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# Influence of Soil Moisture and Crust Formation on Soil Evaporation Rate: A Wind Tunnel Experiment in Hungary

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**Abstract:** In both arid and semiarid regions, erosion by wind is a significant threat against sustainability of natural resources. The objective of this work was to investigate the direct impact of various soil moisture levels with soil texture and organic matter on soil crust formation and evaporation. Eighty soil samples with different texture (sand: 19, loamy sand: 21, sandy loam: 26, loam: 8, and silty loam: 6 samples) were collected from the Nyírség region (Eastern Hungary). A wind tunnel experiment was conducted on four simulated irrigation rates (0.5, 1.0, 2.0, and 5.0 mm) and four levels of wind speeds (4.5, 7.8, 9.2, and 15.5 m $s^{-1}$). Results showed that watering with a quantity equal to 5 mm rainfall, with the exception of sandy soils, provided about 5–6 h protection against wind erosion, even in case of a wind velocity as high as 15.5 m $s^{-1}$. An exponential connection was revealed between wind velocities and the times of evaporation ($R^2$ = 0.88–0.99). Notably, a two-way ANOVA test revealed that both wind velocity ($p < 0.001$) and soil texture ($p < 0.01$) had a significant effect on the rate of evaporation, but their interaction was not significant ($p = 0.26$). In terms of surface crusts, silty loamy soils resulted in harder and more solid crusts in comparison with other textures. In contrast, crust formation in sandy soils was almost negligible, increasing their susceptibility to wind erosion risk. These results can support local municipalities in the development of a local plan against wind erosion phenomena in agricultural areas.

**Keywords:** wind tunnel; wetting front; SDGs; regional planning

## 1. Introduction

Land degradation (LD) (i.e., soil erosion, salinization, and fertility depletion) is one of the challenges facing the sustainability of land resources and presents one of the main obstacles against achieving global sustainable development goals (SDGs) [1,2]. Almost 60% of Earth's land and 3.2 billion people are affected by different types of LD [1]. Yearly, more than 75 billion t of soil is eroded due to different soil erosion types (i.e., wind erosion, water erosion) [3,4].

Wind erosion is considered as one of the main drivers of soil degradation processes in both the arid and semi-arid regions of the world [5], and almost 30% of Earth's land is subjected to it, especially in the arid zone [6]. The main issues are the direct effect on soil quality and fertility reduction, but indirectly the suspended dust can cause health problems [7–9], even in intercontinental range [10,11]. In this sense, many strategies were adopted to mitigate wind erosion, for instance, soil irrigation, breaking wind, i.e., decreasing wind speed (with smaller parcels, strip crops, tree rows, and windbreaks) or decreasing bare surfaces (with vegetation or residues) [12].

The extent of soil erodibility is strongly correlated with the soil moisture content, and the effect of soil moisture content on wind erosion rates is dependent upon soil texture [13]. The erodibility level changes in accordance with the cohesive forces between the water molecules surrounding the soil particles. Bisal and Hsieh [14] demonstrated that wind erosion was prevented by 4% gravimetric soil water content (g $g^{-1}$) in sandy soils. Nickling [15] found that the critical soil moisture content is ca. 3–4% for sandy soils. Troeh et al. [16] demonstrated that wind erosion begins 15–20 min after a heavy rain event in sandy texture if the climate conditions facilitate a fast dehydration of the soil surface. Leuven [17] showed that a linear function revealed the relationship between the water content and the time duration when the surface of wet soil was able to resist the wind forces at the wind velocity of 50 km $h^{-1}$. In wind tunnel experiments, Chen et al. [18] established that the eroded soil material's quantity decreased exponentially with the increase of water content. Yan et al. [19] showed dramatic changes in soil erodibility under small quantities of rainfall.

Rainfalls and irrigation can cause crusting on soil surface. A physical crust is an important soil structural feature in many parts of the world, and two types can be distinguished by formation processes: structural crusts [20] and depositional crusts [21]. Structural crusts form due to the kinetic effect of raindrop impact, while depositional crusts are created when fine particles are translocated to lower areas by flowing water and cover the surface [20]. The process begins with the disintegration of aggregates into elemental particles (sand, silt, and clay), and the next phase is the dispersion. If the dispersion of silt and clay is followed by rapid drying, a thin and hard compact soil layer is formed [22]. Fine particles in the soil have an essential role in the formation of physical crust by binding the particles and increase the crust strength [23,24]. Numerous natural and anthropogenic mechanisms have been suggested to explain crust formation: characteristics of rainfall such as rate, duration, intensity, and impacts of raindrops [25], and physical soil properties such as texture, density, porosity, aggregate stability, clay mineralogy [26], and chemical soil properties (pH, $CaCO_3$ content, and organic matter) [27,28]. Soil management and tillage practices also play an important role in crust formation [29].

Soil crust directly affects the soil surface and can lead to an unfavorable condition, deteriorating the hydrological aspects of top-soil layer through reducing water infiltration and increasing runoff [30,31]. Crusts also have relevant effects on water retention time of soils [32], soil porosity and density, and air exchange rate [33]. However, crusts can also be favorable, decreasing the evaporation by covering the soil surface in agricultural areas [34]; furthermore, crusts, due to their resistance against wind and water erosion, can protect unconsolidated soils beneath them [19,35] and protect the soil from wind erosion in arid and semiarid regions [22].

Wind erosion has a negative effect on agricultural production as well as on soil and environmental quality. In Hungary, the risk of wind erosion is more than 10% of the area [36–38]. One of the most endangered regions is Nyírség, where mismanagement of agricultural land accelerated the current degradation processes [39,40]. The main causes are over cultivation and overgrazing of pastural lands [41]. In our earlier studies, we examined the effect of some selected soil properties on wind erosion in the case of a sandy area [42] and an integrated and predicted spatial assessment of wind erosion risk in Hungary was also conducted [36,37]. However, soil texture and water content against wind erosion was not the focus of our evaluations.

