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Comparison of different mass transport equations for wind erosion quantification purposes in southwest Iran: A wind tunnel study

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Abstract

The objective of this study was to assess the efficiency of three mathematical models (power, exponential and logarithmic functions) for the calculation of the horizontal mass transport (HMT), as compared to the linear spline interpolation for the Cyclone Dust Sampler (CDS) and one with a Cone (CDSC), modified Wilson and Cooke trap (MWAC) and big spring number eight (BSNE). For the purposes of this study, wind erosion was measured at wind velocities of 2–7 ms^{-1} on a clay loam soil in wind tunnel experiments. The test results showed that the HMT of BSNE, MWAC, CDS, and CDSC samplers, calculated by these equations, fitted well to each other ($p<0.01$), such that the HMTs of MWAC (HMT_M), CDS (HMT_S), CDSC (HMT_{SC}), respectively, were 1.10-1.45, 2.28-2.45, 2.48-2.81 times higher than that of BSNE (HMT_B), depending on the equation used. The power equation yielded the best adjustments to HMF as a function of the height. Moreover, the relative efficiencies of CDS, CDSC, and MWAC varied between 140-200%, 220-540%, and 410-860%, respectively. Compared to the MWAC sampler, CDS and CDSC samplers showed a rapid drop in relative efficiency with increasing wind speed. These higher efficiencies of the CDS and CDSC relative to BSNE were attributed to its cyclone design. Adding cone to the CDSC sampler increases its efficiency compared to the CDS sampler, protects the settled dust from resuspension.

Keywords: Cyclone samplers; Efficiency; Wind erosion; Khuzestan; Dust

1. Introduunction

Wind erosion is one of the most serious problems in arid areas which account for about one-third of the world's land area (Lal, 1990). Frequent dust storms in these areas not only have a very spectacular character, showing the nature's power in moving soil particles, but they also affect the physical characteristics of the atmosphere (Buseck and Posfai, 1999; Alpert and Ganor, 2001), agricultural systems (Liblik *et al*., 2003), soil quality (Reynolds *et al*., 2001), biological systems (Jones and Shachak, 1990; Reynolds *et al*., 2001), buildings (Erell and Tsoar, 1999), building materials (Lefèvre and Ausset, 2002), human activities (Riksen, 2004), and public health (Smith and Lee, 2003; Inyang and Bae, 2006).

Reliable and direct measurements of sediment flux are not only required for the confirmation and calibration of theoretically derived flux equations (Nickling *et al*, 1997), but are also necessary for assessing the intensity of aeolian processes in a given environment (Goossens and Offer, 2000). Direct measurements of dust deposition on the earth's surface are a difficult task because of the latter's complex macro- and micro-structure. A large number of studies have been devoted to the development and application of a wide variety of instruments used as samplers for the direct measurement of dust. These dust samplers vary in construction from simple structures such as ordinary household buckets to complex

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instruments supplied with aerodynamic devices to minimize perturbations in the airflow. However, they can all be classified into two groups: those measuring horizontal dust fluxes, and those measuring vertical dust fluxes. Basaran *et al.* (2011) believed that cyclones could provide some advantages in eolian research. They designed a prototype simple cyclone sediment trap (BEST: Basaran & Erpul Sediment Trap) for wind erosion measurements (Basaran *et al.*, 2011). Many samplers have been developed for measuring the material transported by wind (Goossens *et al.*, 2000) although 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 ones most commonly used (Zobeck *et al*., 2003). BSNE samplers are used in many regions like Australia, Middle East, and the USA for the quantification of materials transported by saltation and rolling while the MWAC samplers are more commonly used in Europe (Goossens *et al*., 2000).

The most important characteristic of a dust sampler is its efficiency. The efficiency of a collector depends on the shape and size of the sampler, the deposition surface inside the sampler, the airflow (wind speed, wind direction, level of turbulence), and the characteristics of the sediment (Goossens and Offer, 2000). Due to a combination of these factors, the sampler's efficiency varies with the conditions at the time of measurement. This makes calibrating a dust deposition sampler very time-consuming. Sampling efficiency of the MWAC remains constant but that of BSNE decreases with wind speed, due to the higher stagnation pressure in the BSNE at higher wind speeds (Goossen *et al*., 2000). The stagnation pressure effect is higher for small particles because they have lower inertia and response time to changes in the airflow. 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 relative to MWAC samplers at higher wind speed and lower particle size, and considering that wind speed increases but particle size decreases with height, it can be expected that the amount of material collected by MWAC compared to BSNE will also increase with height. Basaran *et al*. (2011) determined that the efficiencies of the BEST and the MWAC samplers were between 75-100% and 12- 52%, respectively.

