

## Article

# Dependence of the Dust Emission on the Aggregate Sizes in Loess Soils

Gilad Gelbart and Itzhak Katra \*

Department of Geography and Environmental Development, Ben Gurion University,  
Beersheba 8410501, Israel; giladgel@post.bgu.ac.il

\* Correspondence: katra@bgu.ac.il

Received: 21 July 2020; Accepted: 4 August 2020; Published: 5 August 2020



**Abstract:** Dust emission resulted from soil erosion by wind with significant impacts of soil (nutrient) loss and air pollution of particulate matter (PM). The ejection of dust from soil aggregates due to saltation has been hypothesized to play a major role in dust emission. Yet empirical information on the role of different aggregate sizes in dust emission is still lacking. The main goal of this study was to explore the dust emission threshold in different aggregate sizes of a semiarid loess soil. To this end, we conducted targeted wind-tunnel experiment on dust emission. The results show that dust emission from aggregate at size of 63–250  $\mu\text{m}$ , 250–500  $\mu\text{m}$ , and 500–1000  $\mu\text{m}$  is enabled only under the conditions of saltation. The dust-PM threshold at shear velocities of 0.24–0.52 m/s depends on the aggregates size. Aggregates at the size of saltators (125–500  $\mu\text{m}$ ) were the most productive in dust generation by the mechanism of aggregate disintegration. In our bulk sample, the aggregate group of 63–250  $\mu\text{m}$  has the highest contribution to the total dust emission. The study aimed to advance our capability in soil resources management and for model parameterization in dust emission schemes.

**Keywords:** wind tunnel; particulate matter; soil erosion; particle size distribution

## 1. Introduction

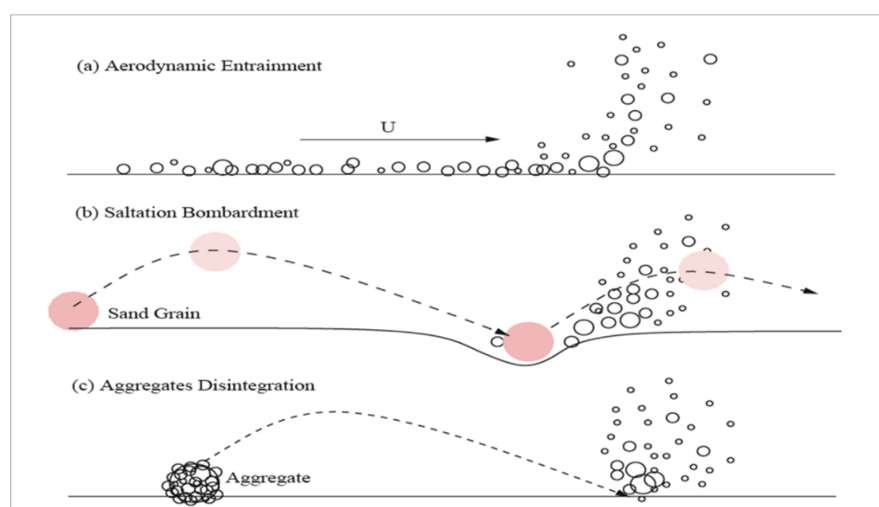
Soil erosion has environmental and socioeconomic significances due to loss of a natural resource. Many arid soils are characterized by bare surfaces that are exposed directly to the erosive forces. The erosion depends on the physicochemical properties of the soil that are reflected in the soil aggregation [1]. Thus, the soil aggregation provides information on soil fertility and soil stability to erosion forces [1–4]. Soil aggregation refers to the adhesion of two or more soil particles by organic and inorganic cementing materials [5,6]. The size and stability of soil aggregates depend on the type and content of the cementing materials [1]. One of the most important elements that bonds between soil particles and forms aggregates is the clay minerals. The clays are characterized by a high specific surface area (SSA) and high cation-exchange capacity (CEC), which generates strong forces of cohesion [7]. Studies have shown that there is a connection between the clay content and the aggregate size and stability [8–11].

Aggregate diameters can range between less than 2  $\mu\text{m}$  to a few millimeters [1,12] with specific aggregate size distribution in a soil sample. It is generally assumed that soils with a greater amount of large aggregates will be more fertile and have stronger resistance against erosion [1]. One of the most popular indices for determination of aggregate size distribution in the soil is the mean weight diameter (MWD), which represents the relative part of each size segment of the aggregates in the soil [13]. This index can also be a representative and convenient measure of the comparison between different soils. Another common index is the division of the aggregates into different groups of sizes with a gross distribution into macro aggregates (>250  $\mu\text{m}$ ) and micro aggregates (<250  $\mu\text{m}$ ) based on

the hierarchy concept of Tisdall and Oades [12]. It was found that macroaggregates were composed of much higher organic matter compared with microaggregates [14].

In wind erosion, the soil erodibility is mostly associated with the aggregates that are smaller than  $840\text{ }\mu\text{m}$  [15]. Erodible fraction (EF) index presents a quantitative value that expresses the weight of the small aggregates ( $<840\text{ }\mu\text{m}$ ) relatively to the total weight of the soil sample. The dry aggregate stability (DAS) also examines the stability of the soil to wind erosion which calculates the proportion between the weight of the small aggregates ( $<840\text{ }\mu\text{m}$ ) and the weight of the large aggregates ( $>840\text{ }\mu\text{m}$ ) [15]. These indices and the soil stability are affected by the cementing materials such as organic matter, clay content and carbonates [16]. Several studies have showed a clear relationship between aggregate and the mean weight diameter (MWD) value and soil stability to wind erosion [17]. Tanner et al. [18] showed negative correlation between MWD and dust emission expressed by particulate matter that is  $<10\text{ }\mu\text{m}$  in diameter (PM10) in agricultural soils. Dust-PM10 emissions can be minimized by reducing soil tillage that prevents breakage of aggregates, thus reducing the soil erosion by wind [19]. In soils with small aggregates, the horizontal sediment fluxes are higher and thus so is the soil erosion [20].