The aim of this study was to explore the drying out times of soils with different textures and moisture contents in wind tunnel experiments, and to examine the development of structural crusts in typical cultivated soils from the Nyírség region.

## 2. Materials and Methods

### 2.1. Study Area

The Nyírség landscape (Eastern Hungary) covers 5000 km$^2$ (Figure 1). It is an alluvial fan formed by sandy sediments that formed in the dry periods of the late Quaternary and the early Holocene. Its geomorphology consists of parabolic and hummocky dunes. Blowouts are primarily built on the alluvial deposits of rivers arriving from the Carpathians by winds blowing from the northeast [39]. The area features moderate continental climate (Dfb climate zone according to Köppen classification system). The average annual temperature is 9–10 °C. The coldest month is January, with an average daily temperature of −3 °C, and the hottest month is July (20.5 °C). The average rainfall is about 550–650 mm year$^{-1}$. However, due to the peculiarity of the climate, drought periods occur on the area when the annual rainfall is <400 mm [39]. Soils in the experimental area are classified as Arenosols, Cambisols, Luvisols, and Phaeozems according to WRB soil classification system [43].

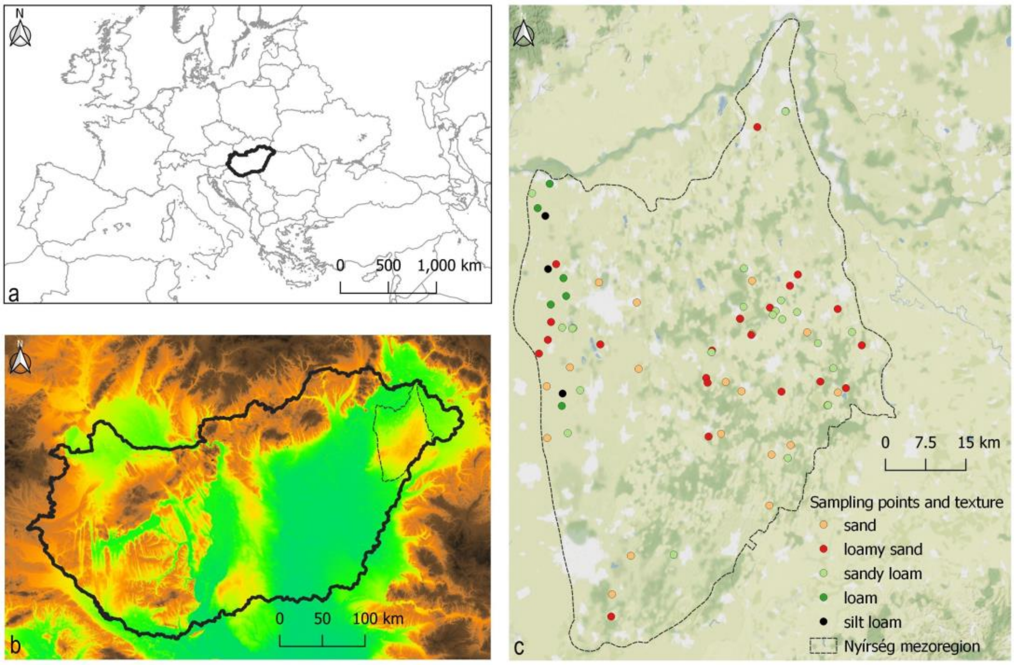


**Figure 1.** Location of the study area in Europe (**a**), in Hungary (**b**), and in the Nyírség mesoregion with sampling sites (**c**) (used background sources are: b: EU-DEM indicating the terrain heights, and c: Stamen Terrain–Open Street Map showing the settlements with white, arable lands with lighter green, and the forests with dark green).

Typical land use types are the arable lands and forests. From the aspect of wind erosion, the most sensitive season is spring, because the arable lands mainly produce autumn-sown cereal crops and corn, so the arable lands are bare and the wind speed can frequently exceed 10 m s$^{-1}$ velocity [40].

### 2.2. Sampling and Laboratory Analyses

Soil samples in four replicates were collected from 80 different sites of the Nyírség. Samples were taken from the upper 30 mm of the ploughed soil layer with a square hand shovel (Figure 1).

We determined the physical and chemical properties of the soil samples in the Complex Environmental Laboratory of the Institute of Geosciences, University of Debrecen. Particle size analysis was conducted by sieving and with the Köhn pipette method [44]. A Scheibler calcimeter was used to measure $CaCO_3$ content [45]. Organic matter (OM) contents were measured by the Tyurin method [46].

*2.3. Wind Tunnel Experiments*

We conducted wind erosion experiments in a wind tunnel of the University of Debrecen (Figure 2). The wind tunnel was of blowing type with 12.3 m long tube (the total length from the ventilator fan to the filtering block), 0.80 m wide and 0.50 m high. Possible wind velocities varied between 0 to 16.5 m $s^{-1}$, but we used the 4.5–15.5 m $s^{-1}$ range as the frequent velocities in the region [40]. Wind velocity was controlled with a Testo 512 manometer parallel with the centerline of the wind tunnel at 10 cm height above the soil samples' surface. Soil samples were dried at 105 °C, then passed through a 2-mm sieve. Metal trays (size: 30 × 50 × 5 cm) were filled with oven-dried soil, bulk density ranged between 1.62 g $m^{-3}$ for sandy soils and 1.49 g $m^{-3}$ for silty soils. The surface of the samples was set to the level of the floor of the tunnel to avoid turbulence induced by the wall of the tray.

**Figure 2.** The laboratory wind tunnel used in the experiments for measuring the amount of evaporation loss of soil samples (University of Debrecen, Debrecen, Hungary).

Simulated irrigation was applied to assess the impact of soil moisture on wind erosion in the wind tunnel. Soil surface (trays) was evenly sprayed with distilled water of 75, 150, 300, and 750 g to simulate the effect of 0.5, 1.0, 2.0, and 5.0 mm of rainfall levels, respectively. We sprayed water onto the soil surface in the form of mist; thus, the drop size as biasing factor can be ignored. Accordingly, simulated results differed from natural rainfall (or irrigation) conditions, but this method enabled us to control the rainfall quantity accurately [19]. To determine the infiltration depth of irrigation into soil surface, a small piece of moistened soil sample was removed and the soaking depth was measured by a ruler.