Accurate estimations of material transport by wind are necessary for the quantification of wind erosion processes, validating wind erosion prediction models, and evaluating the mechanisms for wind erosion control (Zobeck *et al.*, 2003). Though considerable efforts have been devoted to quantifying the amount of wind-transported material (Bagnold, 1941; Greeley and Iversen, 1985; Fryrear *et al*., 1991) and many theoretical and empirical equations have been developed for this purpose (Greeley and Iversen, 1985), the flux profile of blowing dust storm has not yet been well defined. Different equations have been used to describe the vertical distribution of the collected material by height, and their integration makes possible the estimation of HMT (Horizontal Mass Transport). Such equations are of the 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). Greeley *et al*. (1983) and Gerety and Slingerland (1983) concluded that the mass flux in saltation decreased exponentially with height above the bed in all their tests.

Anderson and Hallet (1986) suggested an exponential function for the saltation flux profile and a power function for the suspension profile. Though conditions are different between a wind tunnel and field storm events, the exponential function proposed for the saltation flux and the power function for the suspension flux have been found to agree well with both subsequent field observations and wind tunnel test results (Fryrear, 1987; Vories and Fryrear, 1991; Fryrear and Saleh, 1993). However, Chen *et al.*'s (1996) results of the vertical distribution of wind-blown sand flux in the Taklimakan Desert, China revealed that the saltation flux profile could be described by neither the exponential nor the power function.

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 (Panebianco *et al*., 2010). However, assuming that the major 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. Although quantification methods should be robust enough to be applicable under a wide range of conditions, cost effective, simple to perform; and easy to interpret (Panebianco *et al*., 2010). Therefore, the objectives of this study were: (i) to investigate the effectiveness of the different equations in calculating HMT for BSNE, MWAC, CDS, and CDSC samplers; and (ii) to compare the efficiencies of the CDSC, CDS, and MWAC as compared to that of BSNE in wind tunnel conditions.

2. Materials and Methods

2.1. The Study area

The soil used in the experiments was collected from Horolazim in the southwest of Iran. The region (50°15'- 51°51' N and 31° 20' –32°53' E) is known as one of the most serious dust fields with frequent dust storms. A total number of 30 samples were collected to produce a measure of diversity in the properties of the soil randomly sampled from A horizon. All the samples were then mixed to produce a complex sample. The descriptive statistics of soil properties are given in Table 1. According to the Soil Taxonomy of the USA, the dominate soil texture is clay loam. The soils contained between 36% - 63.20% silt, 12% - 40.8% Sand and from 18.40% -43.20% clay. The analysis showed that soil textures in this region contained more than 67.28% silt and fine sand in the surface horizon. Electrical conductivity (EC) and sodium absorption ratio (SAR) of the area varied between 12.52-238 dSm^{-1} and 15.09-281.93, respectively. Based on table 1, Soil organic matter (OM) has minimum, maximum and mean values of 0.26, 2.58, and 0.67 percent, respectively. As expected, the soils developed in southwest Iran have high content of calcium carbonate ($CaCO_3$) varied from 38.17 to 39.72 percent in this area.

Table 1. Summary of statistics (maximum, minimum, mean and coefficient of variations, CV) for soil properties in the study area

property	Mean	Maximum	Minimum	CV
pH	7.93	8.60	6.58	0.05
EC(dSm^{-1})	182.46	238.00	12.52	0.30
SAR	164.31	281.93	15.09	0.42
OM(%)	0.67	2.58	0.26	0.80
$CaCO_3$ (%)	39.23	39.72	38.17	0.72
$CaSO_4.2H_2O$	4.05	12.24	0.00	0.90
Clay(%)	27.96	43.20	18.40	0.24
Fine silt (%)	23.25	36.00	11.20	0.23
Coarse & Medium silt (%)	24.43	45.6	13.60	0.26
Very fine sand(%)	1.02	4.26	0.20	0.70
Fine sand(%)	19.59	37.22	4.58	0.34
Medium sand (%)	1.91	5.18	0.20	0.70
Coarse sand (%)	0.89	1.34	0.54	0.23
Very coarse sand (%)	0.91	1.58	0.46	0.29
MWD (mm)	0.23	0.36	0.09	0.32

2.2. CDSC (Cyclone dust sampler with cone) and CDS (Cyclone dust sampler without cone)

For the purposes of this study, two versions of the cyclone sampler, i.e., CDS and CDS were designed and constructed for wind erosion measurements based on the archetypes of BSNE (Fryrear, 19861) and BEST (Basaran *et al*., 2011). Figure 1 and 2 show a figure and construction scheme of CDS and CDSC samplers. In addition to these, the Big Spring Number Eight (BSNE; Fryrear, 1986) and the Modified Wilson and Cooke (MWAC; Wilson and Cooke, 1980) were also tested to determine the dust trap efficiencies of the samplers. The samplers especially designed for this study are made of 28-gauge galvanized metal, galvanized 18- mesh screen, and stainless steel 60-mesh screen. Sediment-laden air passes through a vertical opening 20 mm × 50 mm. lnside the sampler, air speed is reduced and the particles settle in a collection pan. Air discharges through a 60-mesh screen which reduces the movement of the deposited material to prevent the breakdown of the collected sediment and the potential loss of fine particles through the top of the screen. A rubber retainer closes any small holes in the back and front of the assembled sampler. A wind vane installed at the rear assures the sampler is facing the wind.

