Characterization of the Fine Dust Particle Production Process by Wind Erosion for Two Types of Bare Soil Surfaces

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1. Introduction

Wind erosion is a serious problem in many parts of the world for people and environment. This phenomenon is a physical process caused by erosive winds on various types of soil surface and the result of interaction between several conditions. Wind shear stress and soil surface characteristics are the main factors controlling dust emission. Fine airborne particles emitted into the atmosphere represent the loss of the most fertile fraction of the topsoil and can be transported over long distances from their sources of production (Péwé, 1981). Dust emissions have consequently an impact on soil degradation but also on climate. Indeed, the very fine fraction of soil-derived dust has significant forcing effects on the radiative budget but also, climatic changes can modify the location and strength of dust sources.

Modeling of the dust cycle, including production, transport and deposition of aerosols, needs some improvements regarding the process responsible of the dust release during erosion : the sandblasting process (Gillette et al., 1974 ; Alfaro et al., 1997b). Dust emissions can be studied using fluxes of particles at the soil surfaces. The vertical flux (*F*) corresponds to the mass of suspended particles with diameter less than 20 µm passing through a surface parallel to the soil. The horizontal flux (*G*) corresponds to the total mass of material transported in saltation movement. By a dimensional analysis Shao et al. (1993) stated that vertical dust flux (*F*) is a fraction of the horizontal flux (*G*). The *F/G* (= α) ratio provides the efficiency of the dust release process. Suspended sediments can occur only when kinetic energy (*Ec*) of the saltating particles becomes larger than the binding energy (e_c) of the fine particles in the soil (Shao et al., 1993 ; Alfaro et al., 1997a).

The objective of this paper is to report, using field experimental data, the process of dust production by wind erosion for various types of soils. The efficiency of that process (α) is directly linked to the soil surface fluxes, dynamic conditions of the boundary surface layer and the immediately available amount of erodible particles. The assessment of that process at the soil-air interface will allow us to determine the important parameters affecting dust production efficiency.

2. Materials and Methods

2.1. Study sites

The areas studied were located in three different regions of the world identified as potential sources of mineral dust by wind erosion (***Table-1***).

The first one was a dry lake bed in the Mojave desert (California) characterized by an arid climate. The evaporation of the 280 km² Owens lake surface left a dry alkaline lake bed with a saline crusted topsoil. The textural analysis highlighted the large potential amount of small particles able to be ejected in the atmosphere by strong winds (***Table-1***). The Lake Owens Dust Experiment (LODE) was conducted in March 1993 in the southern part of the dry lake.

The second region was an agricultural Sahelian zone near Niamey (Niger) characterized by a semiarid climate. In this latest experimental zone, two agricultural fields at different stages of cropping system were selected. In May 1993 the experiment was conducted on a recently weeded fallow field, characterized by a bare, loose, sandy soil. In April 1995 measurements were carried out in a millet culture field isolated in the middle of aged fallow. During this period the cultivated surface consisted of a sandy soil sparsely covered by bushes and decaying roots of millet. The texture of the two soils indicated a large fraction of coarse particles at the soil surface (***Table-1***).

A last experiment was carried out in August 1995 within an agricultural field located in the Zaragoza province, northeast Spain characterized by a semiarid climate. The soil surface had been conventionally tilled with barley (*Hordeum vulgare* L.) grown under cereal-fallow rotation until 1993. At the time of experiment the surface was free of vegetation and the soil was classified as loamy soil (***Table-1***) .

Table-1. Experimental site characteristics

	USA	**Niger**	**Niger**	**Spain**
Localization	California Owens Lake	Sahel Banizoumbou	Sahel Banizoumbou	Ebro Valley Peñaflor
Type	Natural (dry lake)	Agricultural (weeded fallow)	Agricultural (cultivated)	Agricultural (cultivated)
Experimental period	March 1993	May 1993	April 1995	August 1995
(Lat. Long.)	36° N,118°W	13° N, 2°E	13° N,2°E	41° N,0°W
Elevation (m)	1087	200	200	270
Soil characteristics				
% sand (2000-50 µm)	22.3	94.0	95.7	28.5
% silt (50-2 µm)	35.8	2.2	0.9	47.0
% clay (< 2 µm)	41.9	3.8	3.4	24.5
Textural class	Silty clay	Sand	Sand	Fine silty