The amount of evaporation loss from the wetted samples was determined according to four wind velocities for all soils: 4.5, 7.8, 9.2, and 15.5 m $s^{-1}$. These values were chosen because significant a amount of soil can be transported in Hungary and because they occur with high frequency [42]. The weight of trays was measured after ten minutes run, according to the four wind velocities. Evaporated water quantity was determined as the weight difference between the air-dried and the treated soil samples. The measuring accuracy of the used balance was 1 g.

Beside wind velocity, evaporation is also influenced by air temperature and humidity. Therefore, these parameters were constantly monitored in the wind tunnel during the experiments with a Testo air humidity and temperature meter. Air temperature differences fluctuated within 1 °C, whereas air humidity slightly increased (<2%), depending on the starting water quantity and the duration of the experiment.

In the process of dehydration, crusts were being formed on the surfaces of top-soils. Therefore, we made further studies to discover what may influence the features of the crust that would be formed on the surface of soils with different textures. The particle size distribution, $CaCO_{3,}$ and OM contents of each crust were determined. These results were then compared to those data of the previous experiments.

*2.4. Statistical Analyses*

Relationship between wind velocity (independent variable) and the time of evaporation (dependent variable) was revealed by curve fitting, and the exponential regression was chosen based on the $R^2$ and root mean square errors (RMSE) values. Regression analyses were performed by soil texture categories.

We compared evaporation rates of open water surface and the given amount of water evaporated by soil samples of different soil textures. We applied Wilcoxon paired test considering all possible permutations (i.e., exact test) [47] to ensure a robust outcome. $H_0$ was that there was no difference among group medians of soil textures. We calculated the effect sizes as the importance measure of the interaction between the variables [48,49].

Spearman correlation was used to reveal the connection among the soil properties and evaporation. This type of correlation is robust, and outlier data do not or minimally influence its value.

Effects of wind speed and soil texture were analyzed with the two-way ANOVA test, which allows to test the scale type dependent variable against two factorial independent variables. Two-way ANOVA also determines the statistical interaction between the factorial variables. Evaporation rate was the dependent variable, and soil texture and wind speed were of independent variables. Wind speed was involved as factor (using the four degrees of wind speeds as ordinal factors). Both the individual significance and the statistical interaction were evaluated. $H_0$-s were that there were no differences among the group means in terms of wind speeds and soil textures, and there was no interaction between the two factors. LSD *t*-test was used to separate the soil texture categories at $p = 0.05$ within each wind velocity and each water amount treatment.

We determined the factors of evaporation of the soils using the random forest regression (RFR). RFR is a robust algorithm without assumptions on normal distribution and homoscedasticity. Results are reported as Pseudo-$R^2$ (correlation between the observed and predicted values), and mean absolute error (MAE). We determined the relative MAE (RMAE) by dividing the values with mean observed values. Model parameters were optimized using the 10-fold cross-validation with 3 repetitions; thus, the final model was developed using the 30 models. Furthermore, we had an insight to the distribution of RMSE and $R^2$-values based on the 30 models, so we could report the medians and quartiles. The algorithm also provided information on variable importance (%IncMSE, a measure of sum of squares as a prediction error; the larger values indicate larger importance for each variable). We reported relative variable importance where 100% was the most important variable. Two models had been performed with the evaporation as dependent variable and different sets of independent variables (Table 1). Treatments with water were involved as dummy variables.

**Table 1.** Independent variables for the random forest regression (RFR) models, where the evaporation time was the dependent variable.

| Model | Independent Variables |
|---|---|
| all | treatments + sand (%) + silt (%) + clay (%) + OM (%) + $CaCO_3$ (%) + wind speed + soil texture category |
| soil | sand (%) + silt (%) + clay (%) + OM (%) + $CaCO_3$ (%) + soil texture category |

All statistical analyses had been performed in R 4.0.3 [50] by using the caret [51] and rpart [52] packages.

## 3. Results

### *3.1. Laboratory Analyses*

The analyzed soil samples (80 sites × 4 sample replicates) were classified into five soil texture categories according to USDA texture classification system [53]: sand: 19, loamy sand: 21, sandy loam: 26, loam: 8, and silty loam: 6 samples. The particle-size distribution and chemical properties of soils in different soil texture classes varied in a wide range (Table 2). Sand and loamy sand had >80% sand and <4% clay content, while loam and silty loam had <40 sand and >8% clay content. The mean OM was 1.93 ± 1.27 (%) and $CaCO_3$ content was 3.7 ± 1.26 (%), and usually the higher sand content coincided with lower OM and $CaCO_3$ content, although sandy loam had relatively higher OM and $CaCO_3$ content than the loam or sandy loam.

**Table 2.** Particle-size distribution and chemical properties of soils samples. OM: organic matter (mean ± standard deviation).

| | Sand (2-0.005 mm) (%) | Silt (0.05-0.002 mm) (%) | Clay (<0.002 mm) (%) | OM (%) | $CaCO_3$ (%) |
|---|---|---|---|---|---|
| Sand | 92.0 ± 5.0 | 6.5 ± 5.0 | 2.9 ± 2.8 | 1.8 ± 1.4 | 2.7 ± 2.0 |
| Loamy sand | 80.0 ± 5.0 | 15.0 ± 5.0 | 4.0 ± 1.0 | 1.5 ± 0.9 | 2.7 ± 1.7 |
| Sandy loam | 62.5 ± 12.5 | 30.0 ± 1.3 | 5.9 ± 4.1 | 4.3 ± 3.4 | 6.8 ± 6.3 |
| Loam | 40.5 ± 8.5 | 42.0 ± 5.0 | 14.5 ± 5.0 | 1.5 ± 0.5 | 3.5 ± 0.5 |
| Silty loam | 25.4 ± 8.4 | 53.9 ± 2.9 | 8.4 ± 0.9 | 3.9 ± 1.8 | 6.7 ± 5.5 |

### *3.2. Effects of Soil Moisture*

Even spraying water onto the surfaces of a rougher granulometric composition absorbed water more quickly than those with higher silt and clay contents. The infiltration depth of soils depended on the extent of watering. Sprinkling with 0.5, 1.0–2.0, and 5.0 mm water moistened through <5, 8–18, and ~40 mm thick soil layers, respectively. Water infiltration was the fastest in case of soils with sand texture and the slowest in the case of loam texture soil; therefore, a thicker soil layer became wet than other soil types in a given time unit.

