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A cross-comparison of threshold friction velocities for PM₁₀ emissions between a traditional portable straight-line wind tunnel and PI-SWERL

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ABSTRACT

Experiments in large wind tunnels have made vital contributions to our knowledge of aeolian processes. However, the size of these instruments makes them impractical for field application. To facilitate field measurements on the dust emission potential of soils, the Portable In-Situ Wind Erosion Lab (PI-SWERL) was developed. Previous research shows that the PI-SWERL can be used to quantify dust emission potentials and (threshold) friction velocities. Studies that compare the PI-SWERL to traditional wind tunnels mainly focus on the dust emission potential at various friction velocities. In the present study, we quantified the threshold friction velocity for PM₁₀ emission using a PI-SWERL and compare it to results obtained with a straight-line wind tunnel: the Portable Wind and Rainfall Simulator of the University of Basel (PWRS). Tests were performed on two types of substrate: fine sand (NS1) and loamy sand (DS1). For NS1, a threshold friction velocity of 0.33 m s⁻¹ was identified from both the PI-SWERL and the PWRS data. For DS1, identified threshold friction velocities showed differences: 0.25 m s⁻¹ by the PI-SWERL and 0.39 m s⁻¹ by the PWRS. The position of the DustTrak II monitor's inlet tube and variations of the fan's speed by different operators could explain the difference in identified thresholds. Although different threshold friction velocities were obtained for one of the substrates, we believe that comparable results can be achieved by adjusting the experimental design in future research. Therefore, the PI-SWERL can be successfully used to quantify thresholds, facilitating dust emission studies in more remote regions.

1. Introduction

Wind erosion occurs in a large variety of (semi-)arid areas around the globe, and is initiated when the wind exceeds the critical velocity for particle entrainment. This threshold friction velocity is influenced by multiple factors, such as vegetation cover, presence of soil aggregates, and soil moisture (Shao and Lu, 2000; Fécan et al., 1999). Saltation fluxes and dust emission quantities in a specific region are dependent on the threshold friction velocity (Kok et al., 2014). Estimates of threshold values from various soil surfaces are required as input data in most dust emission models. To limit uncertainties in threshold friction velocity data, large quantities of local data are required (Li and Zhang, 2011). Generally, most of these data are collected using large field wind tunnels.

Much of our understanding of aeolian processes, and the susceptibility of a soil to wind erosion, comes from the outcomes of wind tunnel experiments (Van Pelt and Zobeck, 2013). Traditionally, friction

velocities and dust emissions have been quantified in experiments with different types of wind tunnels (e.g., Bagnold, 1941; Gillette, 1988; Shao et al., 1993; Roney and White, 2006). A distinction can be made between small wind tunnels with lengths up to 3.5 m, and large wind tunnels that are above 4 m long (Raupach and Leys, 1990). Large wind tunnels are often preferred for studying aeolian processes, as their properties enable simulation of a more realistic, natural atmospheric boundary layer (White and Mounla, 1991). However, the wind tunnel's size results in several practical disadvantages. Large wind tunnels are relatively heavy, making them less suitable for application in regions with low accessibility and thus limit their overall benefits. In addition, the instrument's size requires relatively large areas of flat terrain to collect accurate measurements (Sweeney et al., 2008). Furthermore, the average construction time in the field is long and multiple people are needed to set up, pack and transport the instrument (Fister and Ries, 2009).

In order to reduce these disadvantages, the Portable In-Situ Wind Erosion Laboratory (PI-SWERL) was developed by the Desert Research

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Institute in Nevada, USA, to facilitate field measurements on the dust emission potential of soils. The main advantage of the PI-SWERL is its compact size, which requires a short set-up time and makes it easier to transport. In this research, we employed the PI-SWERL model MPS-2b (version November 2018), which is described in detail in the Methods Section.