Dust particles are trapped based on a combination of centrifugal and wind resistant forces in CDS and CDSC (Fig. 1, 2). Particles entering the radial, cylindrical and eccentric chamber are separated by centrifugal force while the other suspended particles are separated under gravity. Coarse materials are deposited within the cylinder due to rotation, but fine materials remain in suspension within the sampler chamber and may be gradually deposited or ejected from outlet depending on wind speed.

Three kinds of force are exerted on the dust particles entering the cylinders: particle weight (mg), centrifugal force (F_{cf}), and air resistance (F_w) (Eqs. 1 and 2). The directions of weight, centrifugal, and air resistance forces are downward, perpendicular, and tangential to the particle movement, respectively (Fig. 1, 2).

$$F_{cf} = a_{cf} m \quad (1)$$

$$a_{cf} = \frac{V^2}{R} = R\omega^2 \quad (2)$$

where, acf, R, ω, and V are centrifugal acceleration (ms^{-2}), rotation radius of the particles, angular velocity of the particles (rad s^{-1}), and air speed (ms^{-1}), respectively. If the weight force due to the mass of the particles is greater than air resistance, the suspended materials will move downward (Fig. 1, 2). The centrifugal force tends to stick the particles to the chamber walls so that the dust particles will fall off when the force of gravity becomes greater than the friction force of the walls. In cases when the overall force takes an upward direction, then the amount of wind force is greater than the weight force and the particles will, therefore, remain in suspension and may be ejected by the airflow. Wind force is in most cases far greater than the weight force (at high wind speeds) in the absence of the centrifugal force; but the effect of the latter force is important in reducing air resistance. Dust particles move towards the wall surface when air resistance overcomes the weight force. Near the wall, however, air velocity is almost zero. We used a deflector plate at the end of the inlet pipe because of air disturbances.

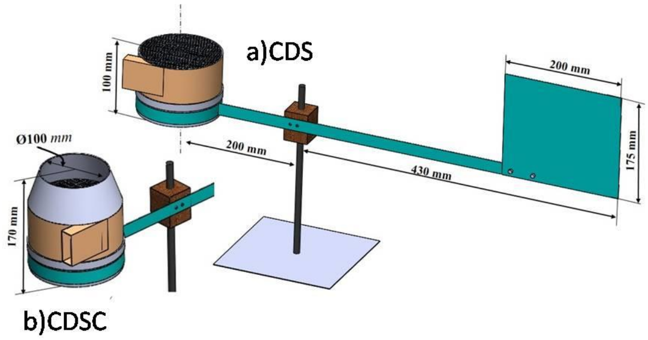

Fig. 1. A general perspective view of CDS (cyclone dust sampler) and CDSC (cyclone dust sampler with cone) samplers

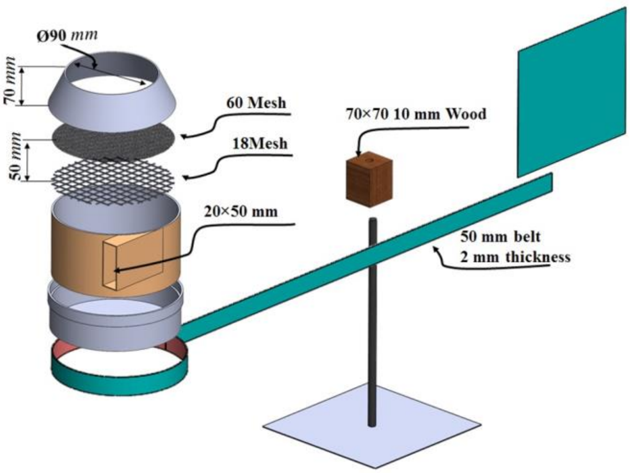

Fig. 2. Construction scheme of the CDS (cyclone dust sampler) sampler

2.3. Wind tunnel experiments

A wind tunnel 0.5 m wide, 0.5 m high, and 8 m long was used to measure the horizontal mass flux (HMF) of the sampler under controlled conditions with no abrasion device used. The samplers were installed at the end of the wind tunnel at heights of 1, 8, and 16 cm. The soil used for the simulations remained smooth and loose during the three simulations. Six wind speeds were selected in the range of 2–7 ms^{-1} in three replicates because 97–99% of the winds which cause wind erosion naturally blow in the range of 4–8 ms^{-1} (Wu *et al*., 2003).

In most continental areas, the average wind speed in the lower parts of the atmosphere is usually 2–5 ms^{-1} (Goossens *et al*., 2000). Field rankings and wind tunnel rankings of the samplers were found to be identical, with the variations observed among the experimental results being due to the rather small differences in average wind speed which cause an unsteady dust flow. It is well known that boundary layer winds are usually highly unsteady (Stout and Zobeck, 1997).

