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Impact of winter conditions on wind erosion susceptibility of clay soils

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Abstract: Wind erosion primarily affects sandy soil in arid areas. However, the specific winter meteorological conditions (freeze-thaw cycles) lead to the disintegration of aggregates into erosion-risk fractions even on clay soils. These changes in the winter erodibility of clay soils were investigated in an area with frequent occurrences of wind erosion in southeastern Moravia (Czech Republic, Central Europe) between the years 2014/2015 and 2020/2021. The percentage of non-erodible fraction (NEF) before and after winter was assessed. NEF was set as particles larger than 0.84 mm and also larger than 2.00 mm (based on field observations), while soils containing less than 40% NEF have the highest susceptibility to wind erosion. Autumn $NEF_{0.84}$ content was 80 and 95%, indicating significant resistance to wind, and although there was a significant decrease in spring to 65%, it still exceeded the 40% threshold. Autumn $NEF_{2.00}$ content of 60–70% also indicates a significant resistance to wind erosion. However, spring values were well below the 40% threshold (8 to 35%), indicating significant susceptibility to wind erosion. It showed a significant negative influence of winter on $NEF_{2.00}$ content and, thus, a greater susceptibility to erosion in spring compared to $NEF_{0.84}$. Our results also document vegetation efficiency on the presence of NEF.

Keywords: aggregates disintegration; aggregates stability; soil texture; vegetation; wind erosion

Wind erosion affects geomorphologically different areas, but mainly occurs on plains. The susceptibility of soils to wind erosion was studied on a spatial scale within Europe by Borelli et al. (2016). Spring and autumn are at the highest risk as the soil is not protected by vegetation (Zamani & Mahmoodabadi 2013). Wind erosion is directly influenced by soil properties and occurs predominantly in soils with low clay content. Among properties affecting soil resistance to wind erosion are grain and aggregate composition, aggregate stability, soil moisture and soil surface roughness (Diaz-Zorita et al. 2002; Amézketa et al. 2003; Colazo & Buschiazzo 2010; Qian et al. 2019). Aggregate stability and, thus, soil structure deterioration are the result of soil moisture regime, frost, $CaCO_3$ and organic matter content, pH, crop

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residues and mechanical cultivation. All this was described in scientific literature already in the 1930s to the 1950s by Yoder (1936) and Chepil (1951, 1952, 1953, 1954, 1958). Pi et al. (2023) summarizing previous studies, concluded that soil aggregation affects the soil erodibility by: (*i*) the amount of loose material that can be transported by the wind in saltation and suspension; (*ii*) the amount of non-erodible component of soil > 0.84 mm (too heavy to be blown by the wind) (Gillette et al. 1996; Zobeck 1991); (*iii*) the size and stability of secondary aggregate > 5 mm (clods) (Zobeck 1991) that increase the roughness of the soil surface, creating drag, and reducing wind friction velocities at the soil surface that could entrain smaller erodible soil aggregates (Raupach et al. 1993). Roughness elements including vegetation and rocks attenuate wind erosion (Zobeck 1991; Zhu et al. 2020; Webb et al. 2020) and their effects on wind erosion have been the subject of extensive research (e.g., Raupach et al. 1993; Batt & Peabody 1999; Chappell & Webb 2016; Miri et al. 2019; Pi et al. 2023). Vegetation has a significant effect on reducing wind speed and trapping soil particles, as shown in a number of studies conducted in wind tunnels (Youssef et al. 2012; Hagen & Casada 2013; Suter-Burri et al. 2013; Hong et al. 2016; Walter et al. 2017; Liu et al. 2021; Ziegler et al. 2023). The significant influence of vegetation in terms of protection from wind erosion is highlighted by King & Nickling (2005); Grantham et al. (2001); Youssef et al. (2012).

