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Full Paper

Mineralogical characterisation of sediment transported by wind erosion of agricultural and natural soils

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Abstract: Soil mineral components lost from wind erosion lead to a lower soil exchange capacity and must therefore be added as fertiliser to avoid decrease in soil productivity. Thus, our objective is to obtain qualitative and quantitative knowledge of soil mineral flow by X-ray diffraction, which is a low-cost technique for evaluating alterations in soil-surface mineralogical components. Mineralogical relationships of sediment of the soil types studied show the influence of main wind direction, with component content varying with catchment height. A two-factor ANOVA with height as the main effect showed that there were no significant differences between samples taken at heights of 0 and 15 cm, whereas the difference between 40 and 70 cm was significant, with the finest components concentrated at 70 cm. Tilled windward Anthrosols showed an increase in the proportion of high cation exchange-capacity minerals with height. This is reproduced first in Leptosols and then in Calcisols, which, because of their high surface stoniness and the aggregating role of their carbonate content, undergo the lowest loss of material by wind. Leeward Arenosols, with a very low content of the fractions most susceptible to wind erosion and strong protection from wind by natural vegetation, show an important marine influence.

Keywords: aeolian loss, tilled soils, soil mineralogy, semi-arid environment

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INTRODUCTION

Wind erosion has been a natural phenomenon since the beginning of time, but is presently accelerated due to human activity, and has become a worldwide agricultural and environmental problem affecting around 42 million hectares. In Europe about 18% of the surface is affected, mainly in the Mediterranean region [1]. In a study on dryland Mediterranean cultivation systems, Benlhabib et al. [2] found sustainable cultivation technologies necessary. Aggressive agricultural methods, overgrazing, abandonment of tillage lands, forest fires, deforestation, etc. are factors intensifying wind erosion and generate considerable soil losses, especially in marginal areas where conservationist strategies are not applied [3-5].

Wind moves large amounts of soil materials, which can cause serious agricultural and environmental problems such as textural changes or variation in soil moisture, especially in arid and semi-arid areas where rainfall is scarce. According to Rawlins et al. [6], disaggregation reduction is higher in soils with more stable aggregates. The intensity of wind erosion can change the inherent properties of soils and vegetation cover [7, 8]. In Spain the worst wind erosion problems are located mainly in the south-east [9]. Hevia et al. [10] found that in absence of tillage there are more aggregates, which, along with vegetation, reduce soil loss from wind by slowing down wind speed and increasing the capacity for capturing eroded material [11-14]. Udo and Takewaka [15] reported that in their wind tunnel studies, in addition to vegetation density, vegetation height and flexibility were important factors generating sediment reduction.

X-ray diffraction is one of the most useful tools for characterisation of crystalline compounds. This technique enables fast, reliable identification and quantification of the crystalline phases present in a sample by comparing the diffractograms obtained with experimental patterns stored in a powder diffraction database (JCPDS-PDF 2 or COD). X-ray diffraction powder method is a technique for structural and microstructural characterisation of crystalline material based on scattered X-ray interference with atoms arranged in a crystal structure. Wind-eroded mineral type and its amount strongly influence the soil cation exchange capacity and hence soil fertility. The objectives of this study are to provide qualitative and quantitative determination of soil minerals lost from the effect of wind, which causes the loss of productivity in different types of soil and worsens degradation, using an effective and completely topical study methodology.

MATERIALS AND METHODS

The study area was located in Almeria province in south-east Spain (Figure 1), which is in the Retamar-Carboneras geomorphological corridor between the Sierra Alhamilla Mountains and the Mediterranean Sea (36º48´-59´N, 2º3´-29´W). Elevation ranges from 5 to 340 m a.s.l. The climate is semi-arid thermo-Mediterranean, with a mean annual temperature of 17.9ºC. Mean annual precipitation is 247 mm, according to government meteorological station records for the last 15 years, qualifying it as one of the driest areas in Europe. Lithological material is mainly a metamorphic basement separated by Neogene and Quaternary sedimentation basins. Natural plant communities are made up of isolated native shrubs surrounded by bare soil with colonisation of annual plant species. Soils are mainly Hortic Anthrosols (AT_h), Eutric Leptosols (LP_e), Haplic Calcisols (CL_h) and Endosalic Arenosols (AR_{es}), with silty clay loam to loamy texture, a weak coarse subangular blocky to medium angular blocky structure and variable gravel fragments.

