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ESTIMATION OF SOIL MATERIAL TRANSPORTATION BY WIND BASED ON IN SITU WIND TUNNEL EXPERIMENTS

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Abstract

25% and 40% of territory of Hungary is moderate to highly vulnerable to deflation. However, precise estimates about the soil loss and related losses of organic matter and nutrients due to wind erosion are missing in most cases. In order to determine magnitudes of nutrient masses removed at wind velocities that frequently occur in SE Hungary, in-situ experiments using a portable wind tunnel have been conducted on small test plots with an erosional length of 5.6 m and a width of 0.65 m. The wind tunnel experiments have been carried through on a Chernozem which is typical for this region. In order to compare the effects of soil coverage on the masses of blown soil sediment and adsorbed nutrients, two soil surface types have been tested under similar soil moisture und atmospheric conditions: (1) bare soil (dead fallow) and (2) bare soil surface interrupted by a row of maize plants directed downwind along the center line of the test plots.

The results of our experiments clearly show that a constant wind velocity of 15 m s^{-1} (at a height of 0.3 m) lasting over a short time period of 10 minutes can already cause noticeable changes in the composition and size of soil aggregates at the top of the soil surface. Due to the grain size selectivity of the erosive forces the relative share of soil aggregates comprising diameters > 1 mm increased by 5-10% compared with the unaffected soil. Moreover it has shown that short time wind erosion events as simulated in this study can result in erosion rates between 100 and 120 g m^{-2}, where the erosion rates measured for bare soils are only slightly, but not significantly higher than those of the loosely vegetated ones. Soil samples taken from sediment traps mounted in different heights close to the outlet of the wind tunnel point to an enrichment of organic matter (OM) of about 0.6 to 1 % by mass referred to the control samples. From these findings has been calculated that the relocation of organic matter within short term wind erosion events can amount to 4.5 to 5.0 g OM m^{-2}. With the help of portable field wind tunnel experiments we can conclude that our valuable, high quality chernozems are struck by wind erosion mainly in drought periods.

Keywords: deflation, wind tunnel experiment, nutrient transport

INTRODUCTION

It is well-known that among other processes of soil degradation, wind erosion can cause enormous damages on the regional as on the global scales. For this reason, research on this topic has started early (Chepil 1942, 1955; Chepil and Woodruff 1963; Woodruff and Siddoway, 1965). However, for a long time attention was mainly given to the physical mechanisms and to the measurement of wind erosion under field and lab conditions (Gillette, 1978; Bódis and Szatmári, 1998). Since the 1980s research focused on the modeling of wind erosion processes including the calculation of soil erosion rates at different spatial and temporal scales and, especially, the estimation of the losses of organic matter and nutrients caused by deflation (Zobeck and Fryrear, 1986; Zobeck et al., 1989; Sterk et al. 1996; Larney et al. 1998; Bach, 2008). The amount of nutrient loss per hectare varies within a broad range, depending on the soil type, the physical properties and the organic matter content. For stronger wind erosion events Neemann (1991) reports about nutrient losses of about 150 kg N ha^{-1}, 200 kg P_2O_5 ha^{-1}, 200 kg K_2O ha^{-1}, 200 kg MgO ha^{-1} and 600 kg CaO ha^{-1} (Neemann, 1991, Charles et al., 2002, Sankey et al., 2012).

In Hungary, the deflation preferentially occurs in regions covered with sandy soils (e.g. the Danube-Tisza Interfluve, Nyírség). Hence, these areas form the recent center of soil erosion research (Borsy, 1972; Harkányiné and Herkó, 1989; Lóki and Schweitzer, 2001; Mezősi and Szatmári, 1998; Mucsi and Szatmári, 1998; Szatmári, 1997, 2005) although the vulnerability of Chernozem soils to wind erosion has been already emphasized in earlier research (Bodolayné, 1966; Bodolayné et al., 1976). The vulnerability assessment of the Hungarian soils to deflation has been made possible after finalizing the 1:100.000 soil maps, which have a special focus on physical diversity (Várallyay et al., 1979, 1980). The assessment of wind erosion risk indicates that 26% of the total area of Hungary is covered with highly vulnerable sandy soils, another 40% of the country has been classified as medium vulnerable, corresponding with the wide spreading areas composed of sandy loam and loam (Lóki, 2003). As stated by Baukó and Beregszászi (1990) in their case study in Békés County, these soils bear large economic potential, which increases the need for sustainable land use practices.

