

Quantifying soil losses and dust emissions by wind tunnel experiments in the cultivated steppe of Kazakhstan

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Abstract. Expanding agriculture and unsustainable farming practices in Central Asia's steppes may increase the risk of wind erosion and severe dust emissions. However, empirical data from field experiments to assess a potential severe dust source is lacking. Therefore, a mobile wind tunnel was used in northern Kazakhstan to investigate the potential wind-induced soil loss and dust emissions under real field conditions common in agricultural practices. Field experiments were carried out on typical surfaces that act as dust sources: seedbeds as they occur after cultivation, in-field tracks, and dirt roads. Measurements were conducted by sediment collection of total eroded material and optical particle counting for particulate matter $\leq 30 \mu\text{m}$. The results of the wind tunnel experiments show that the same soil can emit significantly different amounts of dust depending on the mechanical stress to which the soil was previously exposed. Soil loss and dust emissions increased from seedbeds to dirt roads due to the intensifying effect of pulverization by tires. In order to assess an area as a dust source or for emission inventories, the total emissions must be adjusted separately to these shares. Further insights of the field experiments will be presented at the conference.

1 Introduction

Arid environments are major dust sources globally. However, the role of the surrounding semi-arid regions needs special consideration, especially where human intervention in the form of agriculture takes place. Examples from the past show that former dust sinks could turn into major dust sources by cultivation [1-2]. Multiple natural and anthropogenic factors, including extensive steppe conversion, unsustainable farming practices, and severe drought, caused devastating soil erosion on 20–40 million hectares in the Great Plains of the USA, known as the Dust Bowl era (1935-1938) [3]. Currently, the cultivated steppes of Central Asia are challenged by increasing soil erosion due to extreme climate conditions and unsustainable farming practices [4-5]. The risk potential is reinforced as climate models indicate an increase in the natural factors promoting wind erosion, such as higher temperatures and changes in precipitation patterns [6-7]. Northern Kazakhstan, in particular, faces an increasing risk of soil degradation as it comprises Central Asia's most extensive areas of arable land. As part of the Virgin Lands Campaign, it has been under agricultural management since the 1950s. Large areas of arable land were abandoned after the collapse of the Soviet Union in 1991, but recent steppe conversion is expanding cropland again [8-9]. Hence, more soil is exposed to wind erosion, and cascading effects that could cause severe dust storms are possible [10].

Reliable tools and methods to assess the potential risk of wind erosion and dust emissions in the semi-arid steppe regions of Central Asia are lacking [11-12]. In particular, empirical data sets derived from field measurements are needed to provide in-depth knowledge of aeolian drivers and processes. In this study, field experiments with a mobile wind tunnel were conducted to assess soil loss and dust emissions by the wind on surfaces that are typical in the cultivated steppe of Kazakhstan. The main objective of this study is to quantify soil losses and dust emissions from common wind-exposed surfaces: seedbeds as they occur after cultivation, in-field tracks, as well as dirt roads between fields.

2 Materials and methods

2.1 Study area

The study area in the northeastern part of Central Asia is part of the Eurasian steppe. The test site is in northern Kazakhstan, north of Astana (Fig. 1). The climate is continental, with hot and dry summers (semi-arid). The annual mean temperature is 3.3 °C, and the annual precipitation is 328.4 mm (based on weighted interpolation 1991–2020) [13]. Still, most of the annual precipitation occurs as snowfall. The study area consistently experiences wind, reaching its peak speeds during winter and spring. Wind gusts can even exceed

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40 m s⁻¹ [14]. The dominant soil types in the dry steppe of Kazakhstan are fertile Chernozems and associated Kastanozems with silty and sandy textures. Overall, the area of interest is prone to wind erosion due to the area's parent material, climate, and land use [15].



Fig. 1. Location of test site in northern Kazakhstan and climate classes in Central Asia [16].