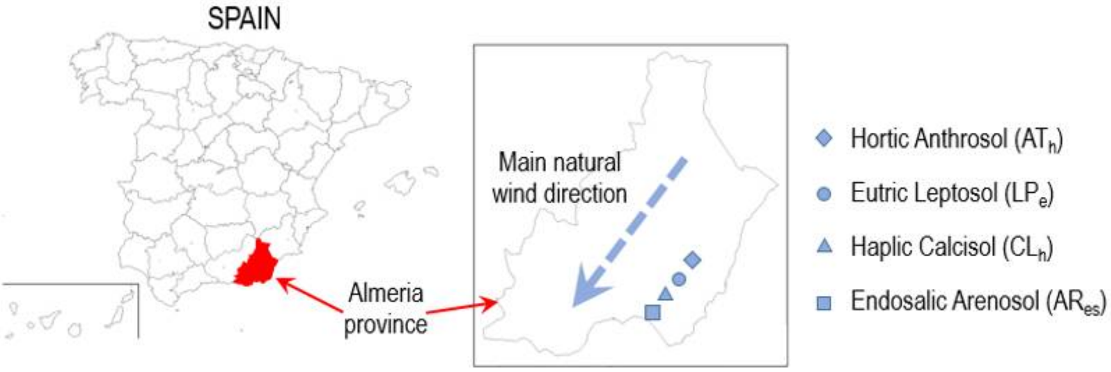


Figure 1. Study area location

Our developed wind tunnel, in which wind-transported material was collected by traps, is shown in Figure 2 [16]. A fan blowing air through the tunnel with honeycomb structure provides a combination of laminar and turbulent flow at a speed of 6.8 m s^{-1}, which corresponds to the maximum daily average natural wind speed recorded in this area. At the end of the tunnel, particle traps (Fryrear BSNE type) located at the height of 0, 15, 40 and 70 cm [14, 17] retain dust for analysis.

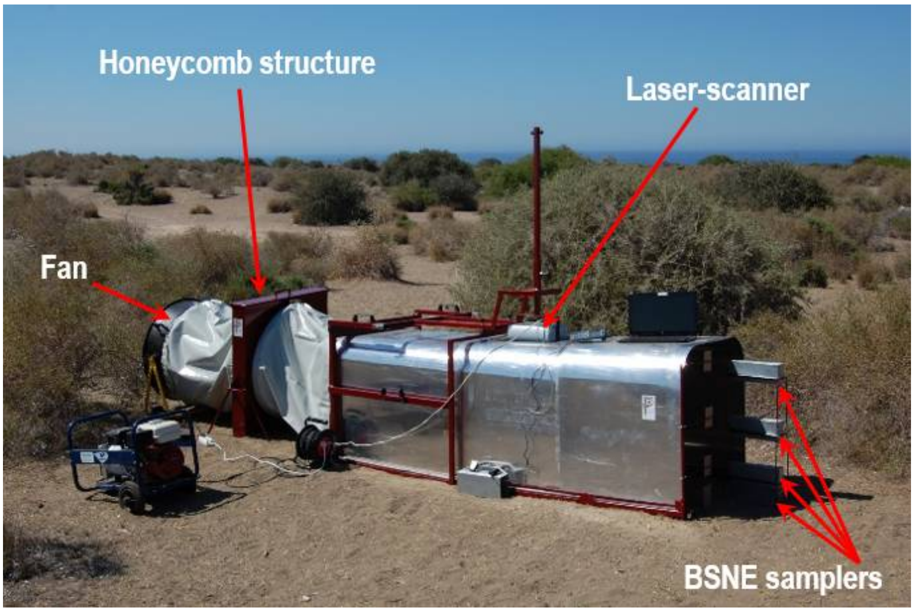


Figure 2. Wind tunnel over Arenosol soil type

Prior to the wind tunnel experiment, several soil properties were determined in samples collected from the upper 3-cm layer. Particle size distribution of the soil and collected dust samples was assessed by dry sieving and the Robinson pipette method [17]. The sand fraction was separated by dry sieving. Organic carbon content was determined using the Walkley-Black wet digestion method [17] and the bulk density was determined by a 100-cm^3 cylinder.