Although wind erosion is mainly a problem on sandy soils, it also affects clay soils. This phenomenon has been approached from different angles by a number of authors (Skidmore et al. 1994; Stout & Zobeck 1996; Bullock et al. 2001; Stout 2007; Kučera & Podhrázská 2016; Pi et al. 2020). In general, such soils have less macropores, a high sorption capacity and therefore lower water permeability and overall aeration, resulting in they are experiencing a double extreme – excess water concentrates at the surface and causes its waterlogging; a lack of water, on the other hand, causes the surface to harden and crack and crust. Crust formation reduces roughness and wind erosion (Singer & Shainberg 2004). Bullock et al. (2001) documented an increase in the erodible fraction of clay loam soils by up to 25% after winter and spring. The greatest change in erodibility occurred when intermittent snowmelt increased water content and enhanced the disintegration of aggregates in the freeze-thaw cycle. As the soil's anti-erosion properties are fundamentally affected by the processes of freezing and thawing, Středová et al. (2015) list studies dealing with this phenomenon. Lackóová et al. (2015) note that erodibility is primarily influenced by soil particle size, while differences in particle shape have little effect. Soils with higher clay content may be more susceptible to wind erosion under the specific course of winter weather (Chepil 1953, 1954; Hinman & Bisal 1967; Skidmore & Layton 1992; Sahin & Anapali 2007; Dagesse 2013, etc.).

As far as the actual investigation of soil aggregates is concerned, the percentage distribution of erodible fraction (EF) and non-erodible fraction (NEF) can be determined by aggregate analysis by sieving air-dried soil sample, as applied even decades ago by Chepil (1962). Soil particles above 0.84 mm are considered by most authors to be non-erodible (Chepil 1953; Hinman & Bisal 1967; Tatarko 2001). However, in a study of wind erosion on clay soils in the southeast of the Czech Republic, Švehlík (1990) found that in the case of strong desiccating winds, even soil particles larger than 2 mm, sometimes as large as 4 mm, can be transported. For such specific cases, it is, therefore, necessary to shift the limit of non-erodible soil particles to 2 mm, as used, e.g. in the study by Kozlovsky Dufková and Podhrázská (2011) and Kozlovsky Dufková et al. (2021). Contributing to the significance of wind erosion in the Czech Republic is the vast size of its fields, with the average farm comprising 133 hectares of agricultural land, in contrast to the EU average of 16.1 hectares (Stašek et al. 2023). Středová et al. (2015) developed a method for estimating the potential risk of wind erosion on clay soils, which takes into account the influence of specific meteorological conditions in winter on the breakdown of soil aggregates.

Main objective of the paper was: (*i*) to assess the impact of the winter season on the formation of EF (NEF) before and after the winter season (Hypothesis H1: Significant changes occur in soil aggregate stability, leading to the creation of erodible fractions before and after the winter season, indicating an impact of winter conditions on soil erosion susceptibility; (*ii*) to investigate the influence of vegetation on EF (NEF) in the spring (Hypothesis H2: Significant differences exist in soil aggregate stability and the breakdown of erodible fractions between areas with and without vegetation, suggesting the influence of vegetation on soil erosion dynamics).

MATERIAL AND METHODS

Area of interest. A starting point for our survey was a regionalization of clay soil susceptibility to wind

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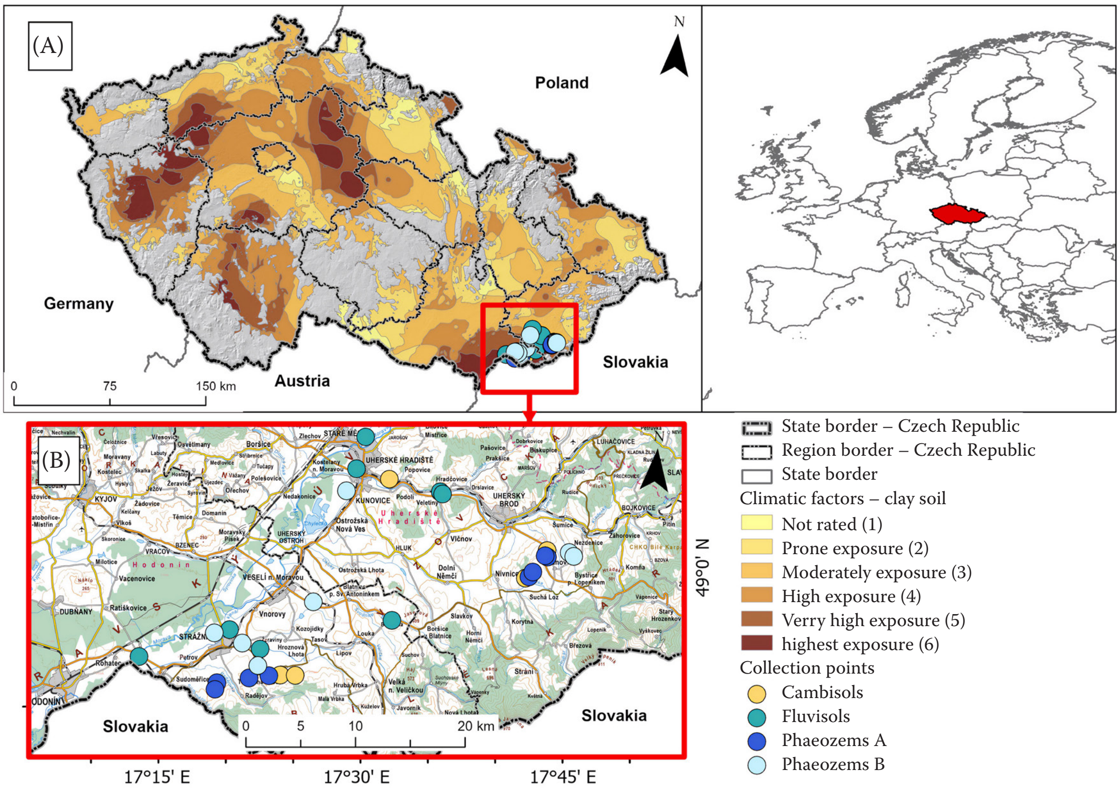