Three independent test runs, each lasting for 3 min, were performed for each test wind speed in each sampler. Before each run, a protective cover was placed over the sampler to keep it free from dust. Once the correct wind speed had been attained, the cover was removed and the experiment started to collect dust particles. After the run, the wind tunnel was turned off and the protective cover was immediately replaced on the sampler to prevent dust entering the trap.

2.4. Relative efficiency (Re, %)

Horizontal mass flux (HMF), defined as 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's opening area. This allowed the calculation of HMF for the MWAC (HMF_M), CDSC (HMF_{SC}), CDS (HMF_S), and the BSNE (HMF_B). The relative efficiency (RE, %) of MWAC, CDSC, and CDS relative to BSNE was calculated using the following equation:

$$RE = \left(\frac{HMF_X}{HMF_R}\right) \qquad (3)$$

where, HMF is the horizontal mass flux of the X (MWAC, CDSC, CDS) sampler (gcm^{-2}) and HMF_B is the horizontal mass flux of the BSNE (gcm^{-2}).

The horizontal mass transport (HMT), defined as the amount of passing soil by unit area of a horizontal plane confined between two definite heights, was calculated for each sampling point by integrating the exponential, power, logarithmic, and linear equations (Eqs. 4, 5, 6, and 7, respectively) which fit an HMF variation as a function of height between 1 and 16 cm (Funk *et al*., 2004; Panebianco *et al*., 2010). The integrations were made between 1 and 16 cm height because slight changes in the lower boundary for the vertical integration may have different effects on the amount of material calculated through each equation (Funk *et al*., 2004; Panebianco *et al*., 2010).

$$f(z) = \sigma e^{\frac{-\beta}{z}} \qquad (4)$$

$$f(z) = \sigma z^{-\beta} \qquad (5)$$

$$\ln f(z) = f_0 + \sigma \ln z \qquad (6)$$

$$f(z) = \sigma z + f_0 \qquad (7)$$

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

The integration of HMF_M, HMF_{SC}, HMF_S, and HMF_B through each equation allowed the value of HMT of each sampler to be estimated for each equation. The HMF_M, HMF_{SC}, HMF_S, and the HMF_B, the HMT of the samplers used, and the equations were correlated using the linear regression analysis program of Microsoft Excel.

3. Results and Discussion

The dust collected in BSNE, MWAC, CDS, and CDSC samplers were between 0.002-2, 0.002-3, 0.002-4 and 0.002-5 g, respectively. The lower amount of the material trapped by the MWAC is related to its opening area which is 2-4 times smaller than those of the other samplers. This indicates that MWAC is not suitable for experiments in which the amount of sediment transported is scant and the main objective is to investigate the transported soil.

In this study, efficiency was defined as the amount of dust collected by the sampler divided by the amount of dust collected by the BSNE. Thus, the relative efficiencies of MWAC, CDS, and CDSC samplers were found to be 140-200, 220-540, and 410-860%, respectively. This finding is in agreement with those of Goossens *et al*. (2000) who reported that MWAC efficiency for sands between 132 and 287 μm is always between 90 and 120% for a wind speed in the range of 6.6 - 14.4 ms^{-1}. In an attempt to calibrate six eolian dust samplers in a wind tunnel and under field conditions, Goossens and Offer (2000) found that the MWAC bottles showed an efficiency value greater than 90% for wind speeds between 2 and 5 ms^{-1} and 75% for a wind speed of 1 ms^{-1}. These researchers used dust composed of 95% silt (2–63 μm) and 5% clay (<2 μm) with a median diameter of 30 μm in their wind tunnel experiments. BSNE efficiency for 30 μm dust is always around 40%

(varying between 35% and 45%) for wind speeds of 1-5 ms^{-1}. Similar results were obtained with the two cyclone samplers used in this study. At low wind speeds, efficiencies were fairly high, but they dropped rapidly with increasing wind speeds above 3 ms^{-1}. At wind speeds of about 5 to 7 ms^{-1}, stabilization was also observed to occur in the cyclone samplers, but efficiency remained fairly constant in MWAC. Mendez *et al.* (2011) believed that MWAC efficiency does not greatly depend on wind speed because of the identical size of the inlet and the outlet that leads to minimum obstruction. Goossens *et al*. (2000) found that five aeolian sand samplers exhibited variations in their efficiency depending on sediment size and wind speed. Zobeck (2002) also reported that the catching ability of a trap might change with the type of sediment. In addition, Feras *et al*. (2008) showed in their wind tunnel study that the efficiencies of both MWAC and Vaseline slide sediment traps depended primarily on particle size and wind speed. The fact that emerges from these different viewpoints is that there is a high probability for a trap with a low consistent efficiency not to catch particles of a given size class. Therefore, heterogeneity in particle sizes in Horolazim soil (used in the present study) strongly affects trap efficiency. Contrary to these findings, Basaran *et al*. (2011) reported that the change in the relative efficiency of the BEST (cyclone trap) with respect to wind speed and particle size was smaller, and that it outperformed MWAC in trapping dust-sized particles.