The results of evaporation time of different soil textures are summarized in Table 3. In this sense, the increase of wind velocity significantly decreased evaporation time. The 15.5 m $s^{-1}$ wind velocity reduced the evaporation time of 5.0 mm watering to 296–393 min. Moisture vanished from soils with sand and loamy sand textures relatively quickly, whereas soils with sandy loam, silty loam, and loam textures desiccated more slowly.

**Table 3.** The average evaporation time in five soil texture categories in the studied watering levels and wind velocities. $LSD_{0.05}$: LSD *t*-test was used to separate the soil texture categories at $p = 0.05$ within each wind velocity and each water amount treatment. Different letters next to the values indicate significant differences within the rows among the five soil texture categories within each wind velocity and each water amount treatment.

| Water (mm) | Amount of Water ($m^3$ $ha^{-1}$) | Wind Velocity (m $s^{-1}$) | Sand | Loamy Sand | Sandy Loam | Loam | Silty Loam | $LSD_{0.05}$ |
|---|---|---|---|---|---|---|---|---|
| | | | Average Evaporation Time (min) | | | | | |
| 0.5 | 5 | 4.6 | 134 a | 134 a | 174 bc | 150 ab | 248 d | 29.1 |
| | | 7.8 | 79 b | 69 a | 99 c | 91 c | 97 c | 9.6 |
| | | 9.3 | 51 a | 53 a | 66 b | 73 b | 71 b | 8.4 |
| | | 15.5 | 32 a | 31 a | 39 b | 29 a | 43 b | 5.2 |
| 1.0 | 10 | 4.6 | 234 a | 288 b | 298 b | 333 c | 245 a | 34.2 |
| | | 7.8 | 138 a | 168 b | 170 b | 155 ab | 255 c | 28.3 |
| | | 9.3 | 103 a | 115 abc | 113 ab | 126 bc | 131c | 16.3 |
| | | 15.5 | 62 a | 71 b | 70 ab | 72 b | 78 b | 8.1 |
| 2.0 | 20 | 4.6 | 368 a | 500 d | 421 c | 373 ab | 408 bc | 37.4 |
| | | 7.8 | 313 d | 265 ab | 283 bc | 256 a | 308 cd | 25.3 |
| | | 9.3 | 208 ab | 194 a | 211 ab | 207 ab | 225 b | 23.8 |
| | | 15.5 | 131 ab | 134 ab | 145 bc | 127 a | 150 c | 15.1 |
| 5.0 | 50 | 4.6 | 1129 a | 1172 ab | 1196 ab | 1254 bc | 1301 c | 93.1 |
| | | 7.8 | 682 a | 722 ab | 765 bc | 812 c | 1006 d | 75.2 |
| | | 9.3 | 439 a | 509 b | 520 b | 571 c | 673 d | 41.3 |
| | | 15.5 | 296 a | 354 b | 359 b | 375 bc | 393 c | 35.9 |

Equal to 5 mm rainfall, with the exception of sandy soils, with regard to the evaporation time durations in Table 3, we can establish that watering with a quantity provided about 5–6 h protection against wind erosion, even in case of a wind velocity as high as 15.5 m $s^{-1}$. Accordingly, longer protection time can be reached with maintaining the soil moisture. Interestingly, observed evaporation time had exponential connection with the wind speed; $R^2$ values were between 0.88 and 0.99 (Figure 3).

As a result of irrigation, the surface of both the sandy and the silty soils became moist relatively quickly. However, depending on the granulometric composition, the desiccation times of the wetted soils highly varied. The amount of evaporation loss of soils changed primarily in accordance with the particle-size distribution (Figure 3); however, changes were not significant between the texture categories (Table 4).

**Table 4.** Comparison of the evaporated water (EW) and soil texture categories (Wilcoxon test; $p < 0.05$ was highlighted in bold).

| | Wilcoxon z | Sig. | Effect Size (r) |
|---|---|---|---|
| EW–sand | −0.827 | 0.437 | −0.21 |
| EW–loamy sand | −2.896 | **0.002** | −0.72 |
| EW–sandy loam | −2.482 | **0.011** | −0.62 |
| EW–loam | −2.689 | **0.005** | −0.67 |
| EW–silty loam | −3.154 | **0.000** | −0.79 |

Granulometric composition had a significant effect on evaporation time in case of all texture categories, except sand (Table 4 and Figure 4). Effect size (r) indicated that soil texture had strong effect on the rate of evaporation; however, the influence was not increasing with the growing ratio of finer particles (i.e., loamy sand and silty loam had similar effect on the evaporation).