Sweeney et al. (2008) acknowledge that the PI-SWERL violates most of the guidelines for large field wind tunnel design, as listed by Raupach and Leys (1990). They mention that the PI-SWERL is not designed to simulate the natural atmospheric boundary layer, as large wind tunnels attempt to do. Instead, the device can provide a measure of soil erodibility, based on the relationship between friction velocity and dust emission. In their study, the PI-SWERL was compared with the straight-line, suction-type, field wind tunnel of the University of Guelph to test its reliability (Sweeney et al., 2008). A close to 1:1 correspondence was found between the dust emissions for most soil surfaces. However, the PI-SWERL systematically measured higher dust emissions for gravel-covered surfaces at all friction velocities. The size and distribution of non-erodible roughness elements, such as gravel, affect the boundary layer flow and thus, the amount of shear stress exerted on the surface. This different behaviour of the shear stress led to underestimation of the threshold friction velocity for rough surfaces by the original relationship between RPM and friction velocity used for the PI-SWERL (Sweeney et al., 2008). To compensate for this underestimation, a surface roughness correction factor must be used for rough surfaces when calculating friction velocities based on the RPMs (Etyemezian et al., 2014).

Most studies that used the PI-SWERL have been focused on studying the dust emission potential of different soil surfaces at various friction velocities in different regions in the world, e.g., the Namib Desert in Namibia (von Holdt et al., 2017), the Tengger and Mu Us Desert in Northern China (Cui et al., 2019), coastal dunes in California, USA (Mejia et al., 2019), the Colorado Plateau in the USA (Fick et al., 2020), Yellow Lake Playa, USA (Sweeney et al., 2016), Athabasca Oil Sands Region in Canada (Wang et al., 2015), and the Mongolian steppe (Munkhtsetseg et al., 2016). Others aimed to compare the dust emission potential of the PI-SWERL to a wind tunnel, for similar friction velocities (Sweeney et al., 2008; Kavouras et al., 2009; King et al., 2011). The PI-SWERL was also successfully used to quantify threshold friction velocities for various substrates, for example on volcanic ashes (Etyemezian et al., 2019) and off-road trails (Goossens and Buck, 2009). In the current study, we aimed to determine if thresholds for PM_{10} emission are comparable between both instruments for two substrates. To accomplish this aim, experiments with a similar design were performed with both the PI-SWERL and a wind tunnel: the Portable Wind and Rainfall Simulator (PWRs) of the University of Basel.

2. Materials and methods

2.1. Materials

Two types of substrate with varying texture (Fig. 1) were used to identify the effects of particle size and sorting on the threshold friction velocity of PM_{10} emission. The first substrate (NS1) originated from a silver sand mine in Limburg, The Netherlands, and was mined from a Miocene formation. The D_{50} , or median particle diameter, of this first substrate was 212 μm , and 70% of its particles were categorized as very fine sand (range between 62.5 μm and 125 μm). The second substrate (DS1) is a loamy sand soil, which was collected from Central Jutland, near Foulum, Denmark, with a D_{50} of 246 μm . Both substrates have a similar D_{50} , but differ substantially in their fraction with particles smaller than 100 μm . Approximately 25% of DS1's mass consists of particles below 100 μm , while NS1 only has 7% of its particles in this fraction.

Both substrates were first oven-dried at 40 °C and then sieved through a 2 mm sieve. This sample preparation reduced the effect of various factors, such as the presence of aggregates and high soil moisture that were likely to affect dust entrainment. The particle size distribution of both substrates was analysed with the Mastersizer 2000, a laser diffraction particle size analyser, using wet dispersion.

2.2. Methods

2.2.1. PI-SWERL

In this research, we employed the PI-SWERL model MPS-2b (version November 2018) (Fig. 2). This model has a cylindrical chamber with a diameter of 30 cm and a height of 20 cm. The chamber is open at the bottom and can be placed over the soil of interest. A foam seal surrounding the edge of the chamber ensures a direct connection with the soil surface. A computer controlled 24-volt DC motor is attached to the top of the chamber, which provides power to a flat annular blade ($\varnothing 25$ cm, 6 cm width). The blade is aligned in parallel to the soil surface, while maintaining approximately 5 cm distance. As a result of the rotation of the blade, a velocity gradient is generated between the blade and the soil underneath, creating a shear stress on the soil surface (Sweeney et al., 2008). The magnitude of the shear stress depends on the revolutions per minute (RPM). A large enough shear stress leads to the entrainment of soil particles. During an experiment, the PM_{10} concentration inside the chamber of the PI-SWERL is monitored by a DustTrak II monitor (TSI Incorporated, 2018). A detailed description of the PI-SWERL system, based on a previous model version, is provided by Etyemezian (2018).