Although X-ray diffraction (XRD) is a semi-quantitative technique that can produce absolute errors, with standardised experimental conditions and interpretation, relative variations are reproducible. For powder sample, we used an “Advance D8 Davinci” model diffractometer (Bruker Corporation, U.S.A.) with copper radiation tube ($Cu_{K\alpha}$, λ=1.54 Å). Analysis of results was done with the XPrep program and evaluation of data was performed with the EVA program, the programs being part of the Diffract Evaluation 2.1 software package. Reference values used are shown in Table 1 [18].

Table 1. Reference values for mineral XRD

Mineral	**Reflection** (nm)	**Reflective power**
Smectite/vermiculite	1.40	0.35
Illite	1.00	0.23
Kaolinite	0.72	0.45
Quartz	0.33	2
Feldspar	0.32	1
Calcite	0.30	1
Dolomite	0.29	1

RESULTS AND DISCUSSION

Tables 2 and 3 show some mean soils characteristics: variable surface stoniness (gravel), organic carbon and equivalent carbonate contents, in addition to textural components. Bulk density was used for estimating wind erosion by the wind tunnel according to laser-scanner differences before and after applying wind [17]. Thus, high wind erosion values were calculated for Anthrosols (AT_h) and Leptosols (LP_e) while low erosion occurred for Calcisols (CL_h) and Arenosols (AR_{es}). Once the average wind erosion of each soil type was known, we focused on losses and sediment captured in the BSNE samplers at different heights. Five replicates per soil type were used for analysis.

Soil particles transported by creep were caught in the sampler at the height of 0 cm; particles transported by saltation were caught at 15 and 40 cm; those transported by suspension were caught at 70 cm, and those that escaped capture were regarded as runaway dust [19]. An ANOVA of the textural components indicated that the effect of interaction between height and soil type was only significant (p-value less than 0.05) for coarser fractions. A two-factor ANOVA with soil type as the main effect showed that there were significant differences for height in most variables. In a two-factor ANOVA with height as the main effect, no significant differences were observed between samples trapped at the height of 0 and 15 cm, whereas the difference between 40 and 70 cm was significant, and the finest components were concentrated at 70-cm height.

Table 2. Gravel, organic carbon (O.C.) and equivalent carbonate ($CO_3^{=}$) contents in soils, with bulk density (B.D.) and estimated wind erosion (W.E.) by wind tunnel

SAMPLE	**Gravel** (%)	**O.C.** ($g\cdot kg^{-1}$)	**$CO_3^{=}$** ($g\cdot kg^{-1}$)	**B.D.** ($t\cdot m^{-3}$)	**W.E.** ($t\cdot ha^{-1}$)
AT_h	5±3	17.0±1.2	230±40	1.24±0.03	11.7±2.1
LP_e	37±5	25.4±1.8	190±30	1.36±0.04	10.6±1.5
CL_h	22±5	9.0±0.8	400±60	1.41±0.05	2.0±0.4
AR_{es}	6±2	12.5±0.7	10±10	1.28±0.02	3.3±0.2

Note: Soils data are means ± standard deviation (n=5).

Table 3. Textural components in soils and sediment traps

Sample	**% Very coarse sand** (2000-1000 μm)	**% Coarse sand** (1000-500 μm)	**% Medium sand** (500-250 μm)	**% Fine sand** (250-100 μm)	**% Very fine sand** (100-50 μm)	**% Coarse silt** (50-20 μm)	**% Fine silt** (20-2 μm)	**% Clay** (< 2 μm)
AT$_h$	5.8±0.4	11.1±0.7	22.6±1.6	31.2±2.7	20.0±1.6	0.4±0.2	2.2±0.3	6.7±0.6
AT-0	0.0	0.6	7.4	15.6	32.5	8.9	12.7	22.3
AT-15	0.0	0.0	1.2	8.3	34.9	11.3	18.6	25.7
AT-40	0.0	0.0	0.0	1.1	32.5	18.4	21.8	26.2
AT-70	0.0	0.0	0.0	0.0	28.5	16.9	22.5	32.1
LP$_e$	15.1±1.2	14.9±0.8	22.4±2.3	24.7±.2.1	5.2±0.4	6.4±0.3	2.6±0.3	8.7±0.5
LP-0	0.2	0.8	6.2	11.7	30.3	18.0	11.2	21.6
LP-15	0.0	0.2	0.8	6.1	37.1	19.3	14.2	22.3
LP-40	0.0	0.0	0.0	0.9	36.9	21.9	16.0	24.3
LP-70	0.0	0.0	0.0	0.0	34.2	17.4	20.6	27.8
CL$_h$	6.0±0.6	6.1±0.4	9.5±0.9	19.3±1.8	22.5±2.3	7.5±0.5	11.7±0.9	17.4±1.2
CL-0	0.0	0.2	3.1	8.1	27.5	19.8	20.0	21.3
CL-15	0.0	0.0	0.4	4.2	21.9	23.3	24.5	25.7
CL-40	0.0	0.0	0.0	0.0	17.6	27.6	29.7	25.1
CL-70	0.0	0.0	0.0	0.0	13.4	26.4	31.3	28.9
AR$_{es}$	0.3±0.1	6.1±0.5	48.8±6.4	38.2±3.7	2.9±0.3	0.5±0.2	0.2±0.1	3.0±0.2
AR-0	0.0	0.1	12.9	21.7	50.4	4.7	3.1	7.1
AR-15	0.0	0.0	2.7	9.4	51.1	26.8	4.7	5.3
AR-40	0.0	0.0	0.0	1.3	50.8	34.6	9.3	4.0
AR-70	0.0	0.0	0.0	0.0	0.0	48.5	18.4	33.1

