.

Table 4
Average and number of significant fits of different equations to the horizontal mass flux profile of BSNE and MWAC.

	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)
	BSNE				MWAC			
Fitting average (R^2)	0.92	0.85	0.72	0.47	0.81	0.72	0.62	0.40
Number fitting ($p<0.01$)	41	28	9	0	33	19	5	0
Number fitting ($p<0.05$)	5	17	18	5	4	20	12	3
Without fitting	4	5	23	45	13	11	33	47

Eq. (1), exponential equation; Eq. (2), power equation; Eq. (3), logarithmic equation; Eq. (4), rational equation.

sequence Eq. (2)>Eq. (3)>Eq. (4)>Eq. (5), and the order was the same for both sampler types (Table 4). This was not expected, as it was supposed that the changes in the efficiency of the samplers with height should modify the HMF profile and, therefore, the adjustment of fitting equations. The analyzed equations fitted better to the HMF_B than the HMF_M, probably because the larger opening of BSNE cause the potential sampling errors to decrease, especially when the samplers are not correctly orientated to the wind direction. Therefore, the small opening and long tube of the MWAC can complicate the free entrance of the saltation particles, which always have an inclination angle with respect to the ground.

The HMT of both samplers, calculated with Eqs. (2), (3), (4) and (5), presented good fitting to each other ($p<0.01$), being that the HMT of MWAC (HMT_M) was from 2.1 to 2.53 times higher than the HMT of BSNE (HMT_B), depending on the used equation (Fig. 5). This result indicates that wind erosion data obtained with BSNE underestimates those obtained with MWAC. If the HMF_B are corrected on the basis of their efficiencies, which vary between 85% and 95% (Fryrear, 1986; Shao et al, 1993) and the HMF_M with efficiencies varying from 44% to 78% (Sterk, 1993; Bakkum, 1994; Pollet, 1995), the differences between the HMT_M and HMT_B will be greater than those mentioned previously. Even correcting the HMF_M by the absolute efficiency of 120% (Goossens et al., 2000), the HMT_M is greater than HMT_B.

The HMT_M was 2.1, 2.24, 2.47 and 2.53 times greater than HMT_B for the Eqs. (2), (3), (4) and (5), respectively (Fig. 5), these being similar to the relations between HMF_M and HMF_B ($RE_{W/B}$). Eq. (3) presented the most similar relation to $RE_{W/B}$, followed by the Eqs. (4), (2), and Eq. (1) respectively (Figs. 2, 5). This indicates that correcting the HMF by the $RE_{W/B}$ found in this study, the HMT_M and HMT_B estimated with the same equations could be compared.

All evaluated equations presented the highest coefficient of determination and greatest fit to the data obtained with BSNE samplers (see R^2 values in Table 4). Because of that, HMT_B was used as the reference for comparisons between equations. The exponential equation (Eq. (2)) presented the best adjustments to HMF_B as a function of height, because of that the HMT_B obtained with Eq. (2) was used as a reference for comparisons with other equations. This result is according to the results obtained by Panebianco et al. (2010) who found that the exponential equation is a very flexible and robust method to estimate the HMT in a loam sandy soil of the semiarid pampas.

The HMT obtained with Eq. (2) were 16% higher than the HMT obtained with Eq. (3), and 62% and 11% lower than the HMT calculated with Eqs. (4) and (5), respectively (Table 5). These results are explained by Fig. 4 which shows that Eq. (3) underestimates the HMF above 35 cm height while Eqs. (4) and (5) overestimate the HMF above 35 cm height. Buschiazzo and Zobeck (2005) found that the HMT calculated with Eqs. (3) and (5) correlated well but the HMT of Eq. (3) was 40% to 55% lower than that calculated with the Eq. (5). This is in agreement with results found in the present study, but we found that the HMT calculated with the Eq. (3) was 25% lower than that one calculated with the Eq. (5), probably because the integration heights were different in each study: Buschiazzo and Zobeck (2005) integrated from the soil surface compared from 12.5 cm in this study. In a loamy-sand soil of the semiarid Pampas the use of different sampling arrangements and different mass flux models has produced