Figure 1. Map of the potential risk of clay soils to wind erosion based on meteorological conditions in winter (Podhrázská et al. 2014) with collection points (A), detailed section of the map with collection points (B)

erosion (Podhrázská et al. 2014) based on relevant winter/early-spring meteorological conditions (i.e. the number of freeze-thaw episodes and the specific state of bare soil surface affected by rain, frost and snow cover parameters – dealt in detail by Středová et al. 2015). The resulting map distinguishes 6 categories of risk (1 = lowest risk, 6 = highest risk). Winter breakdown of clay soil aggregates was investigated in the area of southern Moravia belonging to high-risk categories 4 to 6 (Figure 1) with strong repeated manifestations of wind erosion which were historically documented by Hrádek and Švehlík (1993) (Figure 2) and recently observed by authors themself (Figure 3). During this erosion event, soil samples were collected in a trench near the affected field. An image analysis of the soil aggregates using digital microscope revealed the sizes of the eroded soil aggregates (Figure 4).

Figure 2. Spindle-shaped drifts transitioning into a road ditch covered by soil eroded by wind (Bánov 1990) – left; and spindle-shaped drifts with a pronounced ridge (Bánov 1990) – right (Švehlík 2002)

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Figure 3. An erosion event on clay soils recorded by authors: road ditch covered by soil eroded by wind near Suchá Loz village (spring 2020)

The area of interest, geologically belonging to the outer Western Carpathians, lies in the flysch zone of the Magura flysch escarpment. Climatologically, it is one of the driest areas of the Czech Republic, with the maximum rainfall in summer (mostly in July) and the minimum in winter – the sum of precipitation in winter is 200–300 mm (Voženílek & Květoň 2011). The wind speed and direction depend on the local terrain morphology, with the north-easterly flow prevailing and increasing in frequency in summer. With south-easterly to southerly flow, a downward component of the flow with fan effect may occur in spring. These dry and warm winds are responsible for strong erosion and subsequent deposition of fine soil particles (up to several tenths of meter high) especially at the foot of various barriers. These phenomena have occurred regularly in the area for decades (Figure 2 and 3)

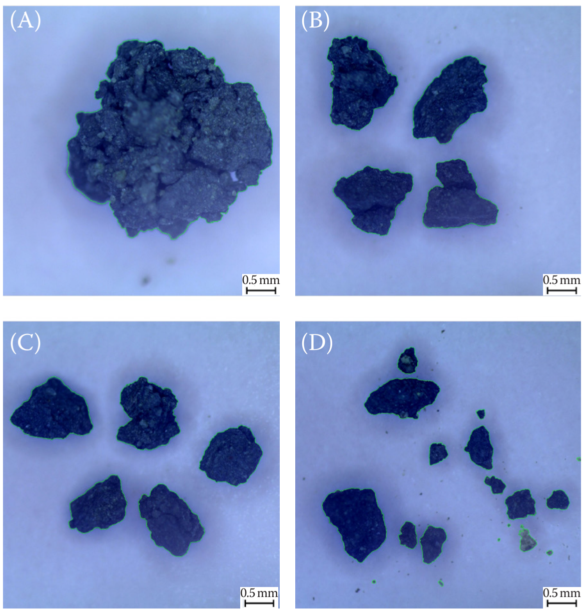

Figure 4. Samples of soil aggregates of different sizes taken from wind erosion drifts in spring 2020: 3.40 mm (A), 1.22–1.68 mm (B), 1.08–1.31 mm (C), 0.15–1.21 mm (D)