2.2. Expression of the soil surface fluxes

In order to characterize the dust release process, expressions for the horizontal and the vertical fluxes of particles mobilized at the soil surface were determined as follows :

*Total horizontal flux of saltating particles (**G**)*

We have used **a modeled expression** of the horizontal flux of saltating particles proposed by White (1979) and adapted by Marticorena and Bergametti (1995) in order to express this flux as a function of soil characteristics. So, the horizontal flux has been computed as a function of the size distribution of the loose erodible particles of soil (Marticorena and Bergametti, 1995) and a partitioning function due to the surface roughness (Alfaro and Gomes, 1995). Thus, in order to compute G ($g.cm^{-1}.s^{-1}$), the wind friction velocity (u_*) and its threshold value (u_{*t}) were needed.

*Total vertical flux of suspended particles (**F**)*

We have **developed an expression** of the vertical dust flux using parameters easily measured on a field. Based on the physics of fluid dynamics, an expression of F ($g.cm^{-2}.s^{-1}$) was found which takes into account the stratification of the surface boundary layer. The vertical dust flux can be computed using the following equation (Sabre, 1997) :

$$F = u_* \cdot k \cdot \left(\frac{C_b - C_t}{\mathrm{Ln}\left(\frac{z_t}{z_b}\right) - \Psi_{mt}\left(z_t/L\right) + \Psi_{mb}\left(z_b/L\right)} \right) \qquad (1)$$

where u_* is the friction velocity ($cm.s^{-1}$), k is the von Karman's constant (= 0.4) , C_b and C_t are the dust concentrations ($\mu g.m^{-3}$) at the two heights z_b and z_t (where b is bottom and t is top), Ψ_{mb} and Ψ_{mh} are the stability functions for momentum at the two same heights and L is the Obukhov length (m).

2.3. Sampling methodology

In order to calculate the saltation and suspension fluxes, aerosol sampling, meteorological monitoring and soil characterizations were carried out using the same method at all sampling sites.

Sensor devices (on one mast or two closely towers)

Airborne dust was collected at two levels (***Table-2***) on Nuclepore filters with a pumping system. Air flow was measured with a volume-counter and the cut-off diameter was generally less than 20 µm. Dust concentrations were determined from the elemental composition of the collected material measured by X-ray fluorescence spectroscopy (XRF). Total vertical dust flux (F) was the sum of the six elemental fluxes (in oxidized form MgO, Al_2O_3, SiO_2, K_2O, CaO, Fe_2O_3).

Wind speed and direction, and air temperature data were recorded on a meteorological tower. Data acquisition at several levels (***Table-2***) provided mean profiles. Based on the well known Prandtl-von Karman equation with Businger-Dyer relationships for all stability surface layer conditions, the wind friction velocity (u_*) and the overall roughness height of the sites (Z_0) were respectively obtained from the wind speed profile. The Monin-Obukhov parameter (z/L) for the stability function (Ψm) was computed from the gradient Richardson number. The wind vane was used to determine the direction of the fetch where the dust came from.

Table-2. Respective heights (m) of the meteorological and dust sensors for the 4 experimental field sites.

Sites	Owens Lake (dry lake)	Sahel 93 (weeded fallow)	Sahel 95 (cultivated)	Ebro Valley (cultivated)
Wind vane	2.00	4.05	4.00	2.00
Anemometers	0.20		0.50	0.75
	0.50	0.93	1.00	1.00
	1.00	1.98	2.00	2.00
	3.00	4.00	4.00	4.00
Air temperature probes	/	0.83	0.50	1.00
	/	2.36	1.00	2.00
Dust samplers	1.06	0.97	1.00	1.00
	4.03	4.07	4.00	4.00

The top 2.5 cm of soil was collected and dry sieved with a standard rotary sieve into 13 size classes (Coll and Fennetaux, 1993). This allowed the determination of the dry mass size distribution of the erodible fraction of soils (< 1000 µm), using a fitting procedure, based on the adjustment of a series of log-normal distribution (Gomes et al., 1990).

Data selection

Dust episodes have been obtained during erosion events. An uprising dust event is characterized by dust concentrations decreasing from the surface (bottom) to the atmosphere (top). The analytical precision of the XRF allowed accurate measurements of dust concentrations between two closely spaced levels (here < 4m). Dust samples were collected during different periods of time ranging from 15 to 150 minutes depending on atmospheric conditions.