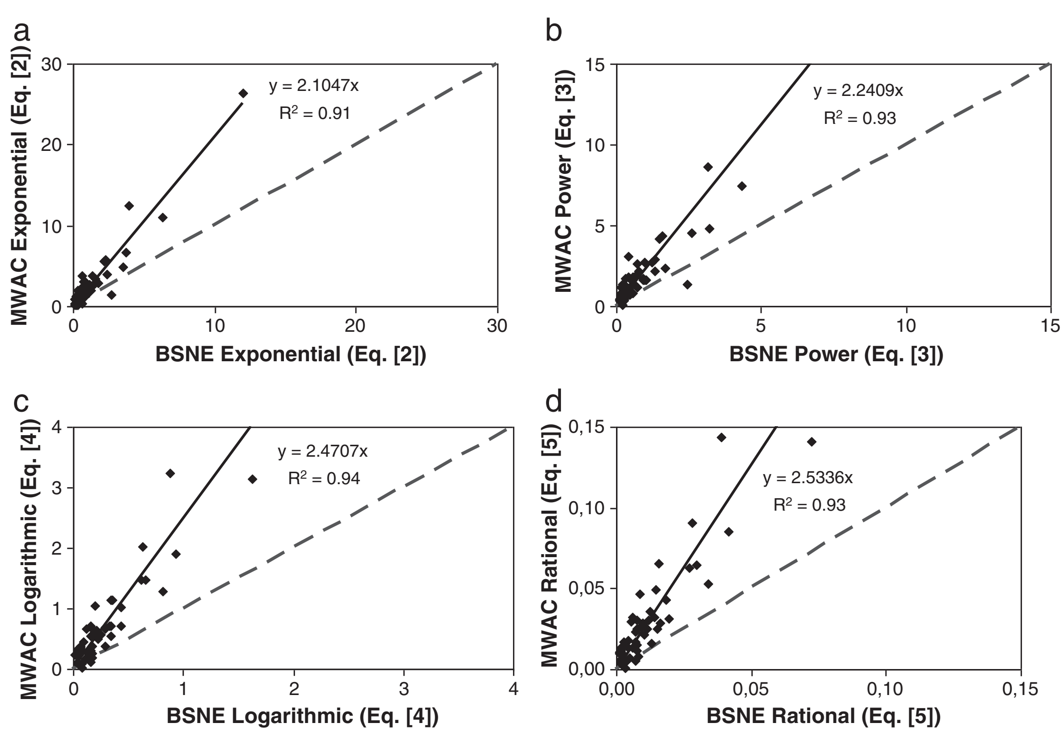

Fig. 5. Comparison of the horizontal mass transport obtained with BSNE and MWAC samplers calculated with a) an exponential equation, b) a power equation, c) a logarithmic equation, and d) a rational equation. Dotted lines represent the 1:1 fits and solid lines represent the regressions.

Table 5
Linear regressions between the horizontal mass transport estimated with Eq. (2) and the horizontal mass transports estimated with the Eqs. (3), (4) and (5).

	Eq. (2) = *a* Eq. [*x*]		
	a	*n*	R^2
Eq. (3)	1.1556	50	0.9767
Eq. (4)	0.3772	50	0.9848
Eq. (5)	0.8928	50	0.9859

a, regression fitting coefficient; *n*, dates number; Eq. (2), exponential equation; Eq. (3), power equation; Eq. (4), logarithmic equation; Eq. (5), rational equation.

differences of more than 45% in mass transport estimates, even under similar field conditions (Panebianco et al., 2010). HMT calculated with different equations correlated significantly ($p<0.01$ Table 5) but the slope of the regression equation was not 1. This indicates that HMT measured with both samplers can be used but a correction is needed to compare results. The relationships between equations developed in the present study should be taken into account when HMT must be estimated with different equations.

4. Conclusions

The first comparison of field measurements between the two most common samplers showed that the MWAC are more efficient than the BSNE samplers and the relative efficiency of MWAC related to BSNE ($RE_{W/B}$) increases with the height as a consequence of higher wind speed and lower particle size. The horizontal mass transport (HMT) of BSNE and MWAC estimated with the same equations are similar providing the horizontal mass flux (HMF) is corrected by the $RE_{W/B}$ obtained in this study. All analyzed equations fit better the HMF of the BSNE, while the exponential equation presented the best fit. The HMT of the exponential equation is underestimated by the power equation and overestimated by the logarithmic and rational equations. However, the HMT calculated with different equations agree well with each other, indicating that the HMT of one equation can be corrected to be compared with the HTM of another equation. The $RE_{W/B}$ and the relationship between equations developed in this study must be taken into account in order to obtain comparable wind erosion measurements.

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