Figure 4 documents the size of particles entrained by an automatic deflameter during the erosion event in spring 2020 (Figure 3). Photographs were processed with an Olympus SZ digital microscope (SZ61TR, Olympus, Japan) with an infinity sensor 1 (0.5 mm scale) and analysed by the digital microscope. In the single parts of Figure 4, the soil aggregate/deflate diameter was shown: part A – 3.40 mm, part B – from 1.22 mm to 1.68 mm, part C – from 1.08 mm to 1.31 mm and part D – from 0.15 mm to 1.21 mm.

Within the area given by Figure 1A, choice of the collecting points for laboratory analyses respected three key parameters: (1) high content of clay particles in the top layer of the soil profile (so primarily clay, silty clay, clay loam and silty clay loam texture classes, based on detailed and up-to-date pedological maps based on the national agro-genetic classification system and subsequent field survey), (2) agricultural arable land and (3) certain degradation caused solely by wind erosion (Figure 1A).

Soils of individual collecting points were analysed (e.g. soil texture classes, Figure 5), classified and aggregated into three groups according to IUSS Working Group WRB (2022), respecting also national classification systems (agro-genetic and morfo-genetic):

(1) Phaeozems group: all local deep humic soils with a dark sorptive saturated diagnostic mollic horizon without significant skeleton and secondary carbonates. Due to specific criteria in the soil

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classification systems of the Czech Republic, this group was divided into two categories:

Phaeozems A: soils developed on unconsolidated clay substrates without a significant manifestation of hydromorphism. Here typically Haplic Phaeozem (Loamic), Vertic Phaeozem (Clayic) or Endostagnic Phaeozem (Clayic).

Phaeozems B: soils linked to depressional positions of category (A) with a higher degree of hydromorphism (often prone to waterlogging and acquire up to the principal qualifier Gleyic) and higher content of organic carbon; they have the character of alluvial sediments, i.e. Stagnic Phaeozem (Loamic), Endogleyic Stagnic Phaeozem (Loamic) or Gleyic Phaeozem (Clayic).

(2) Fluvisols group: soils of flat plain areas along the watercourse (Morava), formed by fluvial sediments. The diagnostic feature is the layered soil profile with an irregular distribution of organic carbon. They are mostly skeletonless and tending to temporary waterlogging of the surface. E.g. Stagnic Fluvisol (Loamic) and Endogleyic Stagnic Fluvisol (Loamic).

(3) Cambisols group: clay soils on polygenetic clays and weathered carbonate-silicate rocks (typically Lower Cenozoic claystones and marl claystones). They can also be skeletonless, but more often skeletal (25–50 Vol. %), i.e Eutric Skeletic Cambisol (Clayic), Eutric Cambisol (Clayic) or Eutric Stagnic Cambisol (Loamic).

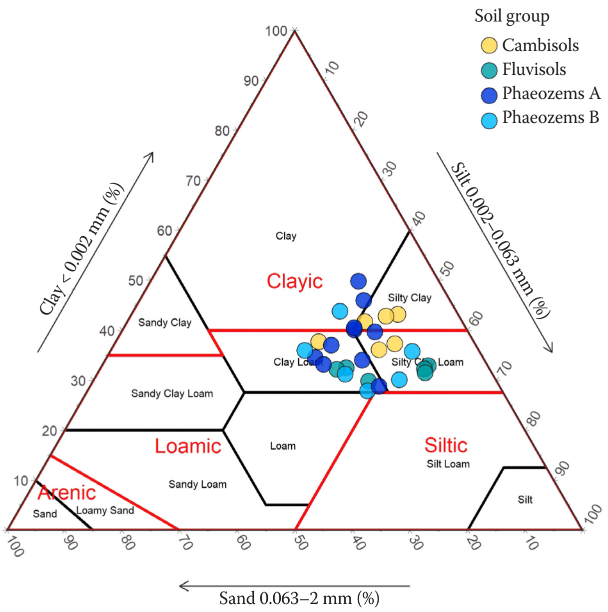

Figure 5. Grain size assignment of soil samples in the soil texture triangle diagram

Each group was represented by 6 collection points; only for Phaeohzems A there were 4 more points (10 in total) as they are the soils of the highest quality from this selection.