Note: Soils data (ATh, LPe, CLh and Ares) are means ± standard deviation (n=5); sediment traps data names include soil type and catchment height in cm.

When establishing textural components, aggregate size was not considered because whole samples taken at the same height and of the same soil type were crushed and passed through a 2-mm sieve for analysis. It is well known that along with organic matter, various mineral components act as colloidal substances that condition cation exchange in soil. Thus, loss of these components by wind erosion leads to lower soil cation-exchange capacity, which requires them to be added as fertiliser to avoid loss of soil productivity [20, 21]. It is therefore important to know what and how much of each soil mineral type is lost. When XRD was applied to our sediment samples, a strong difference in the nature of soil constituents between Arenosol and the rest was observed (Figure 3).

Mineralogical relationships between Anthrosol, Leptosol and Calcisol may have been influenced by deposits generated by continuous wind, mainly from the north-east (Figure 1). Materials from Anthrosols may have been deposited onto Leptosols and Calcisols. Leptosols would have had similar influence on Calcisols. However, Arenosols are different because of their very thick texture, which would favour materials washing into deeper layers due to the effect of marine humidity.

As examples of detailed diffractograms and how the mineral content was evaluated, smectite and/or vermiculite (1.4 nm) in Calcisol from the collector at 40 cm, and illite (1.0 nm) in Anthrosol at ground level are shown in Figures 4a and 4b respectively.

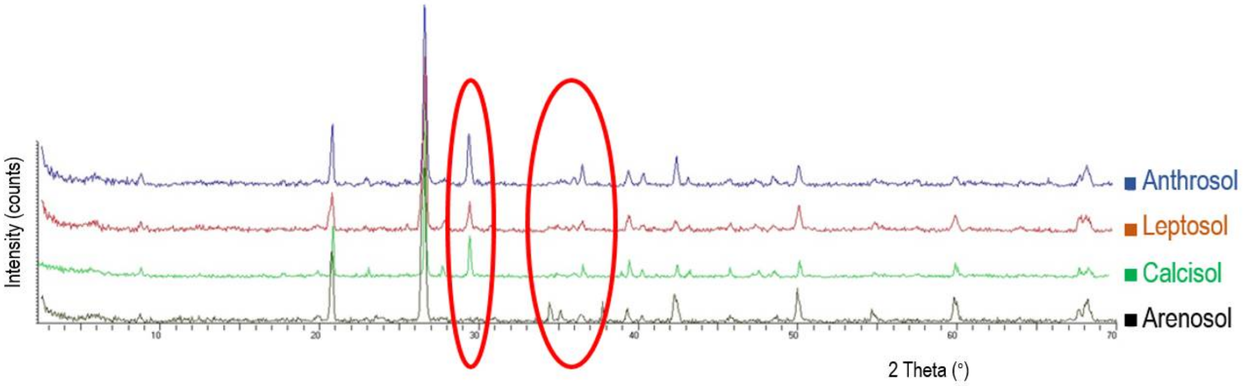
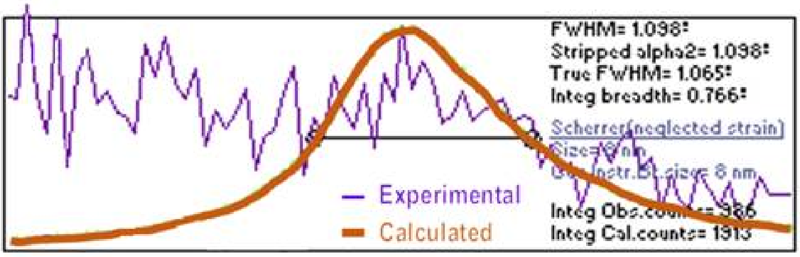
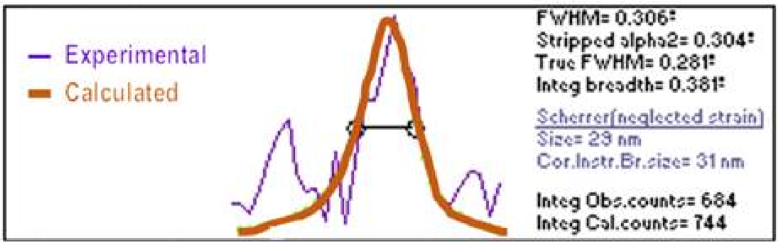