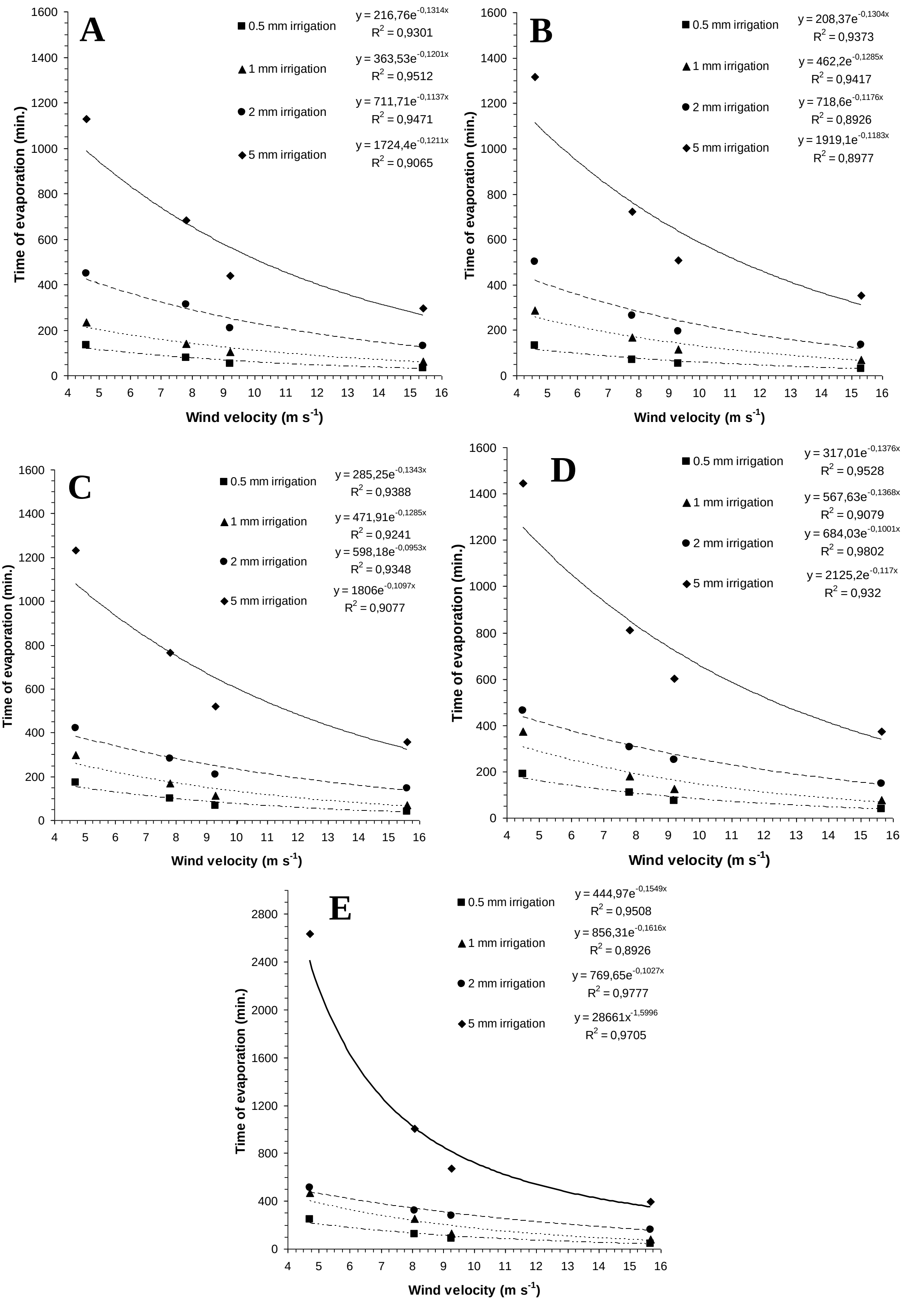


**Figure 3.** Functional relationships between the time of evaporation (min.) and wind velocity (m $s^{-1}$) of 5 soil texture categories ((**A**): sand, (**B**): loamy sand, (**C**): sandy loam, (**D**): loam, and (**E**): silty loam). Commas in the equations and $R^2$ represent decimal points.