The gradient Richardson number (Ri) was used to select the correct mean dynamic conditions. Well established dust events are defined here within the range -0.5 < Ri < 0.21.

Wind direction was necessary in order to know the soil surface responsible for the collected dust. Each experimental region is characterized by dominant winds: north winds in March for the Owens lake site, monsoon winds from W-SW in May and *Harmattan* winds from E-NE in April for Niger, and *Cierzo* winds from WNW for the Ebro valley in Spain. Consequently only dust events collected during those wind directions were selected.

Of the 4 original regional sets, only 4 wind erosion events for the dry Owens Lake, 6 for the Niger 93 field (recently weeded fallow), 6 for the Niger 95 field (millet cropping) and 7 for the Spain field (conventionally tilled), were selected.

3. Results

Mass size distribution of the erodible fraction of soil

Results of the dry sieving of soil samples (***Table-3***) show two dominant populations for the Owens dry lake and three for the others sites. For all sites, the mass median diameter of these populations, is within the same fraction of soil, i.e. a coarse population between 500 and 800 µm (mode 1), a medium population between 200 and 300 µm (mode 2) and finally a fine population between 50 and 100 µm (mode 3). These mass size distributions correspond roughly to the typical size distributions of desert soils described by Chatenet et al. (1996).

Table-3. Statistical parameters of the dry aggregate size distributions (< 1000 µm) of soil in the first 2.5 cm depth (MMD : Mass Median Diameter, SD : standard deviation, Amp : amplitude).

	Population 1			Population 2			Population 3		
Sites	MMD µm	SD	Amp. %	MMD µm	SD	Amp. %	MMD µm	SD	Amp. %
Owens Lake (dry lake)	697	1.50	62.0	216	1.28	38.0	–	–	–
Niger 93 (fallow)	574	1.56	50.6	222	1.28	44.8	83	1.15	4.6
Niger 95 (cultivated)	650	1.26	11.5	249	1.58	80.2	76	1.20	8.3
Spain 95 (cultivated)	812	1.15	10.2	248	2.18	81.2	52	1.38	8.6

During field experiments, the overall roughness height for each site (Z_0) was respectively 0.0023 cm, 0.02 cm, 0.05 cm, and 0.44 cm for the Owens dry lake, the Niger 93 field, the Niger 95 field and the Spain 95 field.

Both the mass size distributions (***Table-3***) and the overall roughness height data were used to calculate the impact threshold friction velocities (u_{*t}) equal to 15, 22, 26 and 33 $cm.s^{-1}$ for the Owens dry lake, the Niger 93 field, the Niger 95 field and the Spain 95 field, respectively.

Particles fluxes at the soil surface

The horizontal flux of saltating particles is an increasing function of the cubic wind friction velocity (***Fig-1***).