Field sampling and laboratory analyses. According to Bisal and Ferguson (1968), López et al. (2007), and Fryrear et al. (2000) the erodibility limit for clay soils is 0.84 mm (sieve of 0.84 mm is being standardly used for extraction of EF/NEF) and if the topsoil contains less than 40% NEF it is rated as highly susceptible to wind erosion. From historical experience (Figure 2) as well as more recent observations (Figures 3 and 4 where we have identified soil aggregates transported by wind bigger than 2.00 mm), aggregate analysis was performed not only for generally acknowledged NEF ≥ 0.84 mm (Lopez et al. 2007 and Borrelli et al. 2016), but also for NEF ≥ 2.00 mm.

Soil samples were taken in the season 2014/2015 to 2020/2021 after the field cultivation in the autumn and before the field cultivation in the spring from a flat, smooth soil surface (up to a maximum of 2.5 cm depth) with a distinguishing between sampling from bare soil or soil with vegetation (i.e. winter cereals or intercrops). An assumed total number of samples was 336 (28 sites/6 years/2 periods). In the end, due to technical issues, the number was 13 lower (i.e. 323). 172 samples represented the variant without vegetation and 151 with vegetation. For the air-dried samples, dry aggregate analysis (López et al. 2007) was then performed in three replicates (200 g) using an AS 200 Retsch electromagnetic vibratory sieving machine (Retsch, Germany) with a duration of 5 min.

RESULTS AND DISCUSION

Aggregate analyses were graphically evaluated by boxplots (Figures 6 and 7), presenting a percentage NEF for mesh size of 0.84 mm ($NEF_{0.84}$) and 2.00 mm ($NEF_{2.00}$) in autumn and spring regardless of vegetation across all measurements (i.e. all years and all collection points). If we set the autumn values as 100%, we can relate them to the over-winter change (autumn–spring) in order to get winter efficiency on NEF formation.

$$\text{Winter efficiency (\%)} = (NEF_A - NEF_S) \times 100/NEF_A$$

where:

NEF_A – non erodible fraction in autumn (%);

NEF_S – non erodible fraction in spring (%).

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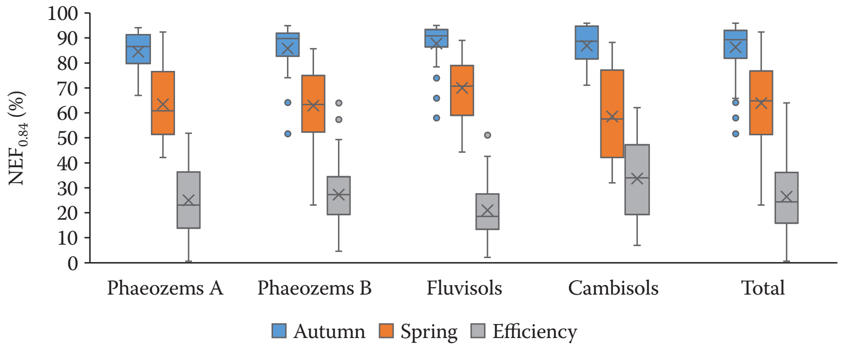

Figure 6. Percentage of non-erodible fraction for mesh size of 0.84 mm ($NEF_{0.84}$) in autumn and spring and winter efficiency (regardless vegetation)

Figure 6 shows that the threshold of 40% $NEF_{0.84}$ was exceeded in the autumn for all soil groups and $NEF_{0.84}$ ranged between 80 and 95%, indicating significant resistance to wind erosion. In the spring, the values still exceeded 40% of $NEF_{0.84}$ with their average content around 65%. Winter efficiency on $NEF_{0.84}$ formation was around 24%.

Although the obtained results showed a negative influence of the winter on the presence of $NEF_{0.84}$ and thus a greater susceptibility to wind erosion in the spring, they did not exceed the threshold of 40% of $NEF_{0.84}$ and winter efficiency remains quite low (i.e around 20% in average). Nevertheless, an analysis of $NEF_{2.00}$ (Figure 7) showed that autumn's content of $NEF_{2.00}$ for all soil groups exceeded 40%, ranging between 60 and 70%, indicating a significant resistance to wind erosion. However, spring values of $NEF_{2.00}$ were well below the 40% threshold (8 to 35%), indicating considerable susceptibility to wind erosion and confirming the contribution of water, frost and thaw to the breakdown of wind transported soil aggregates as reported by (Tatarko et al. 2001; Skvortsova et al. 2018). The average winter efficiency was 72%. The obtained results showed a significant negative influence of the winter on the presence of $NEF_{2.00}$ and, thus, a greater susceptibility to wind erosion in the spring period compared to $NEF_{0.84}$.