To-date only little is known about the quantities of wind-driven soil and nutrient losses from Chernozems as they are typical for the south eastern parts of the Great Hungarian Plain (Apátfalva). In order to gain knowledge about the magnitudes of deflation rates of mineral soil, organic matter and nutrients, wind tunnel experiments have been performed under controlled conditions. Although wind tunnel experiments have been widely used in many other regions (e.g. Maurer et al., 2006; Bach, 2008; Fister and Ries, 2009), this paper describes the first applications of an in-situ wind tunnel experiment in Hungary. The major objectives of this study are (I) to compare the rates of soil loss caused by winds of frequent velocity on uncovered and loosely covered soil surfaces as they are typical for most of the wind erosion events in this area, (II) to analyse the changes of the above-ground soil structure and (III) to calculate the magnitudes of humus- and of the nutrient losses during wind storm events of defined intensity.

STUDY AREA

The study area is located in the Csongrád-plain micro region (*Fig. 1*). The elevation of the area ranges between 79.5 and 107.6 m forming nearly a perfect plain. The clayey, loamy subsurface sediments are covered by infusional loess of various depths. The climate of the area is warm and dry with an annual average temperature of 10.3 °C and an annual precipitation of around 560–570 mm. The aridity index (ratio of the potential maximal evaporation and the annual precipitation) is around 1.3, and may have a considerable effect on the deflation of the soil. The prevailing wind direction is NW, but winds from SE are also frequent (Dövényi, 2010). The synops data, which provide mainly hourly data, measured in Szeged weather station (WMO Index 12982). In the cases of all wind velocity data 160° is dominant, but the strongest winds come from 320°, so this direction is chosen to set the model (*Fig. 2*).

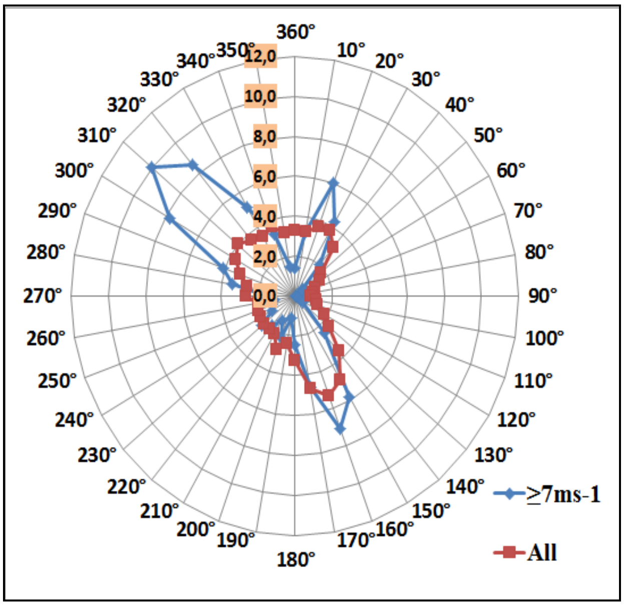

Fig. 2 Wind direction change at Szeged in aspect of wind velocity (March-April, 2000-2011)

The typical soil type is a Chernozem according to WRB, 2006, having a loamy, at some places clayey loam texture (*Fig. 3*) and high humus contents in the A-horizons (4.5-4.8%). The carbonate content varies between 4-12% by weight. During the experiments, the water content of the soil was 7–8 v/v%.