2.2 On-farm experimentation

This on-farm experiment was designed to study wind erosion processes and quantify soil loss under typical conditions that are present in the cultivated steppe. The experiments were conducted with a mobile boundary layer wind tunnel, which allows us to investigate aeolian processes under real soil conditions [17]. The mobile wind tunnel consists of an axial fan, a diesel generator that provides electric power, a 5-m long flexible hose that leads the air stream to a flow straightener, and a measurement section consisting of six single segments (height = 0.8 m, width = 0.8 m, total length = 6.0 m) placed over an open surface area of 4.8 m² (Fig. 2). Further description of the mobile wind tunnel and its properties, including logarithmic profiles and Froude criterion, are described by Koza et al. [18].

Wind tunnel experiments were conducted in June 2023 with a steady wind of a mean velocity of 15 m s⁻¹ for 15 minutes on different surface conditions, reaching from typical seedbeds (S) to in-field tracks (T) and dirt roads (D) under dry conditions. Seedbed surfaces with a light crust and some loose aggregates (S1) and with rough clods and straw residues (S2) were investigated. The in-field tracks covered a tractor track, also known as tramline (T1) and light furrows (T2). Dirt roads include, besides the passing lane (D1), the main lane itself (D2) (Fig. 3).

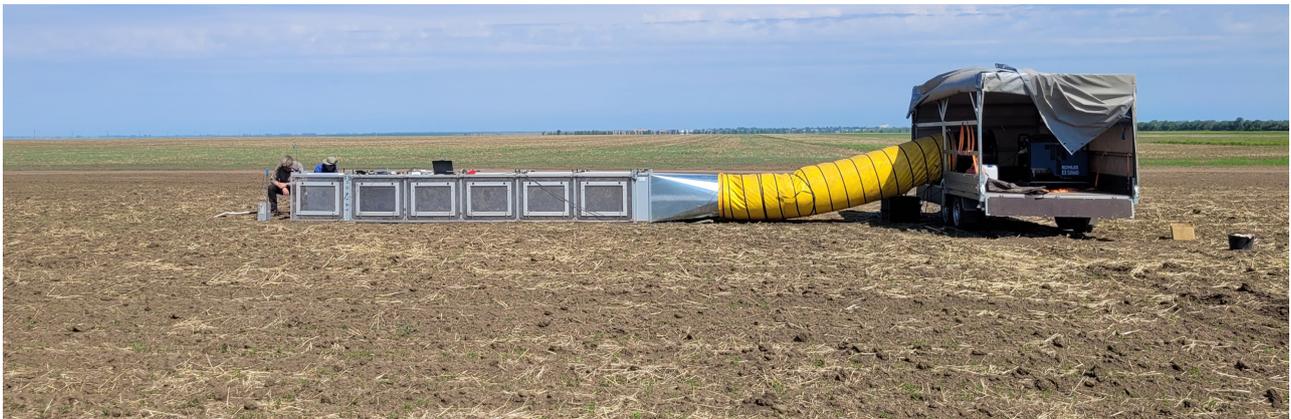


Fig. 2. Field measurement with a mobile wind tunnel on a seedbed surface with clods and straw residues.



Fig. 3. Common surface types that are present in the cultivated steppe of Kazakhstan (above) with aligning roughnesses (below): seedbed with light crust (S1), seedbed with clods and straw residues (S2), in-field tractor tire tracks (T1), light in-field furrow tracks (T2), passing lane of dirt road (D1) and main lane of dirt road (D2). An estimated area of 0.75 m² is shown for each surface.

In order to collect eroded material, Modified Wilson and Cooke (MWAC) samplers were installed at the ground level and attached to a pole at 0.05, 0.1, and 0.3 m height. The sediment mass collected in the MWAC samplers is related to the sampler's inlet surface area and the surface area inside the mobile wind tunnel. The soil loss was then derived from semi-logarithmic regression by fitting the total mass of caught sediments (q_z) at the height (z) to $\ln(z)$ [18-19]. Fine dust emissions ($\leq 30 \mu\text{m}$) in suspension mode were measured with an optical particle counter at 0.2 m height.