The PI-SWERL was programmed with the SwerlView application, provided by the Desert Research Institute. The same pre-programmed

Fig. 1. The cumulative particle size distribution of NS1 and DS1.

Fig. 2. PI-SWERL model MPS-2b – Chamber with mounted DustTrak II monitor.

hybrid test was used for all experiments and consisted of the following phases: i) starting phase: a 30-second period of 0 RPM and running ventilation (100 L min^{-1}) to clean the air in the chamber, ii) ramp phase: slow increase of RPM from zero to a target value of 3175 RPM within a time span of 120 s, iii) constant phase: RPM were kept constant for 240 s and iv) ending phase: RPM were reduced to zero within 30 s. The total duration of the experiment was 420 s.

The RPM are converted to a friction velocity, using

$$u_* = C_1 \alpha^4 \text{ RPM}^{C_2/\alpha} \quad [\text{m s}^{-1}] \quad (1)$$

where u_* is the friction velocity (m s^{-1}), C_1 refers to a constant of 0.000683, C_2 is a constant of 0.832 and α depends on the surface roughness (Etyemezian, 2018). Values of α are based on four roughness categories, where the lowest surface roughness is linked to category A, a silt-clay crusted playa with minimal cracking and sparse gravel, and the highest surface roughness refers to category D, a gravel covered surface. Furthermore categories B (sandy loam desert soil with <5% gravel cover) and C (a rippled dune surface with <10% gravel cover) are defined (Etyemezian et al., 2014). An α of 0.94, corresponding to roughness category B, was chosen to convert the set target value of 3175 RPM to a friction velocity of 0.67 m s^{-1} (Eq. (1)). This specific friction velocity was chosen for the experiment, because previous research by Etyemezian et al. (2007) has shown that the corresponding friction velocity is sufficient to generate dust emission for most soil surfaces.

In addition to running the PI-SWERL program, the SwerlView application was also used to keep track of PM_{10} concentrations and

number of saltating particles during each hybrid test, PM_{10} concentrations in the chamber of the PI-SWERL were measured by a TSI DustTrak II monitor (model 8530) by active sampling with 3 L min^{-1} at a one-second interval. The optical gate sensors (OGS) peak area provides an indication of larger particles moving in the chamber. In the present set-up with high amounts of loose sand, the OGS sensors seemed to detect relatively unreliable numbers, due to the sheer number of particles. Therefore, they were not used in this research.

The hybrid test was repeated 10 times per test substrate (NS1 and DS1). A circular tray ($\varnothing 40.5 \text{ cm}$) was filled with 5 L of substrate before every test and an aluminium bar was used to flatten the surface. Left-over material from completed tests was recycled and mixed with new substrate before the start of each consecutive test run to guarantee a homogenous sample. During the experiment, the test surface was expected to become dust depleted, as dust was removed from the chamber via the exhaust pipe. To test this assumption, a surface sample was collected at the end of each test run. Additionally, to gain insight in the particle size distribution of the total emission, a Dyson V7 Trigger handheld vacuum cleaner was attached to the PI-SWERL (Fig. 3a). A custom-made connector piece connected the Dyson with the exhaust pipe (Fig. 3b). At both sides of the connector piece, two 2 cm holes were drilled to ensure an undisturbed air flow. The particles collected by the Dyson were sampled after every other test run and a corresponding sample was taken from the test surface. The particle size distributions of the surface and Dyson samples were analysed with the Mastersizer 2000, using wet dispersion. Subsequently, these results were compared to the original particle size distribution of the substrates (Fig. 1) to determine the degree of mobilization of PM_{10} -sized dust and larger particles during each test run.