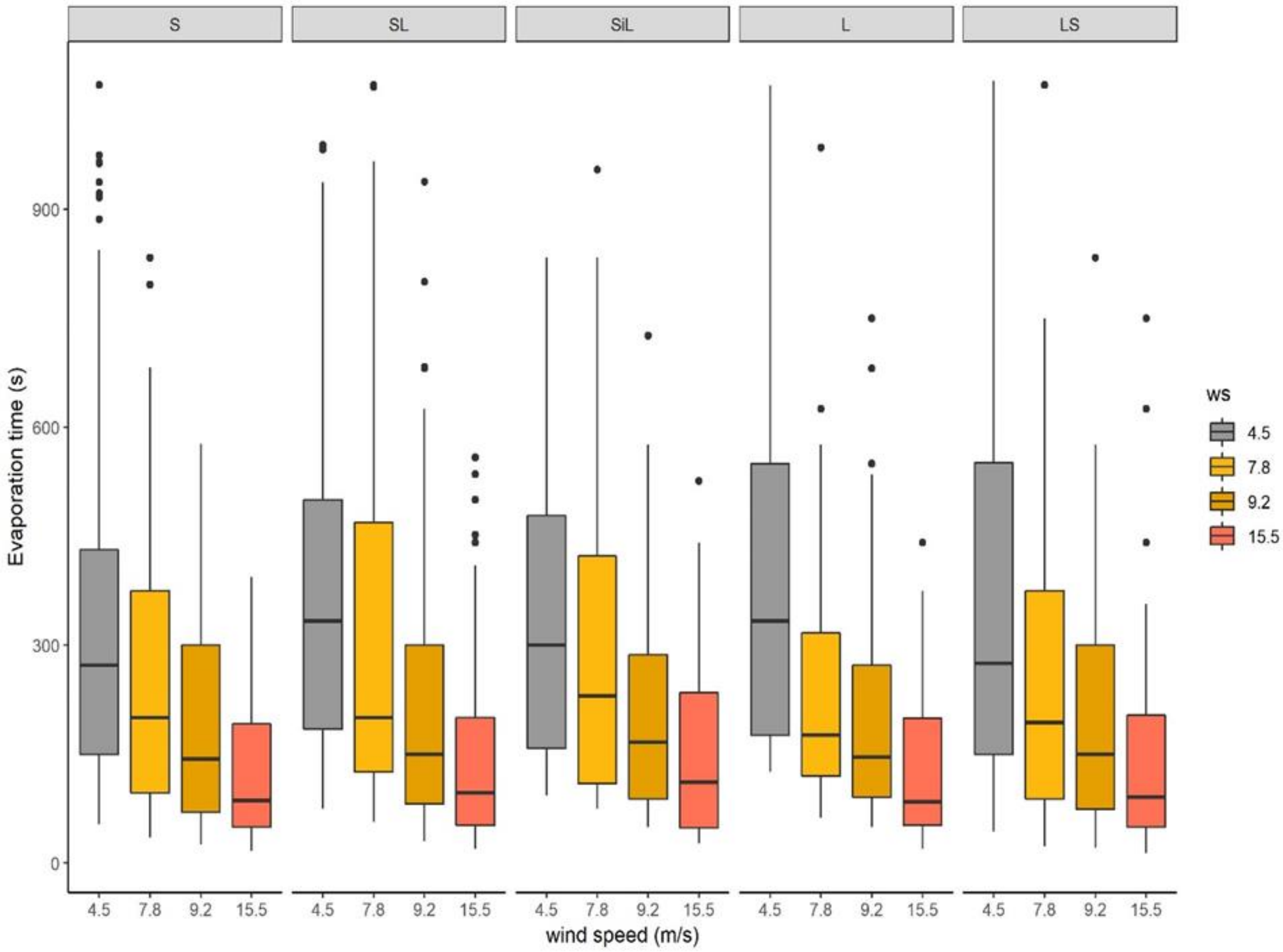


**Figure 4.** Variation of evaporation time by soil textures at different wind speeds (unit is expressed in the duration needed to evaporate of water amounts). S: sand, SL: sandy loam, SiL: silty loam, L: loam, LS: loamy sand, and ws: wind speed.

### *3.3. Crust Formation*

The first sign of water loss was a visible trait: the color of the soil surface changed, then small cracks appeared. Next, the length, width, and depth of the cracks increased in time until the whole surface was covered by crust polygons of various sizes and shapes and the whole soil volume in the tray went dry (Figure 5).

Particle size distribution differences of original soils and their surface crusts could be summarized as follows: (i) generally the ratio of smaller size particles was higher in the crusts; (ii) in low silt and clay content sandy soils, the inter-granular cohesion was weak and crust formation was negligible; (iii) in the crusts on sandy loam soil the mass percent of particles with diameter >0.1 mm decreased, whereas the mass percent of smaller size ones increased; (iv) granulometric composition of the crusts of silty loam and loam texture soils had differences in several size ranges (0.1–0.2 mm and the clay fraction increased, sand and silt content decreased). Silty loam texture soils resulted in harder and more solid crusts related to loam texture ones. This was probably supported by their higher $CaCO_3$ contents as well.

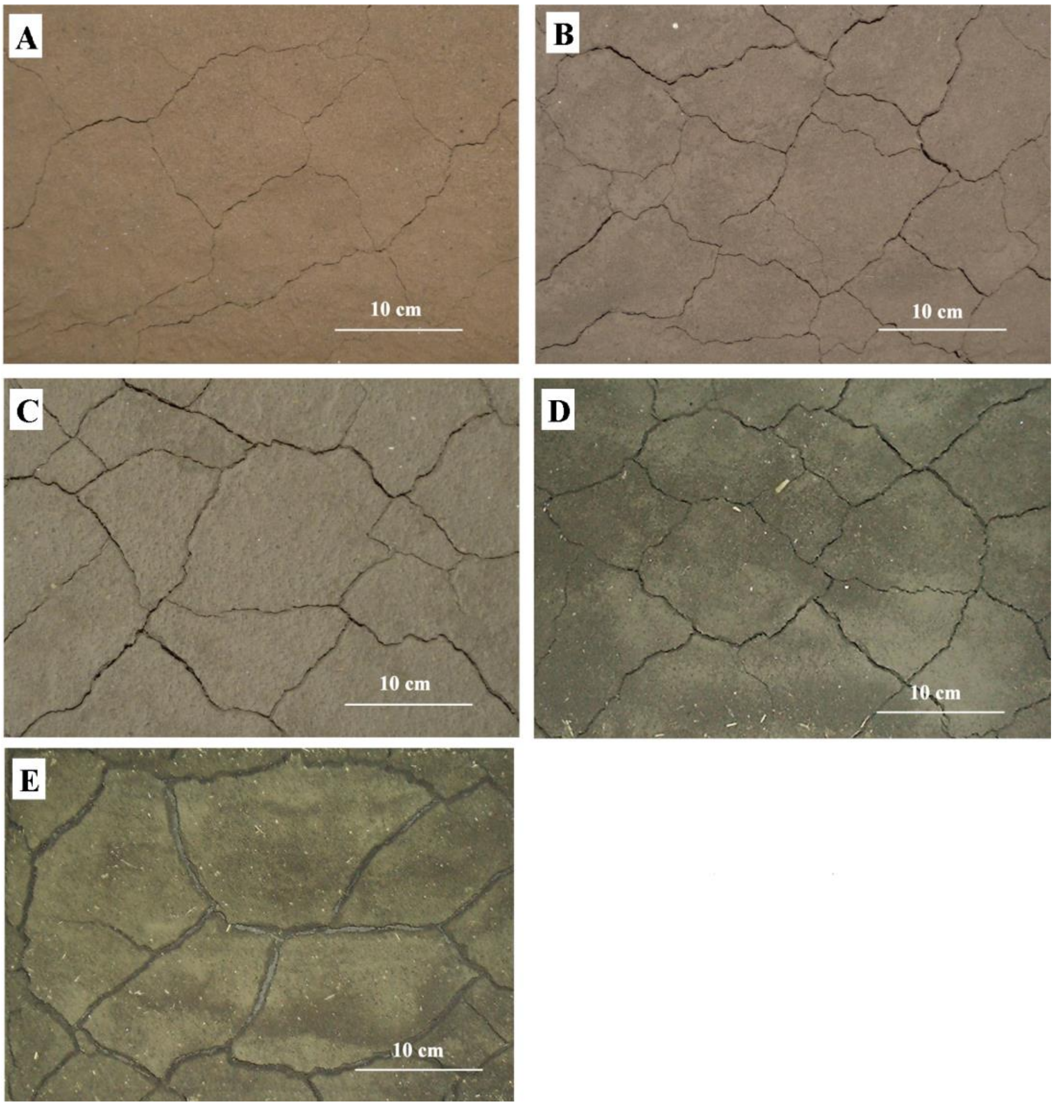


**Figure 5.** Crusts of various shapes, formed on the surface of soils with different textures after the wind tunnel measurement ((**A**): sand, (**B**): loamy sand, (**C**): sandy loam, (**D**): loam, and (**E**): silty loam).