Topsoil samples were collected from the surface up to 10 mm depth before each experiment. Soils were identified as silt loam (sand = 9%; silt = 78%, clay = 13%; USDA soil taxonomy) derived from laser diffraction analyses. The soil's organic carbon content measured by dry combustion at 1130 °C was 28 g kg⁻¹. The pH was 7.8, and the electrical conductivity was 225 $\mu\text{S cm}^{-1}$ (measured in distilled water at a 1-to-2.5 soil-to-solution ratio). Additionally, the dry aggregate size distribution of the topsoil from each surface and the organic carbon content of the eroded material were measured.

3 Results and discussion

The wind tunnel experiments showed great differences between seedbeds and dirt roads. The lowest soil losses were measured on S1 (54 g m⁻²) and S2 (93 g m⁻²). Soil losses on the dirt road were a multiple higher. Soil loss on the primarily used lane of the dirt road was 7814 g m⁻², and on the passing lane of the dirt road, 3351 g m⁻². The soil losses of the in-field tracks were lower than on the dirt road but not as low as on the seedbeds (T1 = 861 g m⁻²; T2 = 1552 g m⁻²). Overall results of the MWACs showed an increased soil loss from seedbeds over in-field tracks to dirt roads caused by the disruption of aggregates due to mechanical stress by tires (Fig. 4A).

The derived soil losses are supported by the dust emission measurements. While soil loss by saltation continuously increases from seedbed to dirt road, the dust emissions by suspension vary, and there is one outlier (Fig. 4B). Comparing soil losses derived from collected sediments and measured dust emissions shows a good agreement ($R^2 = 0.92$) (Fig. 5).

The highest PM₁₀ emissions are calculated on the main lane of the dirt road (D2 = 497210 $\mu\text{g m}^{-3}$) and the lowest on the seedbed with the light crust (S1 = 12008 $\mu\text{g m}^{-3}$). The development over time of the PM₁₀ emissions shows that the destruction of the aggregate structure leads to persistently higher emissions from dirt roads. The PM₁₀ emissions from the tractor tracks in the field reach those of the crusted surface after 15 minutes. Hence, the strong destruction only occurs at the surface layer, and under these conditions, the emissions of both surfaces become similar after the top layer has been blown off (Fig. 6).

An expected relationship between particle loss and dry aggregate size distribution was present. The ratio of soil organic carbon of the aeolian sediments collected with MWACs to the soil organic carbon content of the

topsoil was ~ 1 . Hence, there was no soil organic carbon enrichment in the eroded material.

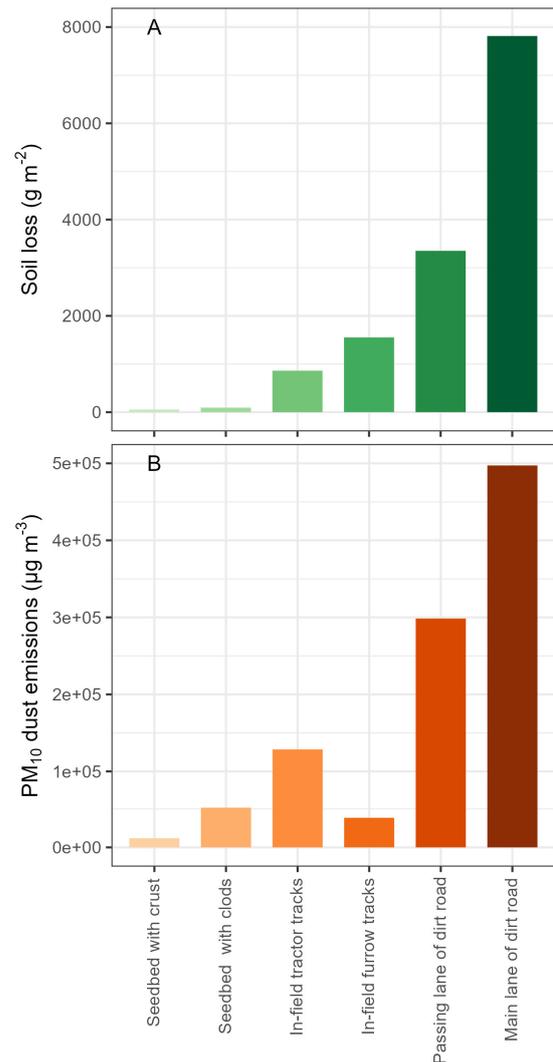


Fig. 4. Soil loss (A) and dust emissions (B) derived from wind tunnel experiments on typical surfaces in northern Kazakhstan.