The results show that both cyclone samplers (CDS and CDSC) were more efficient than MWAC in the tests conducted with six wind speeds using the Horolazim dust in the wind tunnel. This finding is in agreement with those of Basaran *et al*. (2011) who reported that BEST, with its measured efficiency in the range of 75% to 100%, was more efficient than MWAC, with efficiencies recorded in the range of 12% to 52%. Cortes and Gil (2007) stated that the aerodynamic design of cyclone systems create a centrifugal effect within the trap and decrease the static pressure at the entrance. Indeed, the cyclone design adequately generated a pressure difference between inlet and outlet to drive the flow through the trap and to overcome the pressure drop at the trap entrance. Goossens and Offer (2000) point out that collector design is one of the main factors having an effect on the efficiency of a trap. Basaran *et al*. (2011) also showed that BEST, having a cyclone separator by design, not only trapped the coarser particles but also accumulated the finer particles more efficiently at its collector due to its accelerated settling ability. Additionally, neither the differences between the pressures of the trap's inlet and outlet nor the turbulent air circulation inside the body of the BEST appeared to result in significant flow-out losses when compared to the MWAC. The better performance of the BEST in settling particles, particularly for much finer particles, reduced the risk of flow-out losses from the collector. Goossens *et al*. (2000) reported that the overall decrease in the catcher efficiency with wind speed for the BSNE, SUSTRA, and POLCA traps was most probably caused by the increasing stagnation pressure at the catcher inlet, which hindered the particles entering the catcher. In the case of the MWAC traps, Cornelis and Gabriels (2003) concluded that the outlet wind was much slower than that of the inlet, and this was one of the reasons for having increasing static pressures at the entrance which prevented the particles from entering the trap.

The results of the present study show that the relative efficiency of the CDSC sampler is greater than that of CDS due to its cone action although its efficiency depends on wind speed. However, the most recommendable sampler is the CDSC due to its low-cost, ease of installation, small size, and low weight which make it suitable for measuring vertical flux profiles in this region.

The horizontal mass fluxes of BSNE (HMF_B), MWAC (HMF_M), CDS (HMF_S), and CDSC (HMF_{SC}) varied between $2.3{*}10^{-4}$ and 2.6 g cm^{-2}. In spite of these differences, the HMF_M, HMF_S, and HMF_{SC} correlated well with HMF_B when all the sampling heights were considered collectively (Fig. 3a) or when each sampling height was considered individually (Table 2). When all the sampling heights were considered together, it was observed that HMF_M, HMF_S, and HMF_{SC}, respectively, were 1.5, 2.76, and 2.90 times higher than HMF_B, indicating that the relative efficiencies of MWAC, CDS, and CDSC samplers relative to BSNE were 150, 276, and 290%, respectively (Fig. 3, a). This finding is in agreement with those of Mendez *et al*. (2011) who reported that the efficiency of MWAC relative to that of BSNE is 247%. Our results agree with field observations of Goossens *et al*. (2000) who found that the efficiency of MWAC relative to that of BSNE was 276% when the samplers were installed at a height of 12 cm above a sandy soil.

Table 2. Main parameters of the linear regressions between horizontal mass flux calculated for BSNE, MWAC, CDSC and CDS placed at different heights

Height (cm)	CDS		CDSC		MWAC	
	a	R^2	a	R^2	a	R^2
1	0.73	0.86	1.98	0.94	1.5	0.97
8	1.26	0.92	2.30	0.98	1.9	0.97
16	1.77	0.94	2.70	0.99	2.6	0.99