To prevent cross-contamination between experiments, the chamber of the PI-SWERL had to be kept clean. Therefore, the inside of the chamber was cleaned with a brush after each test run. In addition, a cleaning cycle was performed after five consecutive test runs and before changing the test substrate. The cleaning cycle was a ramp test on a clean test surface (i.e., empty sample tray) at 5000 RPMs that lasted for 300 s. This procedure ensured that any dust that was left behind after simple cleaning with a brush was removed from the PI-SWERL's chamber. In addition, the impactor plate of the DustTrak II monitor was cleaned regularly to ensure accurate measurements.

2.2.2. Portable straight-line wind tunnel

For the cross-comparison with the PI-SWERL, the Portable Wind and Rainfall Simulator (PWRS) of the University of Basel was used (Fig. 4). This straight-line wind tunnel is based on the device from Trier University (Fister et al., 2011, 2012). The Basel PWRS consists of five components that together have a length of 11 m: the fan, the transition section, the converter section, the honeycomb air-straightener and the test section. Airflow, or wind, is generated by a push-type fan, which is driven by a 3.7 Kw electro-mechanical system. The velocity of the fan can be set between 2 and 12 m s^{-1} . The honeycomb consists of 448 PVC tubes, each 25 cm long and 4 cm in diameter and the adjacent test section that is 4 m long and has a 0.8 by 0.8 m cross-section.

The test section has four detachable sections. The roof of the test section was lowered by wooden plates along its full length to reduce the tunnel height to 60 cm and thus increase wind velocities near the ground. The floor of the test section is covered with a 2 mm thick bitumen layer, which has a sanded top. At 3.5 m distance from the start of the test section, a square tray ($35 \times 35 \text{ cm}$) with the substrate of interest was placed. The application of Irwin spires and roughness elements in the first meter of the test section creates an artificial boundary layer with a thickness of 26 cm.

During the experiment, no abraders or saltators were added to the set-up, meaning that for both substrates particle entrainment was initiated solely by the fluid force, i.e., the wind. To measure PM_{10} emissions from the test surfaces, a DustTrak II monitor was positioned at the end of the test section. This is the same instrument that was used to quantify

Fig. 3. Modification to the PI-SWERL to collect emitted particles during the hybrid test. (a) Dyson V7 Trigger Handheld vacuum cleaner attached to the exhaust pipe, and (b) the custom-made connector piece.

Fig. 4. The Portable Wind and Rainfall Simulator of the University of Basel stationed in the experimental rainfall laboratory at Witterswil. a) The push-type fan, b) technical 3D drawing of the wind tunnel from (top view) and c) a schematic 2D overview (side view). Dimensions are shown in millimetres (Fig. 4b and c from Fabbri, 2018).

PM₁₀ concentrations during the PI-SWERL experiments. The inlet tube of the instrument was installed at 9 cm above the tunnel floor. Furthermore, sediment traps were installed over a height gradient at the end of the test section to provide information about the vertical distribution of emitted particles. Seven Modified Wilson and Cook (MWAC; Wilson and Cooke, 1980) samplers were positioned with their inlets at respectively 0.5, 3, 9, 15, 22, 27 and 32.5 cm above the tunnel floor.

In the test section of the PWRS, a vane anemometer probe and a hot wire probe were installed at 40 cm height at the end of the tunnel's test section. They were used as reference measurements for the wind speed, the humidity, and air-temperature, respectively. The observed wind velocities by the vane anemometer probe can be transformed into friction velocities, using the logarithmic law of Prandtl-Karman

$$u_* = \frac{u^* \kappa}{\ln\left(\frac{z}{z_0}\right)} \quad [\text{m s}^{-1}] \quad (2)$$

where u is the velocity at height z , u_* is the friction velocity (m s^{-1}), κ is the dimensionless von-Kármán constant with a universal value of 0.40, z is the height (m) above the surface, and z_0 is the surface aerodynamic roughness length in meters (Prandtl, 1935). The PWRS has a surface roughness length of 50 μm (Fabbri, 2018). Measurements from the vane anemometer and the hotwire probe were collected with a hand-held Testo 480 digital temperature, humidity and air flow meter (Testo SE & Co. KGaA, n.d.).