By comparing a winter efficiency on NEF formation for both NEF thresholds 2.00 and 0.84 it is apparent that even though in both cases the effect of winter on NEF formation was proven across all soil types, it is more apparent for $NEF_{2.00}$ as it was in average 3.5 higher than in case of $NEF_{0.84}$ (Figures 8 and 9). Real wind erosive event on clay soil in the area of interest, illustrates significant changes in the course of winter meteorological conditions with the possibility of relevance to the disintegration of soil aggregates. These changes also depend on the occurrence of snow cover, which should be shorter in Central Europe in the future (Lukasová et al. 2020; Středová et al. 2024). Most climate models have predicted changes in the timing, magnitude, and duration of snow cover in the Northern Hemisphere (Brown & DeGaetano 2011; McCabe et al. 2015). Loss of insulation provided by snow cover can reduce minimum soil temperatures, modify the frequency of freeze-thaw cycles (Decker et al. 2003; Ruan & Robertson 2017), and alter the number of days that soils are frozen each year (Sinha & Cherkauer 2010; Rittenhouse & Rissman 2015), while these effects can be modified by vegetation. Vegetation cover can protect the soil from changes in air temperature, freezing and thawing cycles. This effect can reduce the increase in the erodible fraction during the winter period (Boswell et al. 2020).

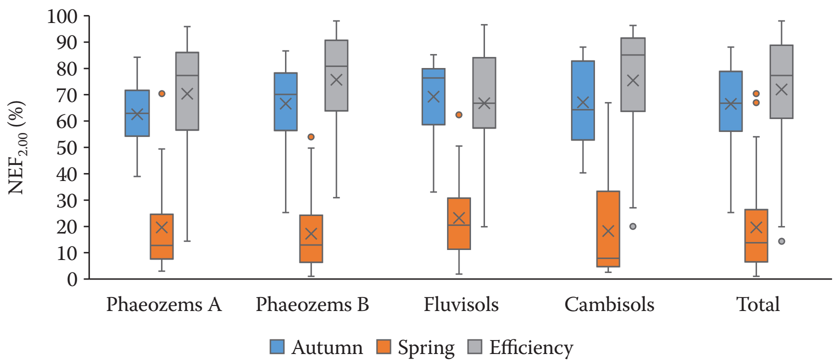

Figure 7. Percentage of non-erodible fraction for mesh size of 2.00 mm ($NEF_{2.00}$) in autumn and in spring and winter efficiency (regardless vegetation)

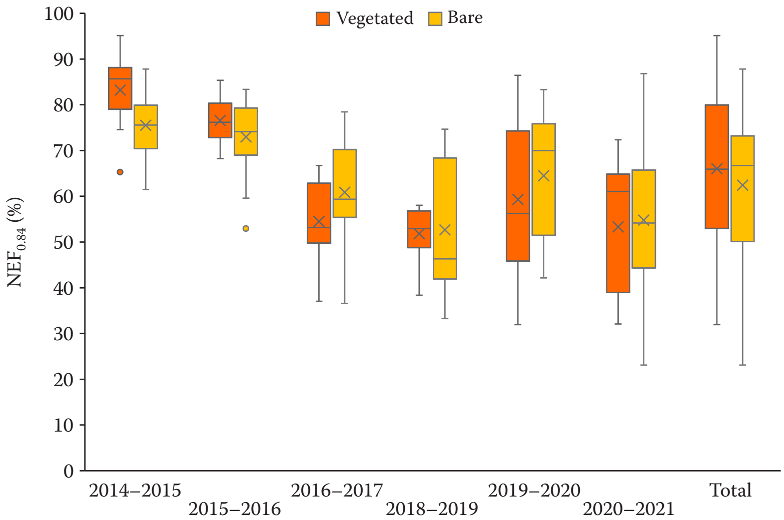

Figure 8. Percentage of non-erodible fraction for mesh size of 0.84 mm ($NEF_{0.84}$) in spring for evaluated periods with and without vegetation

The boxplots in Figures 8 to 10 show a spring percentage of NEF with respect to the presence of vegetation (with/without). Figures 8 and 9 go across all soil groups and show that an average $NEF_{0.84}$ with vegetation was 66% and without 62%, indicating negligible effect of vegetation of $NEF_{0.84}$ formation (Figure 8). However, $NEF_{2.00}$ with vegetation was 25% while without just 15%, suggesting a significant effect of vegetation on $NEF_{2.00}$ formation (Figure 9).