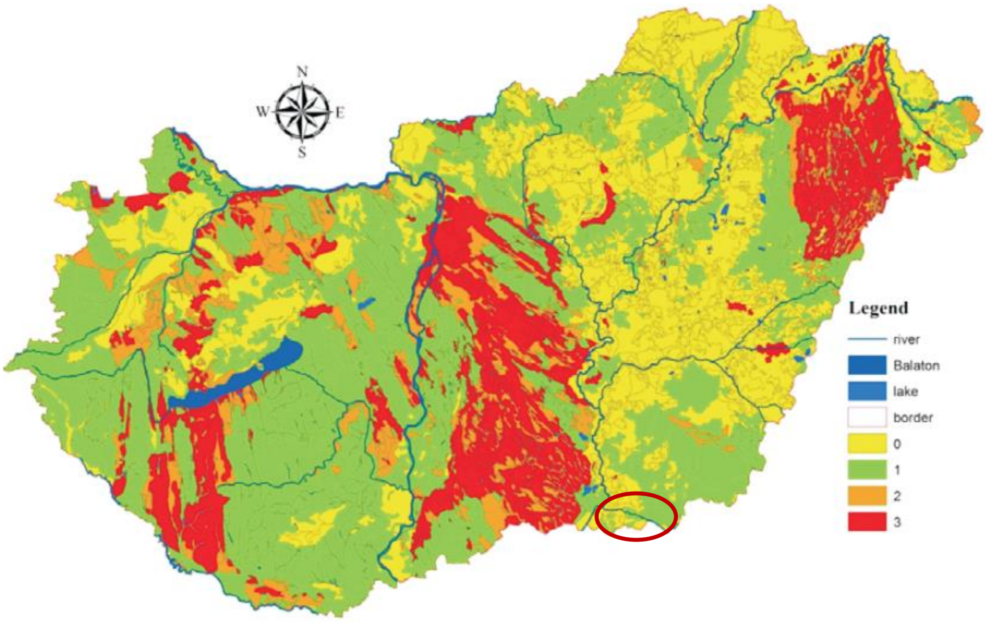

Fig. 1 Potential wind erosion map of Hungary with the studied area (0: insignificant, 1: slight, 2: moderate, 3: severe) (Lóki, 2000)

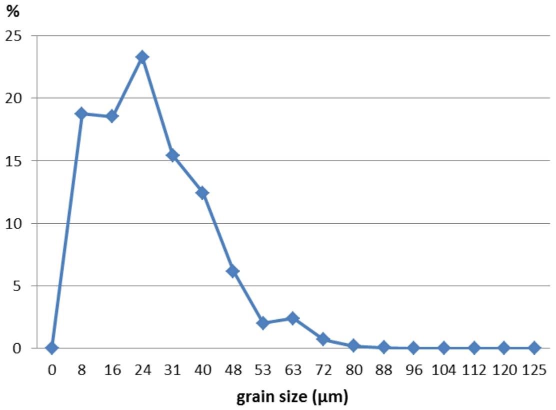

Fig. 3 Grain size distribution of the chernozem soil in the study area

METHODS

The undisturbed surface soil was measured in a portable and adjustable 12 m long field wind tunnel (*Fig. 4*) in situ on the study plot in the summer of 2011. Experiment “A” was conducted upon a non-cultivated, plant-free surface. The “B” series simulate the effects of a loosely vegetated surface. For this purpose a row of maize plants with a height of 25-30 cm and a spacing of 10 cm was placed in the center of the wind tunnel (*Fig. 5*). For both series three parallel deflation experiments where carried through each one with a duration of 10 minutes and approximately 15 ms^{-1} wind speed.

Wind velocity has been measured along horizontal and vertical profile lines during all experiments (*Fig. 7*) using a Lambrecht Jürgens 642 anemometer. The ground area blown within the wind tunnel covers 3.36 m^2. Measurements of wind velocity confirmed the existence of a logarithmic shaped boundary layer of a thickness of about 35.1 cm.

The threshold wind velocity in both experiments was observed at 13 ms^{-1}. Following each wind experiment both the surface soil and the rolling soil fractions were sampled. The latter were collected in boxes positioned at the end of the tunnel. The MWAC (Modified Wilson and Cook) traps at 5, 15, 25, 35, 45 and 55 cm heights at the end of the tunnel were emptied (*Fig. 6*).

The samples were air dried, and after the appropriate preparation, the following parameters were determined: distribution of aggregates by sieving, “Arany” yarn test according to the MSZ-08-0205:1978

Fig. 4 The portable wind tunnel

Fig. 5 Surface soil of the two experiment series: “A” series with an undisturbed surface soil, “B” series on a maize field

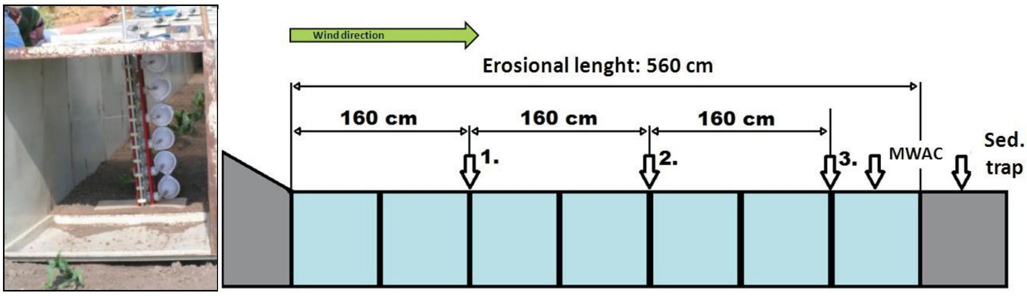

Fig. 6 The location of the soil sample points, the MWAC traps and the sediment traps at the end of the tunnel about 15 ms^{-1} with

specification, pH(H_2O), carbonate content according to the MSZ-08-0206/2:1978 specification, and the organic matter content according to the MSZ 21470/52:1983 specification.