The performed wind tunnel test was designed to mimic the pattern of

the hybrid test of the PI-SWERL. The speed of the fan was increased over the course of 120 s, with 1 V per 4 s, creating a ramp towards its maximum of 50 V. This top speed, translating to 15 m s^{-1} , was maintained for 60 s before switching off the system. The rather short duration of 60 s was chosen, because otherwise the depletion of the material in the sand tray would have been too big, causing further problems, such as scouring or sheltering of the surface by the rim of the tray. The test was repeated 10 times per substrate (NS1 and DS1). Before each test run, the square sample tray was refilled and the material was flattened with an aluminium bar to ensure low surface roughness. After every other test, surface samples were taken from the remaining substrate in the sample tray to verify if dust depletion occurred. The particle size distribution of the samples was analysed with the Mastersizer 2000 using wet dispersion. Unfortunately, due to human error, post-test surface samples were only collected for NS1. Therefore, no particle size distribution analysis was performed on DS1 post-test surface samples. Furthermore, the contents of the seven MWAC samplers were weighed.

2.2.3. Cross-comparison between instruments

To detect the start of PM_{10} emission, and thus the respective threshold friction velocity for the substrate, increasing trends were identified from the PI-SWERL and PWRS datasets. For the PI-SWERL, all replicates showed relatively large variance at the start of the experiment, which made precise determination of the threshold friction velocity difficult. Therefore, as soon as ten data points (1 Hz interval) with an increasing trend could be identified in the measurements, the start of PM_{10} emission was defined, of which the first data point was marked as the threshold friction velocity. To quantify the threshold friction velocity in the PWRS data, the same method was applied. The reference

wind velocities and the observed PM_{10} concentrations were plotted against time. Based on these data, an increasing trend in PM_{10} emissions was observed of which the first data point indicated the threshold friction velocity. To compare identified thresholds between the two experiments, a one-way analysis of variance (ANOVA) was performed to determine if the group mean of the PI-SWERL threshold friction velocities for each substrate differed of those derived from the PWRS experiments. The analysis was done using MATLAB R2018b software.

Furthermore, the PM_{10} emission for both substrates was quantified. For the PI-SWERL experiments, the vertical dust flux (EF) was determined using Equation (3) (Etyemezian, 2018).

$$EF(t) = \frac{C_{\text{dust}} * FR * 0.0000167}{A_{\text{eff}}} [\text{mg m}^{-2} \text{ s}^{-1}] \quad (3)$$

Here, C_{dust} (mg m^{-3}) is the average PM_{10} concentration in the PI-SWERL's chamber, FR (L min^{-1}) is the flow rate through the chamber and A_{eff} refers to the effective area of the instrument, which was estimated to be 0.035 m^2 for this model (Etyemezian et al., 2014). Unfortunately, it was impossible to measure dust emissions over a vertical profile and calculate the vertical PM_{10} fluxes for the PWRS, because only a single DustTrak II monitor was installed in the wind tunnel. Alternatively, the cumulative PM_{10} concentration (mg m^{-3}) was determined. Although not comparable to the vertical dust flux of the PI-SWERL measurements, the average PM_{10} concentration in the PWRS does show which substrate emitted more dust. These trends were expected to be similar to those in the PI-SWERL data.

Fig. 5. Identified threshold friction velocities for the PI-SWERL (5a, 5b) and PWRS (5c, 5d). The average critical friction velocity for PM_{10} emission is marked by the blue square. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Threshold friction velocities