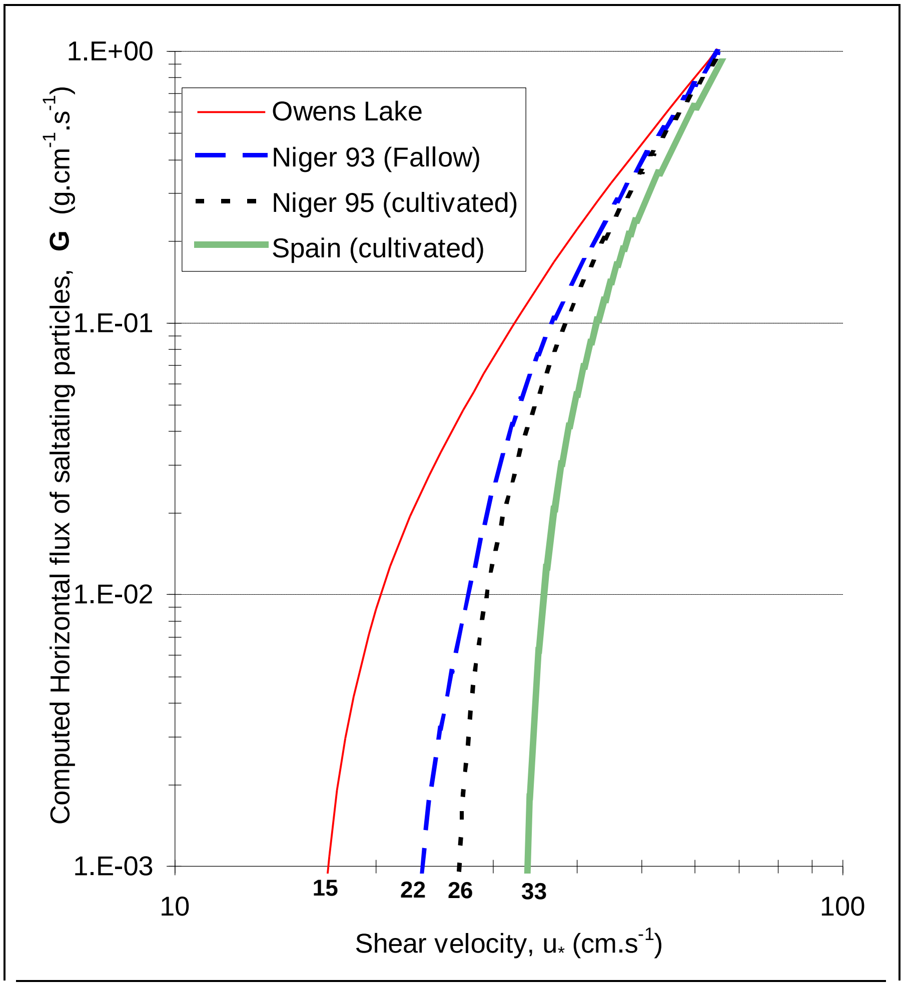


Figure-1. Computed total horizontal flux *G* ($g.cm^{-1}.s^{-1}$) vs. wind friction velocity u_* ($cm.s^{-1}$), for the four experimental field sites.

The main difference between the four field sites is due to the impact threshold friction velocity value (u_{*t}). This result underlines that for a fixed value of friction velocity, higher than the threshold, the saltation of soil particles differed in both the frequency and the intensity terms. Indeed, for example for the two Nigerian sites, saltation would start first on the fallow field and more often than on the cultivated field, and for example, for a friction velocity value around 30 $cm.s^{-1}$, horizontal flux would be more important on the fallow field than on the cultivated one.

The vertical dust flux, computed from equation (1) is an increasing function of the friction velocity (***Fig-2a*** and ***Fig-2b***). As observed in the two figures, *F* is increasing with different slopes for each site and within various intensity ranges.