The total element content of the soil and the captured sediment was determined by XRF HORIBA Jobin-Yvon XGT-5000. The particle size distribution was measured by Fritsch Analysette 22 Microtel Plus.

RESULTS AND DISCUSSION

Analyses of the wind profiles reveal significant differences between the "A" series (bare soil) and the "B" ("maize") series. Figure 5 clearly shows the influence of a different surface roughness and surface structure on the changes of the wind velocity over the whole cross-section of the wind tunnel.

The isotache profile of the “A” series, expectedly reveals a decrease of wind velocity close to the ground, depending on the soil roughness cause by the coarser aggregate on top of the soil. The Z_0-value has been calculated at 0.25 mm.

At a height of 10 cm the wind velocity increases up to 13 m s^{-1} while it reaches its original velocity of 15 ms^{-1} in a height of 20 cm. Surprisingly, the isotache profile of the “B” series shows a different behaviour. In contrast to other studies (Bolte, 2008) that show a strongly reduced wind velocity behind wind breaking obstacles, we found only a minor decrease in wind velocity within and behind the row of maize plants, and even a higher wind speed compared with the same heights of the series "A" experiments (*Fig. 7*). This fact suggests the occurrence of vortex movements around the single maize plants causing an increase in wind velocity up to 16-17 m s^{-1} which might contribute to higher deflation rates along plant rows oriented in downwind direction at this stage of growth.

The 10 minutes wind event had a significant impact on the relative percentage of aggregate sizes in the surface soil (*Fig. 8, Table 1*). The experiments show that the dust fraction was reduced, and therefore the proportion of larger aggregates increased in the top 5 cm of the soil. It is noteworthy that during the “B” experiment series, the ratio of 1< mm aggregates in the surface layer increased by 5 – 10% compared to the original soil (*Fig. 8.*).The largest saltation movement was caused by the increase of the wind velocity along the outer sides the maize row. Comparing the original surface soil and the aggregate composition of the material collected in the traps (mass%, n = 3) afterwards the “A” series experiment, it is obvious that 58% of the soil material trapped in the recessed traps consisted of aggregates with a diameter of 1 to 4 mm (*Table 1*). Compared with the aggregate composition of the original surface soil, in both experiment series the diameter of the soil crumbs increased significantly in the trapped soil material (7%). During the 16-17 ms^{-1} wind speeds of the “B” experi-

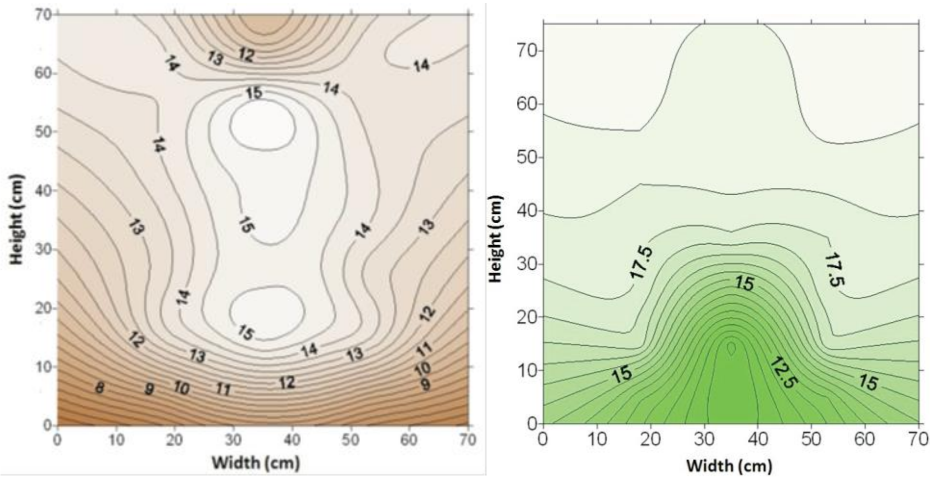

Fig. 7 The wind profiles (ms^{-1}) of the two experiment series (left: “A” series, right: “B” series)