For both NS1 and DS1, the PI-SWERL data show a clear start of PM_{10} emission. The PM_{10} concentration of all replicate measurements followed a similar pattern with increasing RPM (Fig. 5). The threshold friction velocity of NS1 was identified at 0.33 m s^{-1} , on average. DS1 emitted PM_{10} at a lower threshold friction velocity of 0.25 m s^{-1} . As illustrated by Fig. 5, the PWRS data did not show a rapid increase in PM_{10} emissions, as was observed during the PI-SWERL experiments. Instead, PM_{10} emissions increased slower and with more fluctuations. Therefore, it was not possible to identify ten subsequent increasing points in the data, as planned in the original methodology. For NS1, only seven subsequent points could be identified that marked the start of PM_{10} emission. For DS1, the number of subsequent increasing points was even limited to three or four. For the PWRS measurements, PM_{10} was emitted from NS1 after exceeding a friction velocity of 0.33 m s^{-1} . This threshold friction velocity is the same as the threshold observed from the PI-SWERL experiment. In contrast, the PWRS did not yield comparable results for DS1. Here, a threshold friction velocity of 0.39 m s^{-1} was observed, which is higher compared to the 0.25 m s^{-1} from the PI-SWERL measurements. The PI-SWERL and the PWRS results both showed some degree of variation in the threshold friction velocity between replicates. However, the standard deviation of the PWRS data was larger ($\sigma_{NS1} = 0.03$ and $\sigma_{DS1} = 0.04$) than standard deviation of the PI-SWERL data ($\sigma_{NS1} = 0.01$ and $\sigma_{DS1} = 0.01$).

These findings suggest that the PI-SWERL and the PWRS yield similar results for NS1. The average threshold friction velocity of NS1 from the PI-SWERL was 0.9% higher than the threshold measured by the PWRS. In contrast, average threshold friction velocities for DS1 that were measured by the PI-SWERL were 34.7% higher than those derived from PWRS tests. Because the ANOVA returned a p-value of 0.716 for NS1, the

null hypothesis could not be rejected. In other words, this finding suggests that the threshold friction velocities for NS1 are comparable. The group means of DS1, on the other hand, did differ significantly with a p-value of 1.5×10^{-8} .

3.2. Dust emission fluxes

NS1 and DS1 emitted highly variable PM_{10} concentrations for both instruments (Fig. 6). Emission patterns differ between the instruments. Dust emission during the PI-SWERL experiments is marked by a sharp increase in PM_{10} concentrations, while PM_{10} values during PWRS experiments increase more gradually. Variability in PM_{10} emissions was much higher during the PI-SWERL experiments, compared to the PWRS data. Despite the large variance for both instruments, the pattern of PM_{10} emission behaved similarly between replicates of both NS1 and DS1. An average PM_{10} emission flux of $2.86 \text{ mg m}^{-2} \text{ s}^{-1}$ was observed for NS1, which was about two times less than the emission flux of DS1 ($6.91 \text{ mg m}^{-2} \text{ s}^{-1}$). The standard deviations of the observed emission fluxes were $0.53 \text{ mg m}^{-2} \text{ s}^{-1}$ for NS1 and $0.88 \text{ mg m}^{-2} \text{ s}^{-1}$ for DS1. Unfortunately, the set-up of the DustTrak II monitor in the wind tunnel did not allow for the calculation of the PM_{10} emission flux. Alternatively, we determined the cumulative PM_{10} concentration during a wind tunnel test. Calculations show that an average of 10.12 mg m^{-3} was measured by the DustTrak II monitor for NS1, while DS1 emitted 10.91 mg m^{-3} on average. The total PM_{10} emission data had a standard deviation of 3.08 mg m^{-3} NS1 and 3.81 mg m^{-3} for DS1.

During the PWRS experiment, passive samplers 1 to 4 showed that more material was captured for NS1 than for DS1 (Table 1; Fig. 7). MWAC 1 to 4 collected in sum 10.35 and 3.31 g for NS1 and DS1, respectively. For both test substrates, most material was trapped by MWACs 1 and 2. On average, 6.35 g in MWAC 1 and 3.85 g in MWAC 2 were trapped for NS1, while weights of DS1 were significantly lower with only 1.98 g in MWAC 1 and 1.19 g MWAC 2. MWACs 5, 6 and 7 did

Fig. 6. PM_{10} concentrations and corresponding friction velocities (u^*), measured by the PI-SWERL (6a, 6b) and the PWRS (6c, 6d). Star represents the identified threshold friction velocity. Note that the scale of the PM_{10} axis is different for the PI-SWERL and PWRS runs.

Table 1

Mass trapped by the MWAC passive samplers.