The effect of vegetation on $NEF_{2.00}$ formation in individual soil group is described in Figure 10. If we set values with vegetation equal to 100%, we can relate difference between variants (with – without vegetation) to them in order to describe the efficiency of vegetation on NEF formation.

Vegetation efficiency (%) = $(NEF_W - NEF_{NO}) \times 100\ NEF_W$

where:

NEF_W – non erodible fraction with vegetation (%);

NEF_{NO} – non erodible fraction without vegetation (%).

Vegetation efficiency above 0% means higher content of NEF in variant with vegetation (i.e. its higher efficiency). This attitude has statistical relevance only for pairs of measurement carried out at the same time and at the same collection point. Due to limited data, the efficiency for Fluvisoils and Cambisols is disputable. However, the total average vegetation efficiency on $NEF_{2.00}$ is 21% (total median is 28%), while for Phaeozoms A and B, it reaches even 31% (median is 36%) for the former and 43 (median is 62%) for the latter. It should not be concisely taken for correlation between soil type and state of vegetation, but rather as evidence of inner variability of clay soil types (e.g. degree of hydromorphism, etc.).

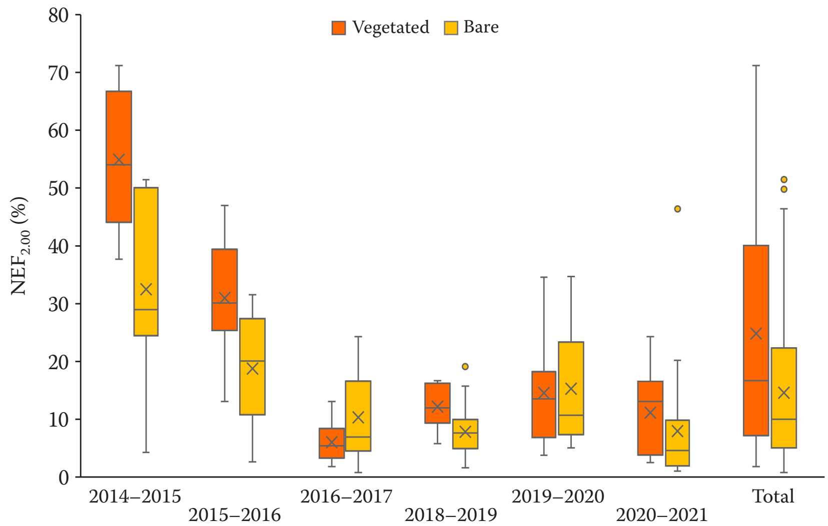

Figure 9. Percentage of non-erodible fraction for mesh size of 2.00 mm ($NEF_{2.00}$) in spring for evaluated periods with and without vegetation

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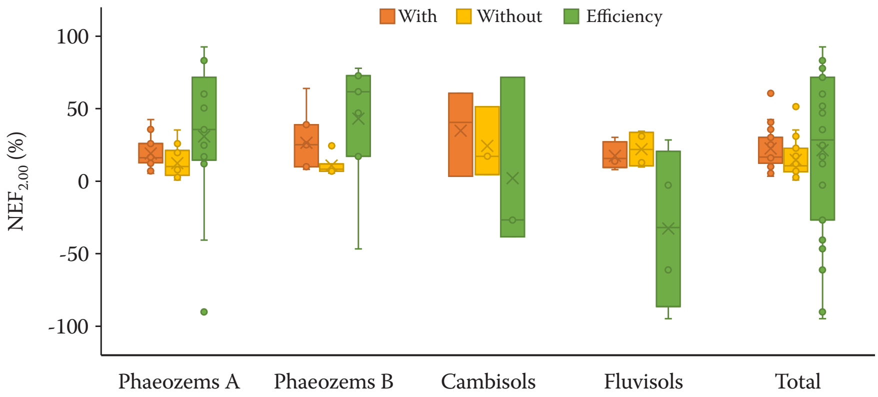

Figure 10. Percentage of non-erodible fraction for mesh size of 2.00 mm ($NEF_{2.00}$) in spring and vegetation efficiency

Our results thus document the positive effect of vegetation on the presence of $NEF_{2.00,}$ as visually captured in Figure 10. Nevertheless, it is important to contextualize these findings within the broader understanding of soil stability dynamics. Cerda (1996) posits that while vegetation does play a role, its influence may be relatively minor compared to lithology, and he also discusses various effects of soil depth and moisture. Their conclusion underscores the complexity of soil aggregate stability, which emerges from a nexus of factors including vegetation, lithology, water content, and depth, among others. An example of fields without vegetation in the spring season of interest is given in Figure 11.