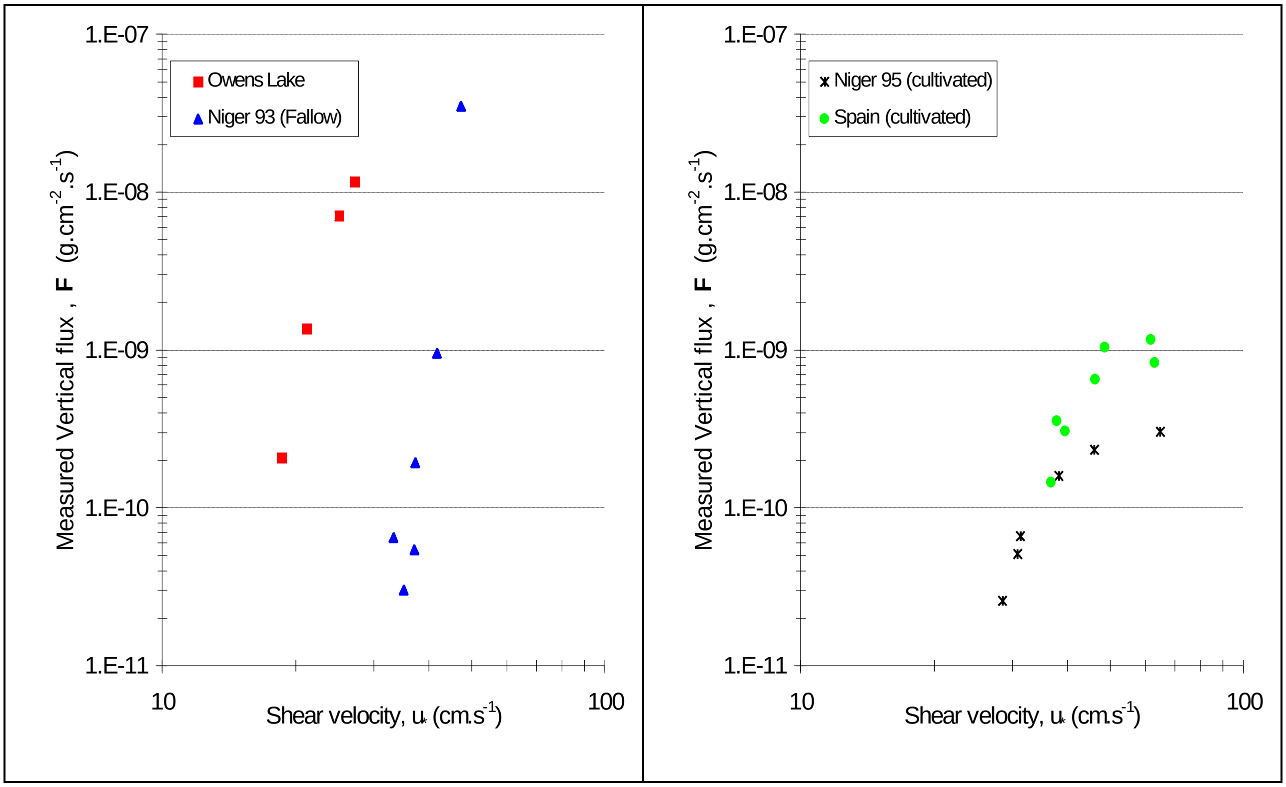


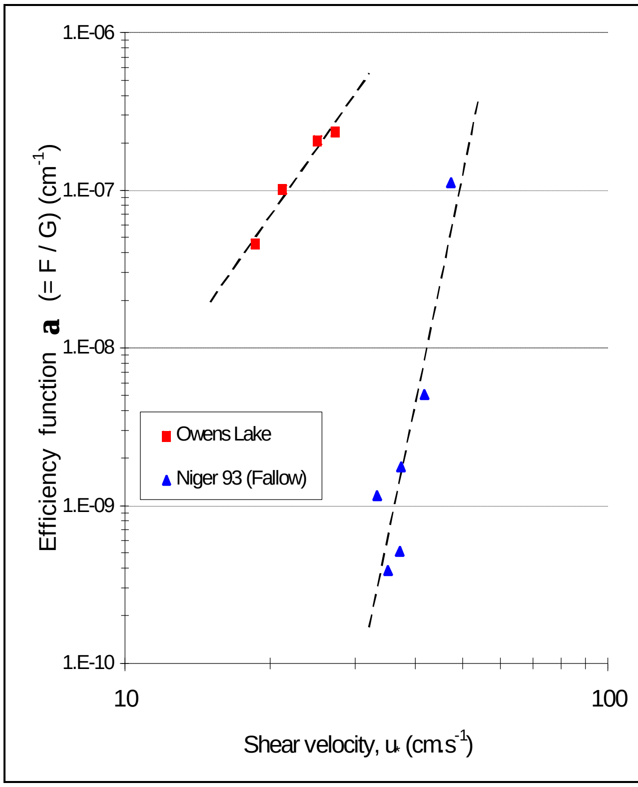
Figure-2a. Measured total vertical dust flux *F* (g.cm^{-2}.s^{-1}) vs. friction velocity u_* (cm.s^{-1}), for the two uncultivated field sites (Owens Lake 93 and fallow field of Niger 93).

Figure-2b. Measured total vertical dust flux *F* (g.cm^{-2}.s^{-1}) vs. friction velocity u_* (cm.s^{-1}), for the two cultivated field sites (millet culture Niger 95 and agricultural field in Spain 95).

This result suggests a difference in dust production. Indeed, uncultivated sites (Owens Lake and field of Niger 93) show values of fluxes between 10^{-11} to 10^{-7} g.cm^{-2}.s^{-1} for friction velocities ranging from 19 to 47 cm.s^{-1}, while on cultivated sites (Niger 95 and Spain 95) the increase of vertical flux is less important (from 2.10^{-11} to 10^{-9} g.cm^{-2}.s^{-1}) for a large range of friction velocities (28 to 65 cm.s^{-1}).

Efficiency of the dust release process

The efficiency of dust release process is characterized by the ratio of vertical to horizontal flux (***Fig-3a*** and ***Fig-3b***).