Dust emission is enabled under a critical value of wind (shear) velocity ( $u^*$ ) at which the aerodynamic force is enough to dislodge particles from the surface [21]. The dust entrainment from the soil is strongly connected with the saltation process. Saltation is initiated when the wind stress is sufficient to lift sand-sized particles ( $63\text{--}500\text{ }\mu\text{m}$ ) into the fluid stream. Lifted particles undergo ballistic trajectories to impact the surface. The resulting impacts can eject, or splash, new particles into the stream [22,23]. Shao [24] and Kok et al. [25] suggested three main theoretical mechanisms of dust emission from aggregates (Figure 1): (i) a direct aerodynamic lifting of loose microaggregates ( $<63\text{ }\mu\text{m}$ ); (ii) ejection of dust particles from soil aggregates by the impact of saltating grains; and (iii) ejection of dust by self-breakdown of the saltating aggregates. In many soils, the small dust-sized particles ( $<63\text{ }\mu\text{m}$ ) are held in aggregates, and thereby are not available for directly lifting by the wind. Kok [25] argues that the emission of fine particulate matter (dust) is produced mainly by the fragmentation of soil aggregates that are transported in horizontal flux (saltation). Aggregates (mainly those  $<63\text{ }\mu\text{m}$ ) that are moved in saltation can break down at a rate of a 38% along fetch distance of 100 m. An experimental study of Swet & Katra [26] found a significant change in aggregate size distribution during dust emission processes. They showed that the rate of saltation and dust emissions depends on the initial size distribution of the soil aggregates at a given shear velocity. The erosion of the larger aggregates ( $>500\text{ }\mu\text{m}$ ) increased the content of the saltator-sized aggregates ( $63\text{--}250\text{ }\mu\text{m}$ ), which affects the rate of the dust emission over time.



**Figure 1.** Illustration of the three dust emission mechanisms: (a) aerodynamic entrainment, (b) ejection of dust aerosols from soil aggregates by impacting saltating particles, and (c) ejection of dust aerosols from soil aggregates that are participating in saltation. Adapted from Shao [24].

The ejection of dust from soil aggregates due to saltation has been hypothesized to play a major role in dust emission [24–27]. Previous empirical studies examined dust emission in relation to the aggregate size distribution of the soil [15–18,20,26]. Yet, information on the role of different aggregate sizes in dust emission is still lacking. The main goal of this study is to explore the dust emission threshold in different aggregate sizes that are subjected to saltation. To this end, we conducted a targeted wind-tunnel experiment on dust emission in a semiarid loess soil. The loess soil-type covers 10% of the Earth’s land surface and it is associated worldwide with dust emissions e.g., [28]. In semiarid areas that are subjected to increased land uses and possible climate change of reduced precipitation, changes in soil erosion and dust emission intensities should be considered for the environmental consequences. The results aimed to improve our understanding and capabilities for model parameterization in dust emission schemes.

## 2. Materials and Methods

### 2.1. Soil Sample Setup

Reference soil samples were used for the experiment on dust emission from aggregates to fit the study’s goal. Natural loess soil from the northern Negev Desert (Israel) was used as a bulk sample and for the preparation of the specific samples. The bulk soil was taken from the upper layer of the soil that is subjected to erosional processes in the field. The loam texture of the loess consists of ~70% clay-silt fraction, and the quartz sand has a typical size range of fine-medium sand (<300 µm). Three reference samples were prepared for aggregate groups at the sizes of 63–250 µm, 250–500 µm, and 500–1000 µm, by sieving of the bulk sample. The samples were dried to an air-dry state (<1.5% gravimetric water content) in order to eliminate effect of soil water content.

The bulk sample was tested for aggregate size distribution (ASD) to determine the mean weight diameter (MWD). The ASD was obtained using the dry sieving method. The samples were placed on a set of six sieves with diameters of 63, 125, 250, 500, 1000, and 2000 µm, and were shaken at a moderate amplitude of 50 rounds per minute for 8 min on an electronic sieving apparatus with horizontal and vertical motions (RETSCH AS 300 Control, Haan city, Germany). Every size fraction was weighed separately to calculate the mean weight diameter (MWD) (mm) as follows:

$$MWD = \sum_{i=1}^n x_i w_i \quad (1)$$

where  $n$  is the total number of aggregates measured,  $w_i$  is the fraction (%) that is the relative part of the group’s size, and  $x_i$  is the equivalent diameter of the aggregate (mm).

The samples of the different aggregate groups (63–250 µm, 250–500 µm, and 500–1000 µm) were analyzed for several soil properties. Particle size distribution was obtained by the ANALYSETTE 22 MicroTec Plus (Fritsch, Idar-Oberstein, Germany) laser diffraction, which measures particles in the size range of 0.08–2000 µm [29]. Replicas (100 mg) were dispersed in Na-hexametaphosphate solution (0.5%) by sonication (38 kHz). The data was calculated using the Fraunhofer diffraction model with a size resolution of 1 µm using MasControl software. Soil organic carbon (SOC) content (%) was determined by the dry combustion method. A 5 g sample of crushed oven-dried (105 °C for 24 h) soil was placed in a combusting oven at 375 °C for 17 h. At this temperature, all organic carbon in the soil oxidizes, with no conflagration of mineral carbon. Carbonate (CaCO<sub>3</sub>) was determined as mass content (%) by a calcimeter. The carbonates present in a 200 mg sample were converted into CO<sub>2</sub> by adding hydrochloric acid 8% (HCl) to the sample. The calcium carbonate content can be calculated with reference to a standard sample of analytical (100%) CaCO<sub>3</sub>.

## 2.2. Dust Emission Experiment

The dust experiment was performed by a boundary layer wind tunnel that was used in previous studies [26,30,31]. Boundary-layer wind tunnels enable the production conditions for the natural aeolian process that occur in the field and make it possible to provide quantitative information on the emission of dust from various soils [32]. The wind tunnel has a cross sectional area of  $0.5 \times 0.5$  m open-floored working sections with a length of 7 m. Air push or air suction flow in the tunnel is generated by an axial fan up to maximum velocity of  $18 \text{ m s}^{-1}$ . Instruments installed in the test section of the tunnel enable quantification of: (1) wind profile for the calculation of frictional velocity, (2) saltation flux, and (3) dust concentrations of PM10.