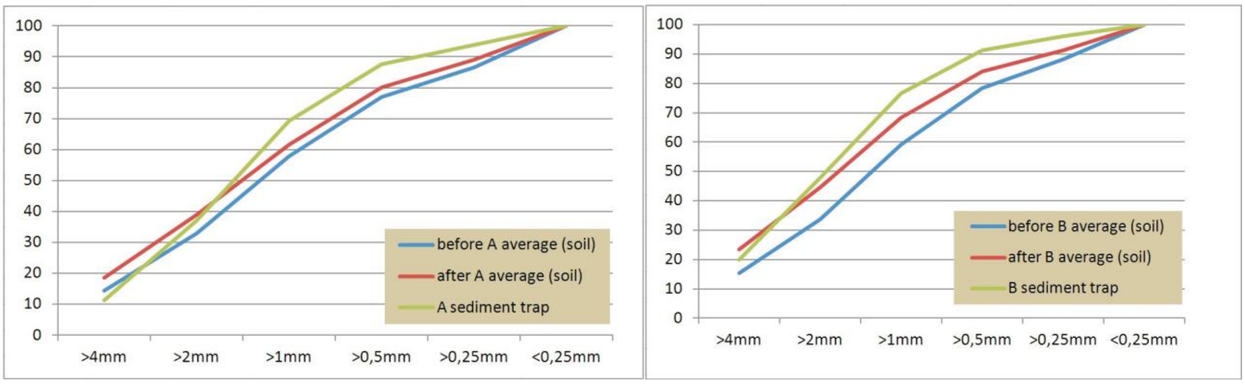

Fig. 8 Change of the aggregate structure (%) of the surface soil (left: “A” experiment series, right: “B” experiment series)

Table 1 The aggregate composition of the original surface soil and the, in the traps accumulated, soil material (Mass%, n=3)

mm	„A" series surface m/m%	Standard deviation	„A" series trap m/m%	Standard deviation	„B" series surface m/m%	Standard deviation	„B" series trap m/m%	Standard deviation
>4	14.4	3.9	11.3	0.2	15.4	1.7	19.9	9.2
2–4	18.4	1.7	25.7	1.5	18.3	0.5	27.8	3.6
1–2	25.1	1.2	32.3	1.8	25.4	1.04	28.8	4.9
0.5–1	19.0	1.4	18.2	0.6	19.3	0.6	14.7	1.6
0.25–0.5	9.7	1.3	6.3	0.5	9.8	0.6	4.8	0.5
<0.25	13.4	2.6	6.1	0.9	11.8	0.9	3.9	0.2

ment series, more 4 mm and larger aggregates where moved. On average 20% of the trapped soil material in the traps had an aggregate diameter larger than 4 mm.

The organic matter (OM) content of the accumulated material in the traps increased (*Fig. 9*). By dividing the OM content of the material captured in the MWACs trap, by the OM content of the original surface soil, an enrichment factor of 1.1 to 1.2 - depending on the strength of the wind - can be found for the traps at a height of 15 and 25 cm. The material taken from the traps at a height between 0.15 m and 0.55 m, the OM content showed an increase of 0.6 – 1% compared to original soil (*Fig. 10*, *Table 2*).