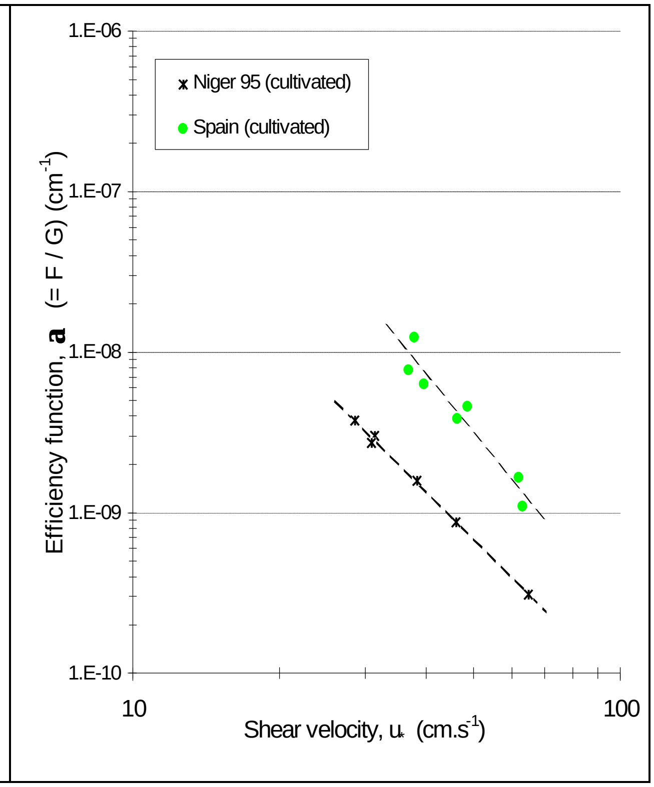


Figure-3a. Efficiency function vs. wind friction velocity for uncultivated sites (Owens Lake 93 and Niger 93).

Figure-3b. Efficiency function vs. wind friction velocity for cultivated sites (Niger 95 and Spain 95).

The figures show that the ratio *F/G* does not have the same behavior for cultivated and uncultivated soil surfaces. Indeed, the efficiency of dust production (α) is an increasing function for uncultivated fields, whereas a decreasing function for cultivated sites was observed, all with an increasing value of the friction velocity. Also slopes are more different on cultivated than on uncultivated fields.

As previously seen, both fluxes, horizontal and vertical, are **increasing** functions of the friction velocity. Differences in slopes, α, between cultivated and uncultivated soil surfaces underline that the friction velocity is not able to control by itself the dust production efficiency.

4. Discussion and concluding remarks

Kinetic energy (*Ec*) of one particle is a function of its mass and its squared speed. The mass of a particle is proportional to the density and the cubic *diameter* of the saltating grain. Its velocity is proportional to the wind *friction velocity* (Owen, 1964).

When the friction velocity is increasing it becomes higher than the threshold friction velocity which is a function of the mass size distribution of the loose erodible fraction of soil. This result means that for each value of the friction velocity there is a corresponding size distribution of the horizontal flux involving the participation of the soil modes.