The soil samples were tested in the wind tunnel under a range of fan frequencies (11–41 Hz). These frequencies represent a range of common wind velocities that are associated with dust emissions in the field. The wind velocity profile was measured for each fan frequency at several heights above the tunnel bed: 0.02, 0.035, 0.05, 0.075, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, and 0.45 m. The wind measurement was conducted with a microvane anemometer with vane diameter of 14 mm that measures wind velocities at the range of 0–30 m/s with reading resolution of 0.1 m/s (KIMO vt 200, Ontario, Canada). The data are logged at time interval of 5 s for each test. The data were analyzed to determine the height of the boundary layer, the average wind velocity in the boundary layer, and the wind shear velocity ( $u^*$ ). The wind shear velocity is expressed by the Prandtl–von Karman equation [25]:

$$\frac{u}{u_*} = \frac{1}{K} \ln\left(\frac{z}{z_0}\right) \quad (2)$$

where  $u$  is the wind velocity (m/s) at height  $z$  (m),  $z_0$  is the aerodynamic roughness length (m) of the surface  $u^*$  is the shear velocity (m/s), and  $K$  is von Karman's constant ( $\approx 0.4$ ).

The soil was placed on the tunnel bed at a soil layer of  $\sim 2$  cm. Each soil sample was tested for all fan frequencies in three replicates—overall 90 runs were performed by the wind tunnel (3 samples, 3 replicates, 10 wind velocities). Each run lasted for 30 s per velocity continuously in order to detect trends of dust emission and saltation. A saltation trap was placed in the wind tunnel to collect saltators in horizontal transport. The saltation mass in the trap was analyzed for the relative contents of sand and dust ( $<63 \mu\text{m}$ ) fractions. The mass of the transported particles was calculated as saltation flux ( $Q$ ,  $\text{kg m}^{-1} \text{s}^{-1}$ ) that crosses a width of 1 m, e.g., [33].

Dust concentration of particulate matter that is  $<10 \mu\text{m}$  in diameter (PM10,  $\mu\text{g m}^{-3}$ ) was recorded by a light-scattering device (DustTrak DRX 8534, TSI, Shoreview, MN, USA), which was placed at 15 cm above the tunnel bed, in the range of  $0.001$ – $150 \mu\text{g m}^{-3}$  ( $\pm 0.1\%$  of reading) at 1-s interval. The recorded PM10 concentrations were converted into mass flux emitted from the soil surface ( $\text{kg m}^{-2} \text{s}^{-1}$ ) based on the wind tunnel dimensions and area of the sand bed [34]:

$$F_{PM} = (C_{PM} - C_{bg}) \times V_{air} \times A_{cs} / A_p \quad (3)$$

where  $C_{PM}$  is the recorded PM concentrations ( $\text{kg m}^{-3}$ ) from the soil,  $C_{bg}$  is the average PM background concentration ( $\text{kg m}^{-3}$ ),  $V_{air}$  is the mean horizontal wind velocity  $i$  over height ( $\text{m s}^{-1}$ ),  $A_{cs}$  is the cross-section (height  $\times$  width) of the wind tunnel ( $\text{m}^2$ ), and  $A_p$  is the area ( $\text{m}^2$ ) of the experimental plot (length  $\times$  width).

The PM10 flux and the saltation flux were used to calculate the sandblasting efficiency  $\alpha$  ( $\text{m}^{-1}$ ), which is the vertical dust flux produced by a unit horizontal sand saltation flux, and is an important property to inform the dust emission mechanism [33]:

$$a = F_{PM} / Q \quad (4)$$

where  $F_{PM}$  is the average PM10 vertical mass flux ( $\text{kg m}^{-2} \text{s}^{-1}$ ), and  $Q$  ( $\text{kg m}^{-1} \text{s}^{-1}$ ) is the averaged horizontal sand flux integrated over the whole experimental time for all sand grain sizes.

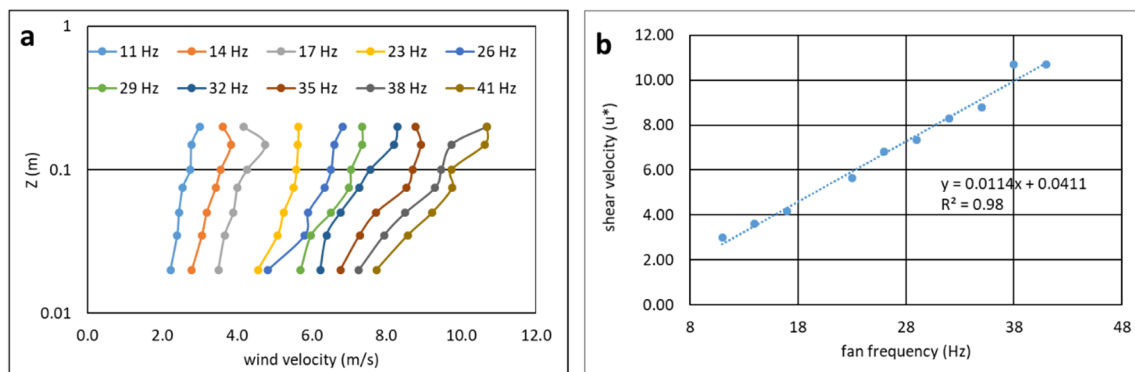
### 3. Results

The aggregate characteristics as measured for the reference samples are shown in Table 1. The small-sized sample (63–250  $\mu\text{m}$ ) contains the largest amount of clay and the lowest amount of sand. The lowest amount of clay was found in the reference sample of 500–1000  $\mu\text{m}$ . Sample 63–250 shows a similar composition of clay, silt, and sand to that of the bulk sample. The other two samples are different from the bulk sample when a lower percentage of clay and silt and a higher percentage of sand exist compared with the bulk sample. Studies have shown that there is a connection between the content of clay and the aggregate size in different soils. The aggregate size increased with higher clay contents [35,36]. Contrary to expectations, the results in the present experiment show an opposite trend in which the smaller aggregates contain more clay and silt than the larger ones. The amount of soil organic matter (SOM) was found to be at the same level (2.1–2.2%) for all the soil samples (Table 1). The SOM of the bulk sample (2.91%) is somewhat higher than the SOM of the fraction samples. We may expect that a high content of SOM is found in aggregates larger than 2000  $\mu\text{m}$ . The content of the carbonate was relatively higher in samples of 63–250  $\mu\text{m}$  and 250–500  $\mu\text{m}$ , compared with the content (8.5%) of the 500–1000  $\mu\text{m}$ . The carbonate content is also contributing to the production of larger aggregates [1,37]. According to the present results, there is an opposite trend, when the large aggregates (500–1000  $\mu\text{m}$ ) contain less carbonate than the small ones.