Figure 12 brings a comprehensive analysis of $NEF_{0.84}$ and $NEF_{2.00}$, taking into account presence of vegetation. This analysis presents specific issues related to the clay soils erodibility assessment. If the erodibility is evaluated using the standard 0.84 mm sieve, the $NEF_{0.84}$ always exceeds 40% threshold (regardless vegetation) and thus the soils are classified as non-threatened.

However, repeated erosion events on these soils with evidence of wind-transported aggregates bigger than 2 mm justified the use of a 2.00 mm sieve to assess erodibility. If the erodibility is evaluated using a 2.00 sieve, the $NEF_{2.00}$ was always well below the 40% threshold (regardless of vegetation), and thus, the soils are classified as threatened.

Our study was designed to show the effect of winter conditions on soil susceptibility to wind erosion in spring. Bullock et al. (2001) states that winter soil properties affecting wind erodibility are highly transient and the timing and form of precipitation play a significant role in determining wind erosion risk.

CONCLUSION

– Winter breakdown of clay soil with subsequent repeated manifestations of wind erosion affects southern Moravia, belonging to the high-risk category in terms of susceptibility to wind erosion.

Figure 11. Fields without vegetation in spring

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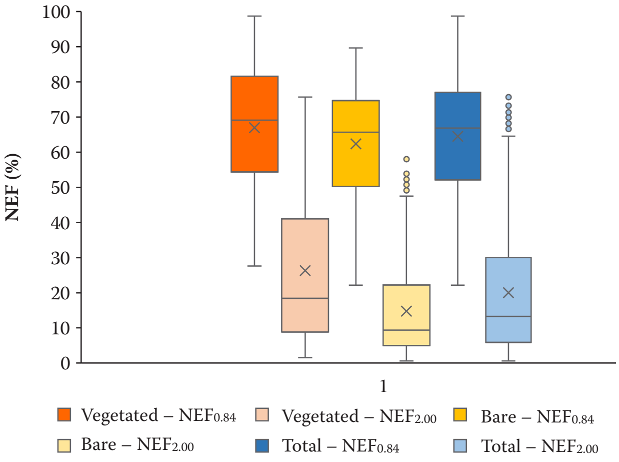

Figure 12. The overall analysis of non-erodible fraction for mesh size of 0.84 mm ($NEF_{0.84}$) and NEF for mesh size of 2.00 mm ($NEF_{2.00}$), taking into account the presence of vegetation

– As the digital microscope revealed sizes of the eroded soil aggregates bigger than 2.00 mm, we conducted aggregate analysis for generally acknowledged $NEF_{0.84}$ and for $NEF_{2.00}$.
– Our results documented the negative effect of winter on EF/NEF of clay soils. Therefore, the increase in the erodible fraction confirms the hypothesis H1.
– The results showed a significant negative influence of the winter on the presence of $NEF_{2.00}$ and, thus, a greater susceptibility to wind erosion in the spring period compared to $NEF_{0.84}$.
– Analysis of spring (i.e. after winter) erodibility revealed a negligible effect on vegetation in terms of $NEF_{0.84}$. However, in the case of $NEF_{2.00}$, there was a significant effect of vegetation on soil erodibility. However, for a more significant confirmation of hypothesis H2, it would be useful to conduct further in-depth analysis on a larger dataset that would include information from detailed monitoring of stand condition, tillage dates or agrotechniques used in the areas of interest. Comprehensive analysis of $NEF_{0.84}$ and $NEF_{2.00}$ proved that $NEF_{0.84}$ always exceeds the 40% threshold, and thus, the soils are non-threatened, while $NEF_{2.00}$ was always well below the 40% threshold, and thus, the soils are threatened.
– These findings advocate for the implementation of anti-erosion measures in areas with clay soils of varied textures, with vegetation establishment emerging as a promising strategy.
– From a practical standpoint, our results contribute as a supplementary module to the evolving framework of "The Road Map to Classify the Potential Risk of Wind Erosion" (Středová et al. 2021). As part of a broader scientific effort, our findings offer valuable insights to inform landscape management practices, aiding governmental agencies in effective land conservation.

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