(a) regression fitting coefficient, (R^2) determination coefficient

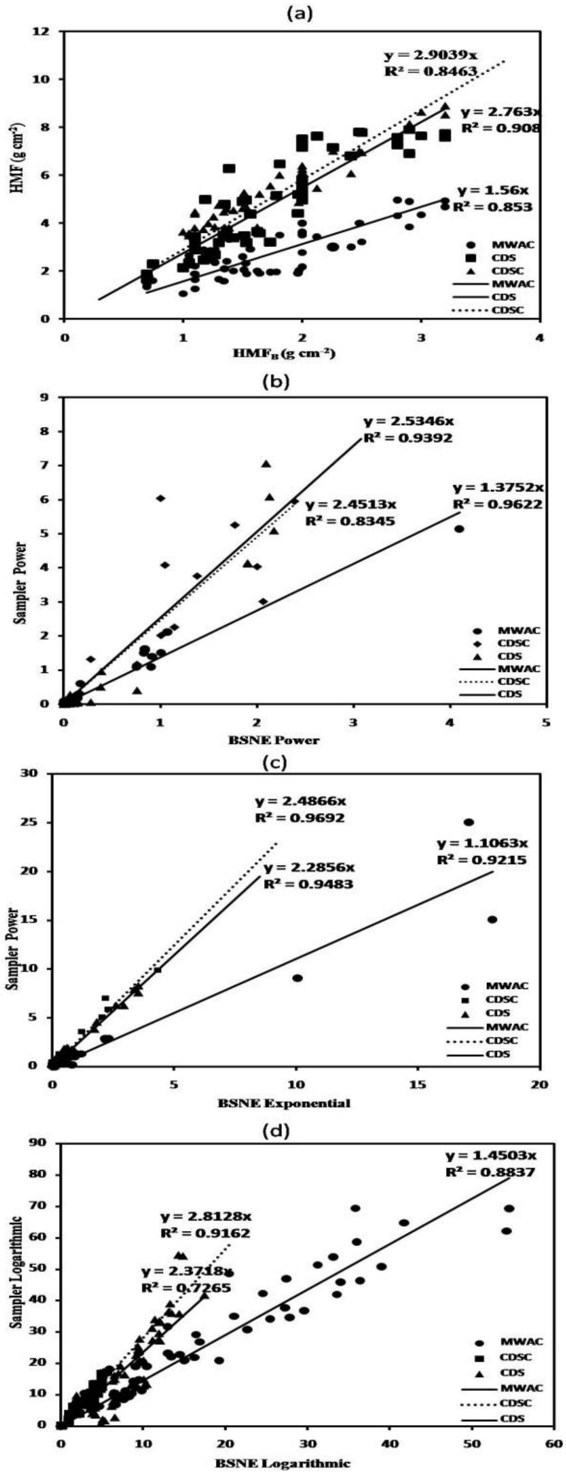

Fig. 3. Comparisons of the horizontal mass transport (HMT) obtained with BSNE related to MWAC, CDS, CDSC samplers calculated with different equations

The efficiencies of MWAC, CDS, and CDSC relative to that of BSNE increased with sample height, as evidenced by the increasing slopes of the regression equations between the HMF_B with HMF_M, HMF_S and HMF_{SC} (See the values for “a” coefficient in Table 2). The greater amounts of material collected by the MWAC, CDS, and CDSC as compared to that by BSNE at higher heights are due to the collector design. In a cyclone sampler, the action of centrifugal force resulting from the rotation of the air in the cylindrical and conical cyclone body promoted accelerated settling of sediment particles, and, more importantly, the centrifugal field generated by the higher circulating velocities reduced stagnation pressure at the catcher inlet, which facilitated the sediment entering the trap (Basaran *et al*., 2011).

It is known that wind speed increases with height and that stagnation pressure increases with wind speed in BSNE but that 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 to the decreasing trap efficiency with small particles. In addition, small particles have lower inertia energy, making them more sensitive to variations in the airflow. This causes them to follow the streamlines of the wind and largely flow around the collector rather than entering the sampler (Goossens and Offer, 2000). This explains why the MWAC collected greater amounts of material than did the BSNE at higher heights.

The fits of the exponential, power, logarithmic, and linear equations to a HMF profile in order to calculate horizontal mass transport (HMT) are shown in Fig. 4 for a wind speed of 2-7 ms^{-1} in the wind tunnel. Table 3 presents the model parameter coefficients for various equations and their fitting, which are rather different for each sampler type. The average fitting of the four equations for BSNE, MWAC, CDS, and CDSC, respectively, are in the following order: Power>Log.>Exp.>Lin.; Power>Exp.>Log.>Lin.; Power>Exp.>Log.>Lin.; Power>Log.>Exp.>Lin. (Table 3).

The equations investigated fitted better to the HMF_S and HMF_{SC} than the HMF_M, probably because the potential sampling errors decreased due to the larger opening area of the cyclone collector, especially when the samplers were not correctly orientated to the wind direction. Therefore, the small opening and the 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 (Mendez *et al*., 2011). These equations also fitted better to HMF_S and HMF_{SC} than to HMF_B, probably due to the cyclone design.

The HMT of BSNE, MWAC, CDS, and CDSC samplers, as calculated by these equations, presented good fitting to each other ($p<0.01$) such that, depending on the equation used, the HMTs of MWAC (HMT_M), CDS (HMT_S), and CDSC (HMT_{SC}), respectively, were 1.10-1.45, 2.28-2.45, and 2.48-2.81 times higher than that of BSNE (HMT_B) (Fig. 3b, c, d). This result indicates that wind erosion data obtained with BSNE underestimate the real conditions and are lower than those obtained with MWAC, CDS, and CDSC.