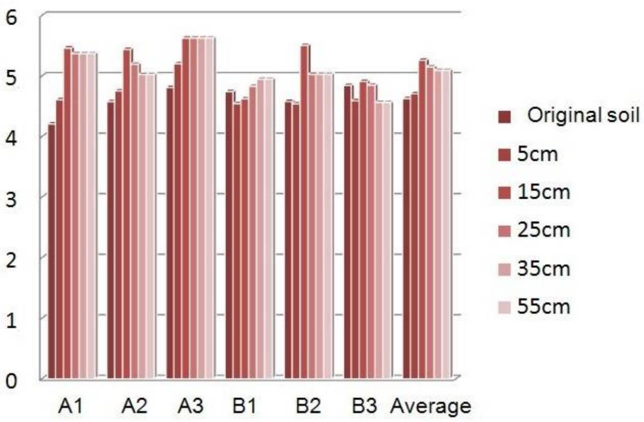

Fig. 9 Amount of the humus

The effect of the soil movement during the 10 minute wind events on the amount of accumulated soil material in the trap has been quantified, given the area of the surface exposed to the wind and the size of the surface of the MWAC traps (*Table 2*). The majority of the soil movement consist of rolling soil material.The amount of trapped soil material not show significant differences; in case of the "A" series 97 g m^{-2} of rolling soil material was registered while during the "B" series 59 g m^{-2} was recorded. In the first place, the soil with aggregates smaller than 0.25 mm (soil dust) was collected in the MWAC traps, which was in case of the "A" series 10.7 % of the total transported material, while during the "B" series this was 17.4 %. The average soil movement during the "A" measurement series was 107 g m^{-2}, and during the "B" measurements series 115 gm^{-2}. From the total amount of transported soil, just the suspended fine fractions are accumulating in the MWAC traps at larger distance; during the 10 minutes 15 ms^{-1} wind event, an amount of 15 g m^{-2} was registered.

The amount of relocated humus **(**g m^{-2}**)** movement was calculated based on the total amount of soil material that was transported during the wind event and the humus content of the accumulated sediments in the traps. The OM content in the sediment traps (above 0.15 m) was 0.6–1% higher than that of the original surface soil (*Fig. 9-10*). The amount of relocated OM content caused by deflation could reach up to 4.5–5.0 g m^{-2} (*Table 2*).

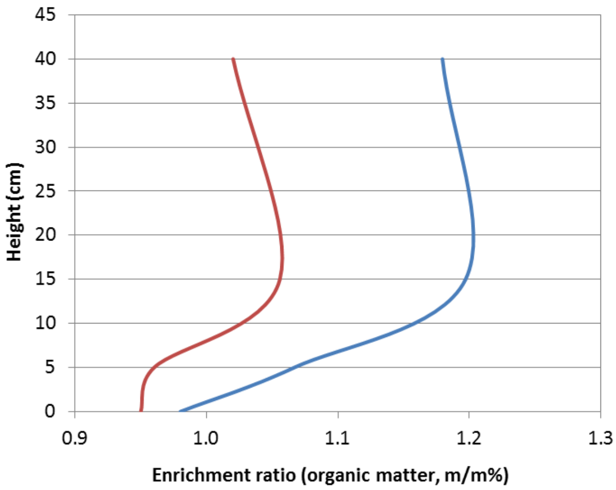

Fig. 10 Variation of the amount of humus enrichment ratios in the sediment collected with MWAC traps at 5, 15, 25, 35 and 45 cm height (red: "A" experiment series, blue: "B" experiment series

Macro elements (P, Ca, K) do not show any increase in the transported soil fraction, their enrichment ratios vary between 0.95 and 1.09 (*Table 3-5*). The 10 minute long wind experiment with 15 ms^{-1} wind speed transported 0.1 g m^{-2} of P, 1.6 g m^{-2} of K and 2.9 g m^{-2} of Ca.

Comparisons between the amount of relocated nutrients calculated in this study and those amounts reported from other studies –are complicated, because of differing wind tunnel characteristics, differing initial conditions and varying soil properties.

Table 2 Amount of the transported soil (g m^{-2}), the relocated humus (g m^{-2}) and the humus enrichment ratios during the two experiment series (A and B) (wind speed 15 m s^{-1}, 10 minute long single experiments)

.	Amount of transported soil (average) (g m^{-2})	OM (%)		Enrichment ratios	Amount of relocated humus (g m^{-2})
		(average)	standard deviation	OM% $_{eroded}/_{original\ soil}$	
The rolling soil fraction collected in recessed boxes at the end of the tunnel					
A - box	97.0	4.47	0.08	0.98	4.34
B - box	95.0	4.44	0.17	0.95	4.22
The suspended soil fraction collected with MWAC traps					
A - 5 cm	5.53	4.86	0.31	1.07	0. 27
A - 15 cm	2.35	5.45	0.12	1.20	0.13
A - ≥25 cm	2.12	5.37	0.12	1.18	0.11
B - 5 cm	8.51	4.56	0.03	0.96	0.39
B - 15 cm	5.24	5.01	0.45	1.06	0.26
B - ≥25 cm	6.25	4.85	0.11	1.02	0.303
Total transported humus (A series): 4.85 g m^{-2}					
Total transported humus (B series): 5.17 g m^{-2}					

Table 3 Amount of the transported soil (g m^{-2}), the relocated P (g m^{-2}) and the P enrichment ratios during the experiments (wind speed 15 m s^{-1}, 10 minute long single experiments)