**Table 1.** Mean values of soil properties for the reference samples and the bulk sample.

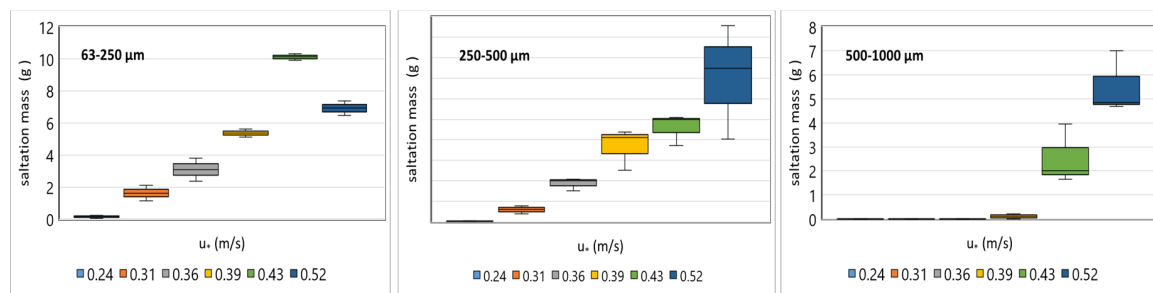
|                        | Clay (%)   | Silt (%)    | Sand (%)    | CaCO <sub>3</sub> (%) | SOM (%)   |
|------------------------|------------|-------------|-------------|-----------------------|-----------|
| 63–250 $\mu\text{m}$   | 16.1 (6.0) | 60.5 (12.3) | 23.3 (18.4) | 14.4 (1.6)            | 2.2 (0.1) |
| 250–500 $\mu\text{m}$  | 12.8 (1.5) | 53.1 (4.2)  | 34.0 (5.7)  | 12.9 (0.8)            | 2.1 (0.2) |
| 500–1000 $\mu\text{m}$ | 11.7 (0.8) | 55.6 (1.2)  | 32.6 (0.3)  | 8.5 (1.5)             | 2.1 (0.3) |
| Bulk sample            | 13.7 (N/A) | 60.4 (N/A)  | 25.8 (N/A)  | 10.6 (0.7)            | 2.9 (0.0) |

The wind velocities were measured at several heights above the tunnel bed in each fan frequency to determine the wind profile in the tunnel (Figure 2). In all fan frequencies tested, the wind velocity increases as the height above the tunnel bed increases. The data show a high positive correlation ( $R^2 = 0.98$ ) between the fan frequency and the wind velocity at height 0.2 m. The wind velocity at height above 0.2 m starts to decrease because of the wall effect at the roof of the tunnel. The changes in the wind velocity with height allows the calculation of the shear velocity ( $u^*$ ). The shear velocity in this experiment ranged from 0.24 m/s to 0.52 m/s. A strong positive correlation ( $R^2 = 0.98$ ) between the shear velocity and the fan frequency was found (Figure 2).



**Figure 2.** (a) Wind velocity (m/s) measured at different heights above the tunnel bed ( $z$ ) under different fan frequencies (Hz) (b) Correlation between the fan frequencies applied in the wind tunnel and the calculated shear velocity.

Figure 3 shows the results of the saltation measurements as weighed from the traps at different shear velocities. The results show that the range of saltation values is not uniform across all samples. In sample 63–250  $\mu\text{m}$  the lowest value is 0.1 g and the highest is about 100 time more (10.1 g). The highest value however was recorded at 0.43 m/s. The material analysis of the saltation mass (Table 2) showed only a small amount (11.8%) of material that is  $<63 \mu\text{m}$  at velocity 0.52 m/s (Table 2). This may explain a decline of about 30% in the saltation mass of 0.52 m/s, compared with 0.43 m/s, in which the stronger wind entered more particle into suspension (dust-PM) rather than in saltation. In sample 250–500  $\mu\text{m}$  the lowest value is 0.07 g and the highest is about 200 time more (14 g). The saltation mass in velocity 0.52 m/s was about 60% higher in relation to velocity 0.43 m/s. In measuring the material smaller than 63  $\mu\text{m}$  in the saltation mass (Table 2), it was found that there is no distinct trend showing the material variability according to the shear velocity. The percentage of matter less than 63  $\mu\text{m}$  at 0.52 was 17.5% while the percentage at 0.31 was 12.3%. In sample 500–1000  $\mu\text{m}$  the highest value was recorded in 0.52 m/s (5.5 g) while the saltation started only from 0.39 m/s. In most velocities, no material less than 63  $\mu\text{m}$  was found in the saltation mass (Table 2). As the velocity increases, the macroaggregates move and break so that only at the last velocity 8.4% of the material in the saltation mass was smaller than 63  $\mu\text{m}$  (Table 2).



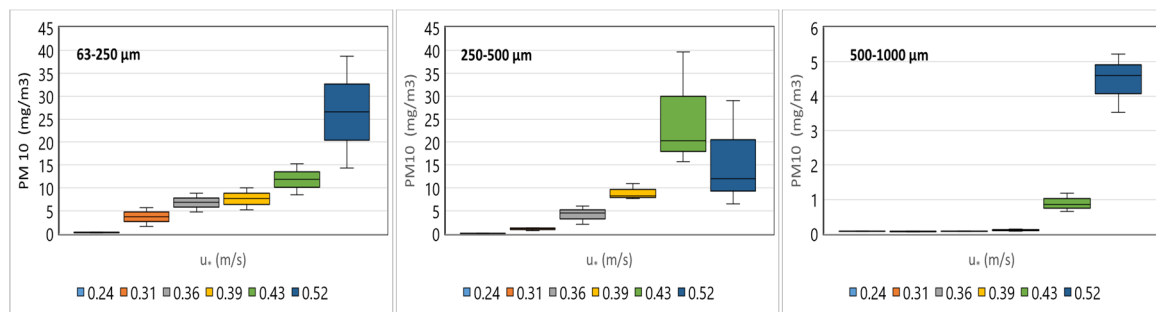
**Figure 3.** Saltation mass measured in the reference samples under various shear velocities. The average mass is presented by the solid line inside the minimum/maximum box, and standard deviations are in dashed lines. Note the differences in the value range of Y axis.

**Table 2.** Percentage of dust-sized aggregates and particle ( $<63 \mu\text{m}$ ) in the saltation mass (Figure 3) under each shear velocity.