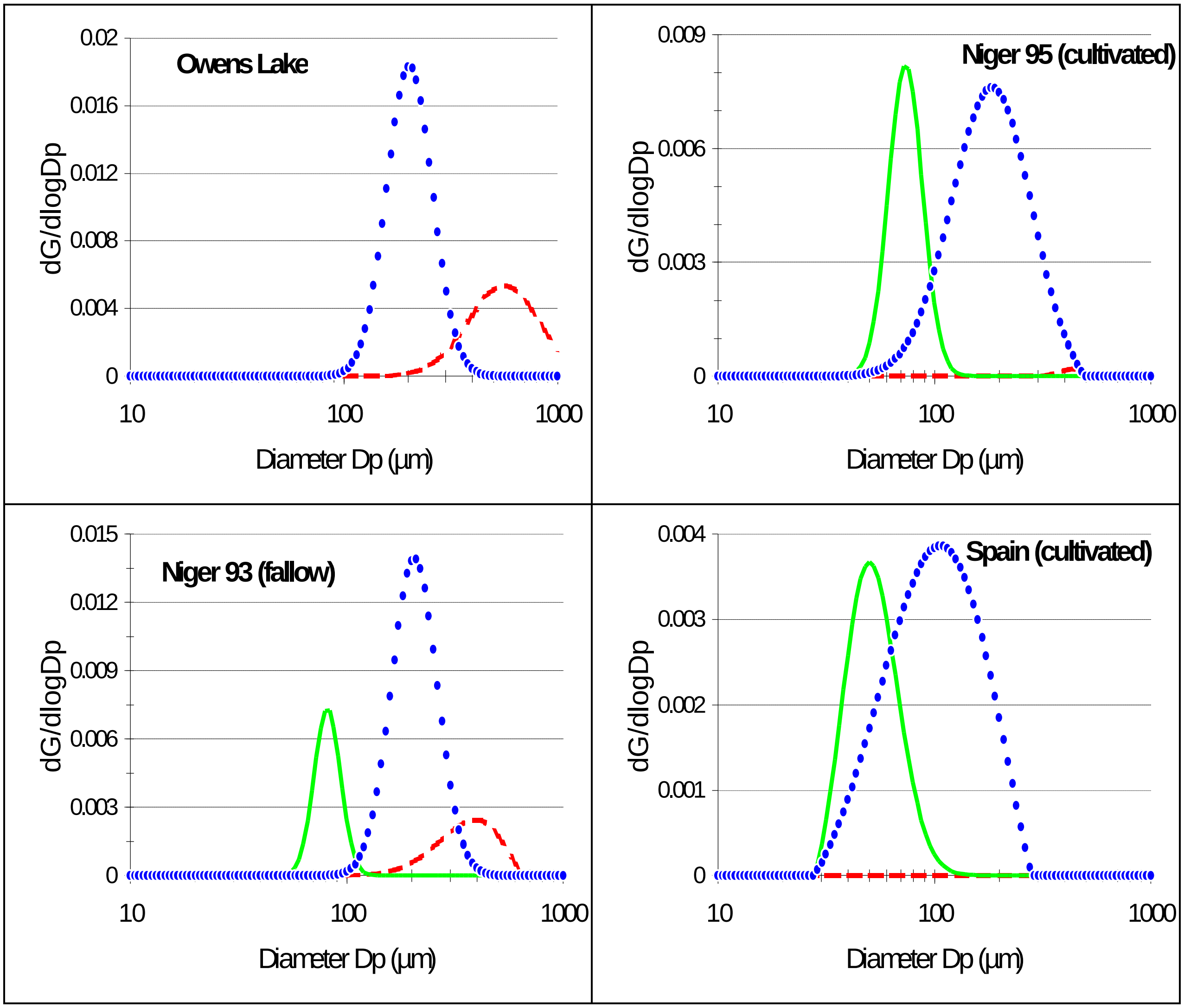


Figure-4. Size distribution of the saltation flux (dG/dlogDp) vs. size of saltating particles for the four experimental sites in a case of a friction velocity value of 46 cm.s^{-1}. *Coarse mode in red* ***dash line***, *medium mode in blue* ***dot line***, *fine mode in green* ***line***.

To illustrated it we have plotted in ***figure-4*** the distribution of the saltation flux as a function of the diameter of the saltating grains for a fixed wind friction velocity value around 46 cm.s^{-1}. This value of u_* allows the mobilization of all the soil modes.

The fine soil population (when it exists), is always in saltation as soon as u_* becomes higher than the minimum threshold for erosion. But the kinetic energy of the particles in this fine mode is relatively less efficient (regarding sandblasting process) than the particles of the medium and the coarse modes.

When saltation flux is characterized by the medium mode (see blue dot line in ***Fig-4***) as for cultivated sites (Niger 95 and Spain 95), the efficiency function (α) is **decreasing** when friction velocity is increasing. Conversely, when in addition the coarse mode (see red dash line in ***Fig-4***) is also involved in the saltation flux as for uncultivated sites (Owens Lake and fallow of Niger 93), the release of dust particles is drawn by an **increase** of the fine aerosol production efficiency.

When only the **medium mode** is efficient, a weak kinetic energy of saltating particles corresponds to a large efficiency of dust production. That result means that the horizontal flux (*G*), composed of more and more coarser particles, increases in mass, faster than the vertical flux (*F*) composed of a fraction with more and more finer particles, with an increasing wind friction velocity. When **in addition** to the medium mode the **coarse mode** is efficient, a large kinetic energy of saltating particles corresponds to a large efficiency of dust production. The vertical dust flux extended by the cumulative total of dust emitted from two modes, increases faster than the horizontal flux. Consequently, α increases with the wind friction velocity.

The efficiency function (α) illustrated by the ratio *F/G* is not a constant for a given soil. It depends on the friction velocity and its threshold value, but also on the kinetic energy of the saltating particles striking the soil surface.

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