Figure 3. Comparative X-ray difractograms for Anthrosol, Leptosol, Calcisol and Arenosol. Signals indicating different mineral compositions among different soil types are shown.



a) CALCISOL



b) ANTHROSOL

Figure 4. Smectite and/or vermiculite found in Calcisol in 40-cm trap (a) and illite in Anthrosol from 0-cm trap (b)

Values found for the different soil types and at different heights appear in Table 4. It may be seen how in samples from Anthrosols, which are highly tilled agricultural soils, quartz dominates over illite and calcite in samples collected at ground level, while illite dominates over smectite/vermiculite at 70-cm height. Leptosols do not have much protection against incident wind and the predominance of transported minerals is similar to Anthrosols. Both are well-studied soil typological features with the highest wind erosion rates.

Calcisols have the lowest erosion rate because of their high surface stoniness and mainly because of their high aggregating carbonate content, which hinders material loss from wind. A clear balance between calcite, smectite/vermiculite and quartz is observed in samples taken at a low height. Smectite/vermiculite and illite dominate as height increases.

Arenosols are different. They show low content of very fine sand and coarse silt, which are the fractions most susceptible to wind erosion. In addition, natural vegetation protects them from the wind [22]. A clear quartz domain is observed in them, with a certain balance in the proportions of smectite/vermiculite, illite and kaolinite, which is maintained at different sampling heights.

Table 4. Mineralogical components in sediment traps

Soil-height	**Smectite/ vermiculite** (%)	**Illite** (%)	**Kaolinite** (%)	**Quartz** (%)	**Feldspar** (%)	**Calcite** (%)	**Dolomite** (%)	**Others** (%)
AT-0	12	24	7	29	4	19	2	3
AT-15	12	23	8	27	5	20	2	3
AT-40	19	28	11	19	4	16	1	2
AT-70	21	33	10	18	3	14	0	1
LP-0	15	20	6	32	8	12	5	2
LP-15	16	22	5	30	9	13	4	1
LP-40	22	30	8	21	6	8	3	2
LP-70	25	36	9	16	4	9	1	0
CL-0	22	13	7	19	5	24	6	4
CL-15	25	19	8	18	4	19	4	3
CL-40	29	28	10	17	3	10	2	1
CL-70	31	29	12	14	4	8	1	1
AR-0	14	13	14	46	5	4	2	2
AR-15	15	12	19	42	6	3	1	2
AR-40	18	14	15	37	12	2	1	1
AR-70	19	15	20	30	15	1	0	0

CONCLUSIONS

The results obtained indicate that materials eroded by wind differ depending on soil type and height of blown-out material. Generally, quartz and calcite dominate in material transported close to the ground, while clay minerals are eroded and transported at greater height, thus being carried away farther.

Highly tilled Anthrosols are more eroded than Leptosols and much more than Calcisols. Arenosols, which have a coarser texture and are protected by natural vegetation and a certain marine influence, show less loss of material from wind.

As it is evident that there is a qualitative and quantitative loss of material, the need for preventive measures for this form of soil degradation must be evaluated. A balance between the cost of using windbreaks and reduction in loss of soil productivity should be analysed in future work.

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