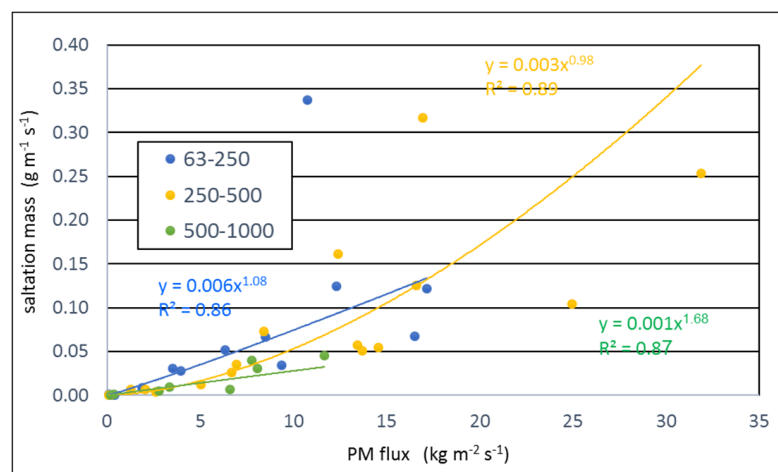
| $u^*$ (m/s) | Sample 63–250 $\mu\text{m}$ | Sample 250–500 $\mu\text{m}$ | Sample 500–1000 $\mu\text{m}$ |
|-------------|-----------------------------|------------------------------|-------------------------------|
|             | $<63 \mu$ (%)               | $<63 \mu$ (%)                | $<63 \mu$ (%)                 |
| 0.24        | 30.5                        | N/A                          | N/A                           |
| 0.31        | 30.3                        | 12.3                         | N/A                           |
| 0.36        | 24.5                        | 24.9                         | N/A                           |
| 0.39        | 16.5                        | 13.7                         | N/A                           |
| 0.43        | 20.5                        | 18.1                         | 6.6                           |
| 0.52        | 11.8                        | 17.5                         | 8.4                           |

The results of the PM10 concentrations that were measured during the experiment are shown in Figure 4. The range of the values differs according to the aggregate size so that the highest PM10 concentration was recorded in the smallest fraction (63–250  $\mu\text{m}$ ) and the lowest one was at the largest fraction (500–1000  $\mu\text{m}$ ). In sample 63–250  $\mu\text{m}$ , the lowest dust concentration was 0.2  $\text{mg}/\text{m}^3$  and the highest concentration was about 170 time more (35.2  $\text{mg}/\text{m}^3$ ). A moderate increase in concentration occurs when the wind velocity increases accordingly. The concentration peak (26.5  $\text{mg}/\text{m}^3$ ) was recorded at shear velocity 0.52 m/s with more than 100% increase relative to velocity 0.43. In sample 250–500  $\mu\text{m}$ , the lowest concentration was 0.1  $\text{mg}/\text{m}^3$  and the highest concentration was about 250 time

more ( $25.1 \text{ mg/m}^3$ ). In 250–500  $\mu\text{m}$  sample, there was a significant increase in PM10 concentration at 0.43 m/s. This PM10 value was even higher than that of 0.52 m/s although not significant. It is reasonable to assume that a vast amount of dust particles was released at 0.43 m/s, and thus the dust supply from aggregates was more limited under 0.52 m/s. In sample 500–1000  $\mu\text{m}$ , a distinct PM10 concentration was obtained only from 0.39 m/s, which is the same threshold of saltation (Figure 3). A positive nonlinear correlation was found between the calculated PM10 flux and the saltation flux (Figure 5) for all soil samples ( $R^2 = 0.86\text{--}0.88$ ).



**Figure 4.** The particulate matter that is  $<10 \mu\text{m}$  in diameter (PM10) concentration calculated from the wind tunnel measurements of the reference samples under various shear velocities. The average concentration is presented by the solid line inside the minimum/maximum box, and standard deviations are in dashed lines. Note the differences in the value range of Y axis.



**Figure 5.** Nonlinear correlation between PM10 flux and saltation flux for the different soil samples. Note the different value range of saltation and PM fluxes between the soil samples.

#### 4. Discussion

Loess soils that are associated with dust emission are typically composed of aggregate size distribution at the range of less than  $2 \mu\text{m}$  to over  $2000 \mu\text{m}$ . In this study we examined soil samples with aggregate size fraction within this range. Previous studies on dust emission from loess soil reported on aggregate size distribution at similar range of the current study [38–40]. Yet information on the properties of each aggregate size is important for the study on dust emission from soil aggregates. The aggregate properties in the present study show that the common cement materials are not the major factor in the formation of large aggregates. The amount of organic matter, soil moisture, and carbonate in aggregates was relatively low and similar among the samples (Table 1). Boix-Fayos et al. [3] show that aggregates at size of  $105\text{--}1000 \mu\text{m}$  contain a large amount of fine sand compared to smaller aggregates containing more clay and organic matter. It can be assumed that the major factor that allows

the large aggregates to exist in our soil is the amount of coarse-silt and fine sand ( $<200\text{ }\mu\text{m}$ ) in relation to the content of the clay in the aggregates. The coarse-silt and fine sand may accumulate with the clay to form larger aggregates.

The wind tunnel was operated under a range of air velocities that start from low velocity that barely start aeolian processes to velocities that are directly identified with dust emission in various soils and specifically in loess soil [18,26,30,31,41,42]. The wind profiles received in this study (Figure 2) have similar trends to profiles of previous works [26,41]. The wide range of the wind shear velocities (0.24–0.52 m/s) enabled us to define the saltation and dust emission thresholds [25,33].