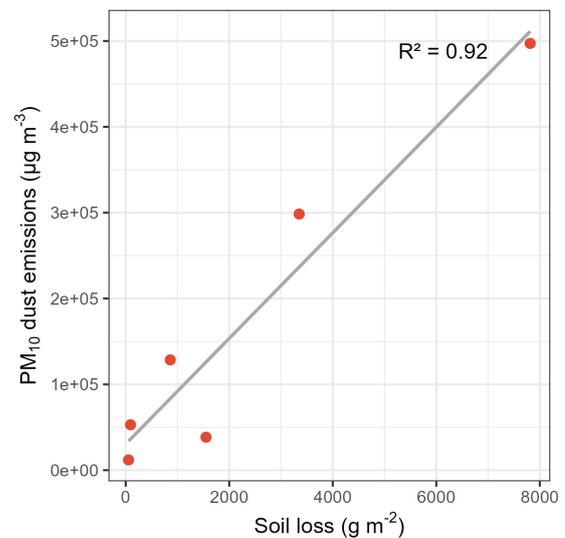


Fig. 5. Scatterplot comparing soil loss collected by MWACs and PM₁₀ dust emissions measured with an optical particle counter during wind tunnel experiments.

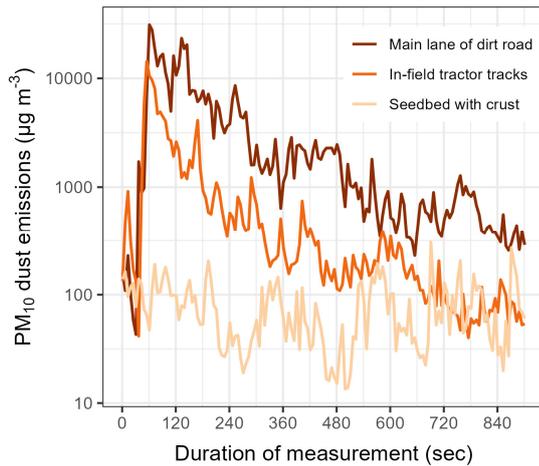


Fig. 6. Development over time of PM₁₀ emissions at constant wind speed over 15 minutes with a time interval of six seconds. Please note the logarithmic scale on the ordinate.

The results of the experiments are consistent with field observations of the emission potentials of various surfaces in the study area. The findings of the wind tunnel experiment indicate a serious risk of wind erosion and dust emissions after steppe conversion. In particular, the crushing of soil clods by tires under dry conditions is a key contributor to particle loss with effects on local and regional scales. While seedbeds occupy most of the area of arable land, in-field tracks cover an estimated 14% of each field (working width of seedbed preparation = 10 m, width of tractor's rear tires = 1.42 m). Additionally, linear dirt roads between fields can act as preferential flow paths for wind and flushes of entrained dust due to missing obstacles and a very low surface roughness that breaks and decelerates the airflow. However, the presence, characteristics, and traffic intensity of dirt roads vary throughout the study area.

An important step in the overall consideration of wind erosion susceptibility is to incorporate these aspects into the design of agricultural systems. Measures to prevent the destruction of dry aggregates include taking soil moisture into account during agricultural practices, such as the timing of sowing, the temporal variations during the day, and the variability in tillage depth. Building and maintaining paved roads could prevent dust emissions from dirt roads.

The development of agricultural land as a variable but possibly increasing source of dust should be closely monitored. While general emissions from arable surfaces are highly unclear, climate and land use change contribute even greater uncertainty to their assessment. Consequently, the evaluation of agricultural soils from this particularly vulnerable region is crucial for the reliable estimation of global dust emissions. This evaluation must include ground-based measurements because these data are not only necessary for the investigation and quantification of Central Asian dust source regions, but also for the development and implementation of conservative and sustainable land use practices.

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