### *3.4. Factors of Evaporation Intensity*

Soil properties correlated weakly (r < 0.1) with the evaporation loss, but valuable connections were revealed among the soil properties, which helped the interpretation of the reasons of the results. Soils with larger silt and clay content were in strong positive (r = 0.553 and 0.582), and their sand content was in strong negative correlation with the $CaCO_3$ content (r = −0.616). We observed similar pattern with the OM, but the correlations were only weaker. Furthermore, $CaCO_3$ and OM content were in weak positive correlation (Table 5).

The two-way ANOVA revealed that both wind speed (F = 45.17, df = 3, $p < 0.001$) and soil texture (F = 3.32, df = 4, $p = 0.010$) had significant effect on evaporation intensity, but their interaction was not significant (F = 1.22, df = 12, and $p = 0.260$). Thus, both factors were important, but considering the evaporation rate, the effect of wind speed was independent of soil texture.

**Table 5.** Spearman correlation coefficients (r, below diagonal) and significance (*p*, above diagonal) among soil properties. OM: organic matter.

| | Sand | Silt | Clay | OM | $CaCO_3$ | Evaporation |
|---|---|---|---|---|---|---|
| Sand | – | 0.000 | 0.000 | 0.000 | 0.000 | 0.034 |
| Silt | −0.989 | – | 0.000 | 0.000 | 0.000 | 0.030 |
| Clay | −0.858 | 0.796 | – | 0.000 | 0.000 | 0.112 |
| OM | −0.341 | 0.346 | 0.202 | – | 0.000 | 0.486 |
| $CaCO_3$ | −0.616 | 0.582 | 0.553 | 0.313 | – | 0.042 |
| Evaporation | −0.063 | 0.064 | 0.047 | 0.021 | 0.060 | - |

Median of the RFRs involving all variables ('all') model indicated 69.9% explained variance, with MAE of 112 mm (RMAE: 34%). Variable importance was the following in decreasing order: treatment of 5 mm water (100.0%) > wind speed (50.0%) > treatment of 2 mm water (41.8%) > treatment of 1 mm water (12.9%) > clay (12.3%) > silt (11.3%) > sand (9.1%) < OM (5.6%) > $CaCO_3$ (4.9%). Furthermore, the model considering only the soil properties ('soil') performed very weakly, and the explained variance was only 0.5% (Table 6).

**Table 6.** Model performances of random forest regressions (RFR) based on 10-fold cross-validation and three repetitions (Q1–Q3); (all: possible variables; soil: only soil properties according to Table 1).

| Models | Q1 | | Q2 | | Q3 | |
|---|---|---|---|---|---|---|
| | $R^2$ | MAE | $R^2$ | MAE | $R^2$ | MAE |
| all | 0.558 | 95 | 0.699 | 105 | 0.782 | 123 |
| soil | 0.002 | 233 | 0.005 | 249 | 0.012 | 384 |

## 4. Discussion

Wind erosion is a crucial soil degradation issue of arid and semi-arid regions. Experimental studies are direct methods to quantify wind erosion along with laboratory simulation, which can help to develop local and/or national plans against this natural, but due to intensive agricultural cultures, anthropogenically intensified phenomenon.

### *4.1. Impact of Water Treatment and Different Soil Properties on Wind Erosion and Evaporation*

Many parts of Europe are subjected to wind erosion, even such as northern Germany, and Belgium [54]. In Hungary, wind erosion predominates in eastern part where the soil texture is fragile and easily moved by the wind. Agricultural practices enhance this phenomenon with large bare soil surfaces (e.g., spring sowings or after harvesting). However, only a few studies were carried out to assess the interactions between different soil properties (i.e., soil water content, texture, OM%, and $CaCO_3$) and wind erosion. In this context, the results of this research showed that watering with a quantity equal to a 5 mm rainfall, with the exception of sand soils, provided about 5–6 h protection against wind erosion, even in case of a wind velocity as high as 15.5 m $s^{-1}$. This result is supported by the early exploration of Troeh et al. [16], which emphasises the delaying effect of soil moisture. Accordingly, longer protection time can be reached with maintaining the soil moisture. These results can be discussed from different perspectives: (i) high percentage of organic matter (1.93% ± 1.27) and fine soil particles (silt + clay), with the exception of sand soils, improves soil's water-holding capacity, which improves the cohesion and adhesion forces between soil particles and the stability of soil aggregates against wind erosion; (ii) the increase of soil water content improves liquid-bridge bonding [55], which reduces wind erosion through linking soil fine particles with each other [56]. Ultimately, both factors upgrade the soil system resistance against wind erosion. Previously, Bolte et al. [54] highlighted the critical role of soil moisture against wind erosion. Thus, due to the direct relationship between increasing soil moisture and wind erosion, irrigation helps to prevent land degradation [57–60].

Evaporation rate differed significantly between the water and soil surface, influenced by the physical and chemical soil properties. Soil texture had significant effect on evaporation rate due to the surface electric charge and specific surface area of soil particles. In this context, sand particles have less net electric charges, and low specific surface area, as a consequence smaller amount of water, can be adsorbed in comparison with finer textured soils [61]. Wind speed is considered to be one of the most important factors that accelerates evaporation rate and wind erosion. Our wind tunnel experiments also confirmed this result. Increasing wind speed accelerated soil evaporation, which led to less water in the surface soil pores (i.e., changing in matric potential) and minimized the coherent binding in favor of the granular structure, which amplified the soil erodibility [54].