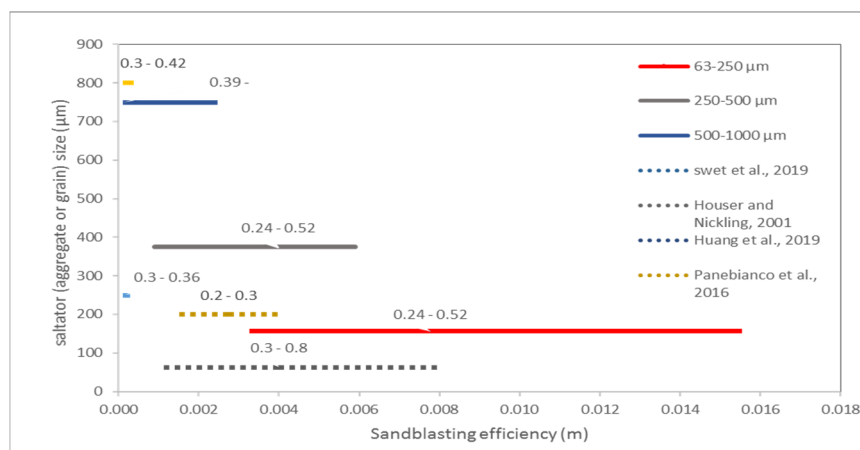
According to the results of this study, the threshold value of dust emission in aggregates 63–500  $\mu\text{m}$  is a shear velocity of 0.31 m/s and in macroaggregates 500–1000  $\mu\text{m}$  is 0.39 m/s (Figure 5). The aggregate size is critical to determine the emission rate at any given wind velocity. For example, the highest rate of PM10 at velocity of 0.43 m/s is received from aggregates 250–500  $\mu\text{m}$ . In this size group all the aggregates are at saltator sizes, which move in saltation at the shear velocities of 0.31–0.52 m/s to provide high saltation mass. In the group of 63–250, only the fraction of 125–250  $\mu\text{m}$  is moving in saltation, while the smaller ones (63–125  $\mu\text{m}$ ) may enter into suspension, and thus lower saltation and dust fluxes are received compared with the aggregate group 250–500  $\mu\text{m}$ . Saltation of larger aggregates (500–1000  $\mu\text{m}$ ) requires more energy to be transported and release dust by aggregate breakage.

Assuming that loose dust-sized particles ( $>63\text{ }\mu\text{m}$ ) in most soils are barely available for direct lifting due to cohesive forces, the main mechanism that allows the dust emission is the breaking of the aggregates by the saltation [25,43]. In all samples, the emission of dust occurs only when the saltation begins, according to the threshold velocity of the different samples (Figures 3 and 4). The reduction in the aggregate size as a result of saltation and aggregate breakage was demonstrated by Swet and Katra [26]. They showed that following macroaggregate saltation ( $>500\text{ }\mu\text{m}$ ), the amount of aggregates 63–250  $\mu\text{m}$  could increase by 10–34% so that the initial state of the aggregate size distribution could indicate the erosion expected to affect in the soil. Examination of the saltation material in the traps (Table 2) cannot provide us information on aggregation reduction as suggested by Swet and Katra [26]. The current study examines only three size groups while the combination of macro and micro aggregates in the saltation can create an increased fracture that does not occur when groups are divided.

Knowing the initial aggregate size distribution of a soil would be an advantage in estimating dust emission levels. The results of the distribution of soil aggregates in the present study show that the fraction 63–250  $\mu\text{m}$  is about 55% from the bulk sample (all aggregate sizes) and the fraction of 250–500  $\mu\text{m}$  and 500–1000  $\mu\text{m}$  is about 5% each. It can be assumed that during a wind event that is above the shear threshold ( $>0.31\text{ m/s}$ ), there is a saltation and dust emission from most of the aggregates ( $>500\text{ }\mu\text{m}$ ) at the same time. Our results indicate that the total dust emission from the bulk sample will be mostly like the dust flux from the fraction 63–250  $\mu\text{m}$ . This is demonstrated by the sandblasting efficiency (Figure 6), which is the ratio between the PM10 flux and the saltation flux [33,43]. The sandblasting efficiency in sample 63–250  $\mu\text{m}$  (presented as 156  $\mu\text{m}$ ) was found to be the highest compared with other samples with a similar size range [33,44,45]. In the studies of Swet et al. [33] and Huang et al. [46], the sandblasting efficiency is low despite the similarities to samples 63–250  $\mu\text{m}$  and 250–500  $\mu\text{m}$  of this study. These studies dealt with sand from dunes, in which there is a low availability of dust particles in the samples and no breaking of aggregates. In sample 500–1000  $\mu\text{m}$  (presented as 750  $\mu\text{m}$ ), the saltation starts only at shear velocity 0.39 m/s when the wind is strong enough. The values of the sandblasting efficiency are relatively low compared with the other samples in this study but still higher than those of sandy soils.

Our methodology has some limitations. First, we applied three aggregate size groups which may not represent the entire range of soil sizes. However, these groups are common in many soils and specifically in loess soils that are associated with dust emission processes. The division into macroaggregates ( $>250\text{ }\mu\text{m}$ ) and microaggregates ( $<250\text{ }\mu\text{m}$ ) allows the analysis of the emission mechanism of the aggregates moving in saltation and those that need to be broken by the impact

of saltators in order to emit dust. Second, the use of a wind tunnel to examine the dust emission may not reflect the natural wind in the field where the velocity and direction are constantly changing. However, the controlled wind velocities by the tunnel make it possible to examine the emission thresholds of various soil samples. Third, the saltation and dust fluxes calculated in this study by the wind tunnel experiment do not necessarily fit the values measured in the field, but they do allow for the quantitative comparison between soil samples (e.g., sandblasting efficiency).



**Figure 6.** Sandblasting efficiency of the 63–250  $\mu\text{m}$  sample (red), 250–500  $\mu\text{m}$  sample (green), and 500–1000  $\mu\text{m}$  sample (blue). The size is represented by the mean of the size fraction of the aggregate samples. The chart shows some previous works (dashed line) showing the results with different shear velocities. The range of the sandblasting efficiency in each work is related to the range of shear velocity applied at work.

In recent decades, there have been environmental changes associated with intense human activity. Climate change and global warming can cause dehydration in some areas and cause degradation of the soil [47]. The advancement of modern agriculture, along with increased use of massive mechanical tillage and extensive human activity, results in loss of important soil stabilization materials [48]. The different effects on soil can cause a decrease in the size and stability of the aggregates and thus change the rate of soil erosion [49]. When the size of the aggregates decreases significantly and there is drought, the aeolian transport can be more significant and be a catalyst for the degradation process in the soil.