The HMT_M, HMT_S, and HMT_{SC} were 1.37, 2.45, 2.53; 1.10, 2.28, 2.48; 1.45, 2.37, 2.81 times greater than HMT_B for the power, exponential, and logarithmic equations, respectively (Fig. 3b, c, d), these being similar to the relations among HMF_M, HMF_S and HMF_{SC} and HMF_B (Fig. 3, a). The relation most similar to the relative efficiency of the samplers was the one due to the logarithmic equation, followed by the ones yielded by the power and exponential equations (Fig. 3a, b, c, d). This indicates that the HMT_M, HMT_S and HMT_{SC}, and HMT_B estimated by the same equations become comparable by correcting the HMF yielded by the relative efficiency obtained in this study. This finding is in agreement with the results reported by Mendez *et al*. (2011).

Table 3. Fitting of the exponential, power, logarithmic and linear equations to a horizontal mass flux profiles of BSNE, MWAC, CDSC, CDS placed at different heights(1, 8 and 16 cm) related to tunnel floor in 2-7 ms-1 velocities.

Velocity	Parameter	BSNE				MWAC				CDSC				CDS			
(ms^{-1})		Exp.	Power	Log.	Lin.	Exp.	Power	Log.	Lin.	Exp.	Power	Log.	Lin.	Exp.	Power	Log.	Lin.
2	σ	1.80	0.25	-10.70	-87.09	0.49	0.16	-16.61	-51.65	0.29	1.20	-20.70	-29.93	1.80	2.23	-11.61	-20.00
	β	-0.10	1.41	-	-	-0.67	2.76	-	-	-1.84	3.20	-	-	-0.56	1.67	-	-
	$f0$	-	-	16.06	18.84	-	-	12.78	23.79	-	-	1.34	27.91	-	-	1.18	19.00
	R^2	0.92	0.97	0.985	0.91	0.96	0.99	0.93	0.77	0.97	0.99	0.94	0.90	0.91	0.96	0.99	0.93
3	σ	1.83	1.80	-10.70	-21.40	1.50	3.96	-10.70	-10.76	0.76	4.69	-14.41	-21.80	2.60	8.39	-9.29	-6.74
	β	-0.40	1.40	-	-	-0.90	1.50	-	-	-1.81	2.30	-	-	-0.90	1.40	-	-
	$f0$	-	-	0.99	18.84	-	-	5.60	18.14	-	-	6.74	13.82	-	-	10.46	-8.68
	R^2	0.92	0.97	0.98	0.91	0.959	0.99	0.95	0.87	0.97	0.99	0.94	0.88	0.87	0.93	0.99	0.88
4	σ	1.90	3.40	-10.70	-14.97	1.42	3.50	-10.70	-11.12	0.30	12.05	-14.41	-8.96	1.40	11.69	-11.61	-6.93
	β	-0.60	1.30	-	-	-0.90	1.60	-	-	-3.4	2.93	-	-	-1.37	1.47	-	-
	$f0$	-	-	3.15	19.17	-	-	5.18	18.06	-	-	12.61	21.46	-	-	12.81	19.97
	R^2	0.91	0.96	0.99	0.93	0.95	0.99	0.95	0.86	0.99	1.00	0.89	0.83	0.93	0.96	0.99	0.93
5	σ	1.62	2.60	-10.30	-13.49	38.78	7.23	-10.51	-7.09	1.25	17.03	-12.81	-6.31	1.73	46.00	-10.90	-2.53
	β	-3.19	1.50	-	-	-1.44	2.03	-	-	-2.47	1.80	-	-	-4.51	1.60	-	-
	$f0$	-	-	18.37	18.15	-	-	10.20	18.33	-	-	15.51	20.65	-	-	22.07	18.68
	R^2	0.94	0.98	0.96	0.88	0.98	0.99	0.96	0.88	0.94	1.00	0.97	0.91	0.94	0.98	0.96	0.93
6	σ	1.60	41.71	-10.50	-2.41	1.71	15.65	-10.51	-4.85	0.64	72.43	-10.50	-4.93	1.30	112.00	-12.11	-1.87
	β	-2.40	1.50	-	-	-2.1	2.03	-	-	-5.08	2.40	-	-	-7.37	2.33	-	-
	$f0$	-	-	21.52	18.32	-	-	14.18	18.31	-	-	24.28	23.02	-	-	22.99	19.94
	R^2	0.94	0.98	0.96	0.88	0.96	0.98	0.94	0.88	0.97	0.99	0.94	0.89	0.94	0.97	0.97	0.90
7	σ	38.39	2.04	-10.50	-3.81	1.89	23.72	-10.21	-3.81	0.64	82.89	-14.70	-2.63	29.8	160.00	-10.00	-1.23
	β	-0.78	25.21	-	-	-0.77	2.03	-	-	-10.92	2.54	-	-	-9.25	25.21	-	-
	$f0$	-	-	16.61	18.25	-	-	16.15	17.79	-	-	31.30	21.96	-	-	28.84	17.02
	R^2	0.94	0.98	0.96	0.88	0.96	0.99	0.93	0.85	0.98	0.99	0.93	0.87	0.96	0.99	0.94	0.86