The two-way ANOVA justified the significant effects both for the soil texture and the wind speed, but their interaction was not significant. Accordingly, both are important in the desiccation process, but the wind speed did not have significantly different effects on different soil texture categories. Wind speed, however, had relevantly larger effect than texture as it was reflected in the RFR model. Although RFR model did not directly contain the soil texture categories, the sand, silt, and clay proportions held the same information. Soils moistened with different water amounts and the wind speed were the most important influencing factors of evaporation rate, similarly to Ishizuka et al. [59]. Regarding the soil properties, granulometric composition (clay, silt, and sand) had the largest importance (but only the 10–20% related to the relevance of water treatment), and the OM and $CaCO_3$ content (5–10% related to water treatment). Bodolayné et al. [62] and Li et al. [63] found that soil texture relevantly changed within a two-year period due to wind erosion, texture became coarser, and fine particles (<125 µm) were significantly depleted. They also highlighted a side effect: even a small change in the fraction can cause the decrease of soil carbon and nitrogen content. Consequently, the loss of silt fraction coincides with OM-loss. Thus, relevance of soil properties is small, and if it is possible to ensure at least a minimal soil moisture with irrigation under field circumstances, it is more important than soil texture, organic matter, or $CaCO_3$ content. Estimation of evaporation based on RFR explained ~70% of variance but also had uncertainty of 34% based on RMAE. Considering that evaporation is influenced by several factors, including by some we could not determine, relevance of the gained 34% uncertainty was smaller than the advantage of the method as our model also revealed the importance of the involved factors. It could help practitioners and agricultural managers to prevent or mitigate the effect of wind erosion by identifying the most endangered spots.

### *4.2. Crust Formation*

Soil crusting is a well-known phenomenon, especially after rainfalls [64,65]. Soil crust reduces the sensitivity of the soil to wind erosion [13,35,66,67]. In fact, erosion of loose or single-grain soil is reduced 85–98% after a crust formation on the soil surface [13,35]. Zobeck [35] found that crusts formed on soils of silty loam and clay can have greater effect in limiting the wind erodibility of soils than can those formed on sandy or sandy loam soil. Furthermore, soil crusts raise the threshold of motion, as has been pointed out by many works that aim to examine how crust disturbances affect dust emission [68–70]. Sharratt and Vaddella [71] found exponential relationship between threshold friction velocity and crust strength and crust formations on the soil surface decreases the potential for wind erosion. Feng et al. [22] noticed a difference in crust strength regarding soil texture, while soil texture did not affect crust thickness. Regarding sandy soils (with low silt and clay content), the intergranular cohesion was weak and the crust was also weak and thin. This was also the consequence of the lower $CaCO_3$ content (Table 1). However, in the crusts formed on soils with sandy loam texture, the mass percent of particles >0.1 mm decreased, whereas the mass percent of smaller sizes increased. The increase in the ratio of finer particles and the higher $CaCO_3$ content resulted in strong crust formation. Soil texture of silty loam resulted in harder and more solid crusts related to loam texture ones, which was supported by their higher $CaCO_3$ content as well (Table 1).

The surface crust formation is caused by (i) the rearrangement of soil particles, due to an effect of water sprinkling in the form of mist; (ii) after wetting, the adhesion (sticking together) of the drying soil particles induced by hydration shells that envelope the soil particles and shrink during dehydration. The desiccation of soils, i.e., the evaporation of water is always accompanied by weight loss and volume decrease in case of shrinking soils. There, where the cohesive forces between the particles are weaker on the drying surfaces, cracks and gaps form. In turn, because of the crust formation, the roughness/smoothness of soil surface changes. Due to the sharp fissure edges, the air-flow pushing in the cracks becomes turbulent. In turn, the whirling air quickens the drying of the polygon edges and it also facilitates the drying of the lower soil layers. The quicker dehydration of the polygon edges results in a quicker decrease in volume, which is clearly shown by the curling up of the edges. This phenomenon can often be observed in natural environments, on bare soil surfaces.

In the Nyírség region (Eastern Hungary), agricultural practice and unsustainable land management have accelerated the susceptibility of soil to wind erosion due to many factors such as conventional tillage and soil compaction due to machines wheeling [72]. Conservation agriculture, along with improvement of soil texture through adding organic matter especially to sandy soil, could significantly minimize wind erosion.

## 5. Conclusions

The main objective of this study was to investigate the impact of various levels of simulated irrigation rate (0.5, 1.0, 2.0, and 5.0 mm) and four levels of wind speeds (4.5, 7.8, 9.2, and 15.5 m $s^{-1}$) on soil crust formation and evaporation by using a wind tunnel experiment. Results of this research can be summarized as follows:

1. Longer protection time can be achieved by maintaining the appropriate soil moisture conditions. Interestingly, observed evaporation time had an exponential connection with wind speed.
2. The amount of evaporation loss in soils changed primarily in accordance with the granulometric composition; however, changes were not significant between the soil texture categories.
3. Granulometric composition had a significant effect on evaporation rate in the case of all texture categories except sand. The effect size (r) indicated a strong soil texture effect on the rate of evaporation.
4. An amount of watering, equal to 5 mm rainfall, significantly hindered the erosive effect of even a strong (15.5 m $s^{-1}$) wind for 4-6 h depending on soil texture.
5. Soil texture and other soil characteristics had a remarkable impact of soil crust formation and hardness.
6. Within the study area, sandy lands were more subjected to wind erosion hazard due to weak water-holding capacity, and low $CaCO_3$%.

These results present new insights into the dynamic interaction between some soil properties (texture, OM%, and $CaCO_3$%), different irrigation levels, and wind speeds from a wind erosion point of view. This research recommends repetition of watering against wind erosion in farm lands (Eastern Hungary), especially in spring when the soil is directly exposed to wind speed.

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