## 5. Conclusions

In this study we examined dust emission from soil aggregate with different sizes. The significance of this study was to provide a better understanding on the role of the soil aggregation in soil erosion and dust emission processes. The wind tunnel results show that the PM<sub>10</sub> emission is associated with saltation and the breaking of the aggregates. Basically, aggregates at the size of saltators (125–500  $\mu\text{m}$ ), at typical wind shear velocities (0.24–0.52 m/s), are the most productive in dust generation by the mechanism of aggregate disintegration. In larger aggregates, a strong shear velocity is required to initiate saltation and cause breakage and dust emission. Nonetheless, the aggregate size distribution of the (bulk) soil is important in determining the dust fluxes. In our case, in a semiarid loess soil, the aggregate group of 63–250  $\mu\text{m}$  has the highest percentage in the bulk sample, and this should be considered in dust emission assessments. Many soils throughout the world are already associated with soil erosion and dust emission, especially in arid climates. Human activities and land uses alter the soil properties, and thus the soil aggregate sizes. A management strategy of preventing soil aggregate disintegration, and/or increasing the soil aggregate sizes by soil stabilization methods, is necessary in order to keep our natural resource of soil and possibly decrease environmental pollution by dust-PM.

**Author Contributions:** Conceptualization, I.K.; methodology, I.K. and G.G.; formal analysis, G.G.; writing—original draft preparation, G.G.; writing—review and editing, I.K. and G.G.; funding acquisition, I.K. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Amézketa, E. Soil aggregate stability: A review. *J. Sustain. Agric.* **1999**, *14*, 83–151. [\[CrossRef\]](#)
2. Le Bissonnais, Y.L. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. *Eur. J. Soil Sci.* **1996**, *47*, 425–437. [\[CrossRef\]](#)
3. Boix-Fayos, C.; Calvo-Cases, A.; Imeson, A.C.; Soriano-Soto, M.D. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. *Catena* **2001**, *44*, 47–67. [\[CrossRef\]](#)
4. Hevia, G.G.; Mendez, M.; Buschiazzi, D.E. Tillage affects soil aggregation parameters linked with wind erosion. *Geoderma* **2007**, *140*, 90–96. [\[CrossRef\]](#)
5. Allison, F.E. Soil aggregation—Some facts and fallacies as seen by a microbiologist. *Soil Sci.* **1968**, *106*, 136–143. [\[CrossRef\]](#)
6. Horn, R.; Taubner, H.; Wuttke, M.; Baumgartl, T. Soil physical properties related to soil structure. *Soil Tillage Res.* **1994**, *30*, 187–216. [\[CrossRef\]](#)
7. Rhoades, J.D. Cation exchange capacity. In *Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties*; Page, A.L., Miller, R.H., Keeney, D.R., Eds.; American Society of Agronomy, and Soil Science Society of America: Madison, WI, USA, 1982; Volume 9, pp. 1489–1589.
8. Ben-Hur, M.; Yolcu, G.; Uysal, H.; Lado, M.; Paz, A. Soil structure changes: Aggregate size and soil texture effects on hydraulic conductivity under different saline and sodic conditions. *Aust. J. Soil Res.* **2009**, *47*, 688–696. [\[CrossRef\]](#)
9. Norton, L.D.; Mamedov, A.I.; Huang, C.; Levy, G.J. Soil aggregate stability as affected by long-term tillage and clay type. *Adv. GeoEcol.* **2006**, *38*, 422–429.
10. Haynes, R.J.; Swift, R.S. Stability of soil aggregates in relation to organic constituents and soil water content. *J. Soil Sci.* **1990**, *41*, 73–83. [\[CrossRef\]](#)
11. Reichert, J.M.; Norton, L.D.; Favaretto, N.; Huang, C.H.; Blume, E. Settling velocity, aggregate stability, and interrill erodibility of soils varying in clay mineralogy. *Soil Sci. Soc. Am. J.* **2009**, *73*, 1369–1377. [\[CrossRef\]](#)
12. Tisdall, J.M.; Oades, J. Organic matter and water-stable aggregates in soils. *J. Soil Sci.* **1982**, *33*, 141–163. [\[CrossRef\]](#)
13. Kemper, W.D.; Rosenau, R.C. Aggregate stability and size distribution. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods*; Soil Science Society of America: Madison, WI, USA, 1986; Volume 5, pp. 425–442.
14. Puget, P.; Chenu, C.; Balesdent, J. Dynamics of soil organic matter associated with particle-size fractions of water-stable aggregates. *Eur. J. Soil Sci.* **2000**, *51*, 595–605. [\[CrossRef\]](#)
15. Chepil, W.S. Measurement of wind erosiveness of soils by dry sieving procedure. *Sci. Agric.* **1942**, *23*, 154–160.
16. Colazo, J.C.; Buschiazzi, D.E. Soil dry aggregate stability and wind erodible fraction in a semiarid environment of Argentina. *Geoderma* **2010**, *159*, 228–236. [\[CrossRef\]](#)
17. van Bavel, C.H.M. Mean weight-diameter of soil aggregates as a statistical. *Soil Sci. Soc. Am. J.* **1949**, *14*, 20–23. [\[CrossRef\]](#)
18. Tanner, S.; Katra, I.; Haim, A.; Zaady, E. Short-Term soil loss by eolian erosion in response to different rain-fed agricultural practices. *Soil Tillage Res.* **2016**, *155*, 149–156. [\[CrossRef\]](#)
19. Sharratt, B.; Wendling, L.; Feng, G. Windblown dust affected by tillage intensity during summer fallow.  *Aeolian Res.* **2010**, *2*, 129–134. [\[CrossRef\]](#)
20. Zobeck, T.; Popham, T.; Skidmore, E.; Lamb, J.; Merrill, S.; Lindstrom, M. Aggregate-Mean diameter and wind-erodible soil predictions using dry aggregate-size distributions. *Soil Sci. Soc. Am. J.* **2013**, *67*, 425–436. [\[CrossRef\]](#)
21. Bagnold, R. *The Physics of Blown Sand and Desert Dunes*; Methuen: London, UK, 1941; Volume 10, p. 265.