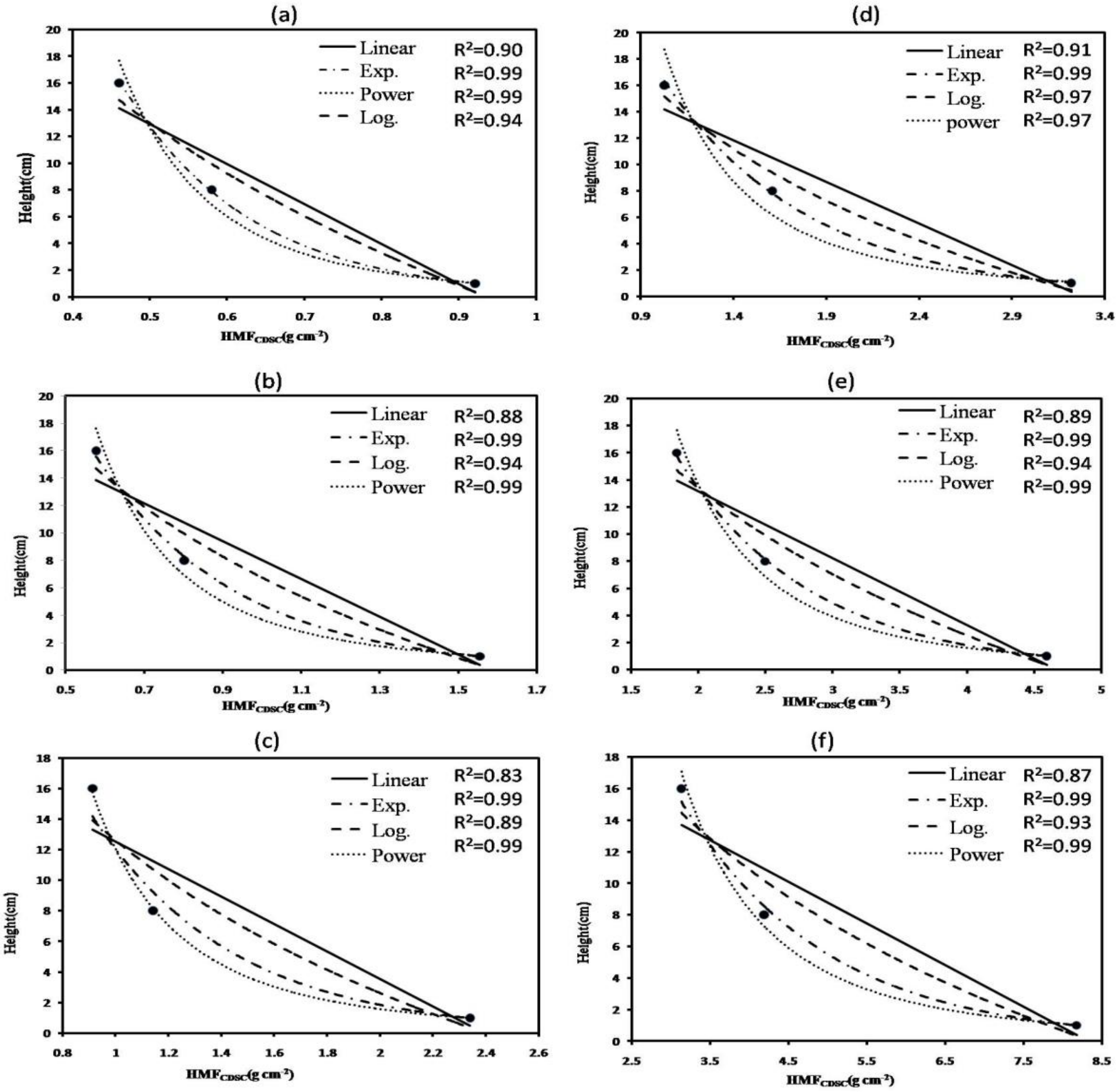

Fig. 4. Fitting of the exponential, power, logarithmic and linear equations to a horizontal mass flux profiles of CDSC sampler(HMF_{SC}) in the a)2, b)3, c)4, d)5, e)6, f)7 ms^{-1} velocities

All the equations evaluated, except for the linear model, yielded the highest coefficients of determination and the greatest fit to the data obtained by using all the samplers (R^2 values in Table 2). The power equation yielded the best adjustments to HMF as a function of height. Contrary to our results, Panebianco *et al*. (2010) and Mendez *et al*. (2011) maintained that the exponential equation is a very flexible and robust method for estimating the HMT in the loam sandy soils of the semiarid pampas.

4. Conclusion

All the equations investigated were found to fit better to the HMF of the BSNE, while the power equation yielded the best fit. The HMT of the power equation was overestimated by the other equations. However, the HMT calculated by the different equations agreed well with each other, indicating that the HMT obtained by one equation may be corrected to make it comparable with that obtained by another.

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