	Amount of transported soil (average) (g m^{-2})	P (ppm)		Enrichment ratios	Amount of relocated P (g m^{-2})
		(average)	standard deviation	P $_{eroded}/_{original\ soil}$	
The rolling soil fraction collected in recessed boxes at the end of the tunnel					
Box	96.0	1004.2	249	1.07	0.096
The suspended soil fraction collected with MWAC traps					
5 cm	5.53	887.8	63.2	0.95	0.005
15 cm	2.35	903.3	107.5	0.97	0.002
≥25 cm	2.12	861.6	63.4	0.92	0.002
Total transported P/experiments: 0.106 g m^{-2}					

Table 4 Amount of the transported soil (g m^{-2}), the relocated K (g m^{-2}) and the K enrichment ratios during the experiments (wind speed 15 m s^{-1}, 10 minute long single experiments)

	Amount of transported soil (average) (g m^{-2})	K (ppm)		Enrichment ratios	Amount of relocated K (g m^{-2})
		(average)	standard deviation	K $_{eroded}/_{original\ soil}$	
The rolling soil fraction collected in recessed boxes at the end of the tunnel					
Box	96.0	15018	2072	1.00	1.44
The suspended soil fraction collected with MWAC traps					
5 cm	5.53	16167	1916	1.06	0.089
15 cm	2.35	16374	2204	1.08	0.039
≥25 cm	2.12	16493	929	1.09	0.035
Total transported K/experiments: 1.605 g m^{-2}					

Table 5 Amount *of* the transported soil (g m^{-2}), the relocated Ca (g m^{-2}) and the Ca enrichment ratios during the experiments (wind speed 15 m s^{-1}, 10 minute long single experiments)

	Amount of transported soil (average) (g m^{-2})	Ca (ppm)		Enrichment ratios	Amount of relocated Ca (g m^{-2})
		(average)	standard deviation	Ca $_{eroded}/_{original\ soil}$	
The rolling soil fraction collected in recessed boxes at the end of the tunnel					
Box	96,0	26961	5925	0.9	2.59
The suspended soil fraction collected with MWAC traps					
5 cm	5.53	29253	5862	0.97	0.162
15 cm	2.35	31753	5900	1.04	0.075
≥25 cm	2.12	31983	1848	1.08	0.068
Total transported Ca/experiments: 2.89 g m^{-2}					

Bielders et al. (2002) calculated nutrient balance of sandy soil triggered by three natural storms in Sahel. They measured a soil loss of about 0.3-1.9 kg m^{-2}. Because of the low nutrient content of the native soil, total nutrient losses remained very low: P loss was calculated at 9-65 mg m^{-2}, K 20-128 mg m^{-2} and Ca loss 7-62 mg m^{-2}. The study of Sterk et al. (1996) was conducted to quantify nutrient losses by saltation and suspension transport. During two convective storms mass fluxes of wind-blown particles were measured in Niger on sandy soil. The trapped material was analysed for total element content (K, P, C, N). The following nutrient losses were estimated: 5.7 g m^{-2} K and 0.61 g m^{-2} P. In the study of Sankey et al. (2012) the nutrient concentrations by Mehlich3 extraction (P, K, Mg, Cu, Fe, Mn, Al) in wind-transported sediment were determined. The soils were collected from burned and unburned soil surfaces in Idaho, USA. They estimated 0.256 g m^{-2} y^{-1} P mobilization and 1.451 g m^{-2} y^{-1} K mobilization.

Nutrient transport determined by us are congruent to the values measured by Sterk et al. (1996) because their experiments also focused on wind events and the total element was investigated from captured sediment, as well.

CONCLUSION

During this research measurements with a field wind tunnel were executed on the chernozem soils on the southern part of the Great Hungarian Plain. The experiments were repeated three times with two different types of surface cover . They make obvious that already short-time wind events of a wind velocity of 15 ms^{-1}, can erode more than 100 g m^{-2}.

If one hypothetically assumes that the simulated conditons would be true for a complete field this would equalize a loss of 1 ton of treasurous and highly fertile agricultural soil per hectare that would have been lost

From this material, the main part is transported on or close to the surface. Only 10 to 15% is moved in suspended form. This material can be transported over a much larger distance, and this way losing permanently its significantly higher humus content than the original soil, which is crucial for the agriculture.

Acknowledgements

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