22. O'Brien, P.; Neuman, C.M. PTV measurement of the spanwise component of aeolian transport in steady state. *Aeolian Res.* **2016**, *20*, 126–138. [\[CrossRef\]](#)
23. Anderson, R.S. Eolian sediment transport as a stochastic process: The effects of a fluctuating wind on particle trajectories. *J. Geol.* **1987**, *95*, 497–512. [\[CrossRef\]](#)
24. Shao, Y. *Physics and Modelling of Wind Erosion*; Springer Science & Business Media: Berlin, Germany, 2008.
25. Kok, J.; Parteli, E.; Michaels, T.; Karam, D. The physics of wind-blown sand and dust. *Rep. Prog. Phys.* **2012**, *75*, 106901. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Swet, N.; Katra, I. Reduction in soil aggregation in response to dust emission processes. *Geomorphology* **2016**, *268*, 177–183. [\[CrossRef\]](#)
27. Kok, J.F.; Mahowald, N.M.; Fratini, G.; Gillies, J.A.; Ishizuka, M.; Leys, J.F.; Mikami, M.; Park, M.-S.; Park, S.-U.; van Pelt, R.S.; et al. An improved dust emission model—Part 1: Model description and comparison against measurements. *Atmos. Chem. Phys.* **2014**, *14*, 13023. [\[CrossRef\]](#)
28. Yue, Y.; Song, Y.; Kaskaoutis, D.G.; Chen, X.; Mamadjanov, Y.; Tan, L. Atmospheric dust dynamics in southern central Asia: Implications for buildup of Tajikistan loess sediments. *Atmos. Res.* **2019**, *229*, 74–85.
29. Katra, I.; Yizhaq, H. Intensity and degree of segregation in bimodal and multimodal grain size distributions. *Aeolian Res.* **2017**, *27*, 23–34. [\[CrossRef\]](#)
30. Yulevitch, G.; Danon, M.; Krasovtsov, B.; Fominykh, A.; Swet, N.; Tsesarsky, M.; Katra, I. Evaluation of wind-induced dust-PM emission from unpaved roads varying in silt content by experimental results. *Atmos. Pollut. Res.* **2020**, *11*, 261–268. [\[CrossRef\]](#)
31. Katra, I. Soil erosion by wind and dust emission in semi-arid soils due to agricultural activities. *Agronomy* **2020**, *10*, 89. [\[CrossRef\]](#)
32. Sirjani, E.; Sameni, A.; Moosavi, A.A.; Mahmoodabadi, M.; Laurent, B. Portable wind tunnel experiments to study soil erosion by wind and its link to soil properties in the Fars province, Iran. *Geoderma* **2019**, *333*, 69–80. [\[CrossRef\]](#)
33. Swet, N.; Elperin, T.; Kok, J.F.; Martin, R.L.; Katra, H.Y.I. Can active sands generate dust particles by wind-induced processes? *Earth Planet. Sci. Lett.* **2019**, *506*, 371–380. [\[CrossRef\]](#)
34. Katra, I.; Elperin, T.; Fominykh, A.; Krasovtsov, B.; Yizhaq, H. Modeling of particulate matter transport in atmospheric boundary layer following dust emission from source areas. *Aeolian Res.* **2016**, *20*, 147–156. [\[CrossRef\]](#)
35. Six, J.; Degryze, S.; Bossuyt, H.; Denef, K. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* **2004**, *79*, 7–31. [\[CrossRef\]](#)
36. Denef, K.; Six, J. Clay mineralogy determines the importance of biological versus abiotic processes for macroaggregate formation and stabilization. *Eur. J. Soil Sci.* **2005**, *56*, 469–479. [\[CrossRef\]](#)
37. Vaezi, A.; Sadeghi, S.; Bahrami, H.; Mahdian, M.H. Modeling the USLE K-factor for calcareous soils in northwestern Iran. *Geomorphology* **2008**, *97*, 414–423. [\[CrossRef\]](#)
38. Roth, B.; Eggert, T. Mechanisms of aggregate breakdown involved in surface sealing, runoff generation and sediment concentration on loess soils. *Soil Tillage Res.* **1994**, *32*, 253–268. [\[CrossRef\]](#)
39. Chen, H.; Hou, R.; Gong, Y.; Li, H.; Fan, M.; Kuzyakov, Y. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. *Soil Tillage Res.* **2009**, *106*, 85–94. [\[CrossRef\]](#)
40. Wang, R.; Li, Q.; Zhou, N.; Chang, C.; Guo, Z.; Li, J. Effect of wind speed on aggregate size distribution of windblown sediment. *Aeolian Res.* **2019**, *36*, 1–8. [\[CrossRef\]](#)
41. Raupach, M.; Leys, J. Erodynamics of a portable wind erosion tunnel for measuring soil erodibility by wind. *Soil Res.* **1990**, *28*, 177–191. [\[CrossRef\]](#)
42. van Pelt, R.; Baddock, M.; Zobeck, T.; Schlegel, A.; Vigil, M.; Martinez, V.A. Field wind tunnel testing of two silt loam soils on the North America Central high plains. *Aeolian Res.* **2013**, *10*, 53–59. [\[CrossRef\]](#)
43. Shao, Y.; Raupach, M.; Findlater, P. Effect of saltation bombardment on the entrainment of dust by wind. *J. Geophys. Res. Atmos.* **1993**, *98*, 12719–12726. [\[CrossRef\]](#)
44. Houser, C.A.; Nickling, W.G. The emission and vertical flux of particulate matter <10 µm from a disturbed clay-crust surface. *Sedimentology* **2001**, *48*, 255–267.
45. Panebianco, J.E.; Mendez, M.J.; Buschiazzi, D.E. PM10 emission, sandblasting efficiency and vertical entrainment during successive wind-erosion events: A wind-tunnel approach. *Bound. Layer Meteorol.* **2016**, *161*, 335–353. [\[CrossRef\]](#)

46. Huang, Y.; Kok, J.F.; Martin, R.L.; Swet, N.; Katra, I.; Gill, T.E.; Reynolds, R.L.; Freire, L.S. Fine dust emissions from active sands at coastal Oceano Dunes, California. *Atmos. Chem. Phys.* **2019**, *19*, 2947–2964. [[CrossRef](#)]
47. Feddema, J.J.; Freire, S. Soil degradation, global warming and climate impacts. *Clim. Res.* **2001**, *17*, 209–216. [[CrossRef](#)]
48. Amundson, R.; Berhe, A.; Hopmans, J.; Olson, C.; Sztein, A.; Sparks, D. Soil and human security in the 21st century. *Soil Sci.* **2015**, *348*, 1261071. [[CrossRef](#)]
49. Lavee, H.; Imeson, A.; Sarah, P. The impact of climate change on geomorphology and desertification along a Mediterranean-arid transect. *Land Degrad.* **1998**, *9*, 407–422. [[CrossRef](#)]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).