MWAC nr.	Height [cm]	Mass trapped			
		NS1 – mean [g]	NS1 – std [g]	DS1 – mean [g]	DS1 – std [g]
1	0.5	6.35	0.72	1.98	0.43
2	3	3.85	0.50	1.19	0.24
3	9	0.13	0.05	0.13	0.04
4	15	0.02	0.02	0.01	0.01
Total mass trapped [g]		10.35		3.31	

not collect any (measurable) material during the wind tunnel experiments, because they were located above the artificial boundary layer.

Particle size analysis of NS1 showed that after the PWRS experiments, the cumulative mass percentages of the sample's surface were comparable to the original distribution of the substrate (Fig. 8). This lack of depletion of fines could have been caused by either too short exposure times or a non-selectivity of the erosion process due to high shear stresses applied. Similarly, the PI-SWRL's post-experiment particle size distribution did not change much for NS1. On the contrary, for DS1, depletion of the finer fractions ($<100 \mu\text{m}$) was observed when comparing the surface samples to the particle size distribution of the original sample. Furthermore, for both substrates, the samples from the Dyson attachment showed that only smaller particles ($<100 \mu\text{m}$) were emitted from the PI-SWRL.

4. Discussion

In this research, we aimed to explore the ability of the PI-SWRL to quantify the threshold friction velocities for PM_{10} emissions. We hypothesised that the threshold friction velocities measured by the PI-SWRL and the PWRS would be comparable. For NS1, the threshold was identified at 0.33 m s^{-1} from the PI-SWRL data, which corresponds to a wind speed of 6.35 m s^{-1} at 2 m above the surface. The same threshold friction velocity was derived from the PWRS data, which indicates comparability of the two methods. However, for DS1 the threshold friction velocities differed significantly between instruments. The PI-SWRL obtained a critical value of 0.25 m s^{-1} , whereas a threshold of 0.39 m s^{-1} was identified from the PWRS data. For reference, these threshold friction velocities correspond to 4.79 and 7.33 m s^{-1} at 2 m above the surface for NS1 and DS1, respectively.

On close observation there is little variability in PM_{10} emission

patterns between replicates for both substrates (Fig. 6c and d) in the PWRS data. This low variability between replicates suggests that the experimental set-up of the PWRS itself is correct and repeatable. However, as illustrated by Fig. 6c and d, variation in PM_{10} emission between replicates was more diverse for DS1 compared to NS1. The results of DS1 showed relatively more and higher peaks in PM_{10} concentrations. This higher variability could have led to incorrect identification of the threshold friction velocity of DS1. Because of the absence of a clear, rapid increase of PM_{10} emission, caused by diverse PM_{10} emission patterns, the variability of threshold friction velocities for the PWRS was higher (Fig. 5). However, it is quite surprising that this limitation only affected the threshold friction velocities for DS1, while not imposing issues for NS1. This indicates that another factor influenced the results as well. The particle size characteristics differed between materials, with DS1 having higher mass percentages for the 75 to $100 \mu\text{m}$ fraction. In various aspects, the substrates in this research can be considered as ideal soils (e.g., no rocks, vegetation cover, etc.). Yan et al. (2013) found that when using such ideal soils, fractions below or above a certain critical particle size (125 to $210 \mu\text{m}$) will be depleted easier. The high mass percentage of very fine particles in DS1 ($<100 \mu\text{m}$) may suggest a faster depletion of material when compared to NS1. This effect does not explain why different threshold friction velocities were observed by the PI-SWRL and the PWRS, but does give rise to the question if we should use such ideal substrates for these types of experiments. Since no physical explanation for the higher variability in dust emission patterns and thus identified threshold friction velocities of DS1 could be found, we believe that the differences could have methodological reasons, assuming that the two methods are comparable to each other. Possible methodological issues are described below.

The most likely factor explaining the different thresholds could have been the position of the inlet tube of the DustTrak II monitor during the PWRS experiments. The inlet was positioned at the end of the PWRS' test section at 9 cm height above the tunnel floor. This height was chosen because we expected that most PM_{10} particles would be moved due to direct aerodynamic entrainment, leading to particle transport close to the tunnel floor. Too high PM_{10} concentrations could potentially damage the DustTrak II monitor. Therefore, we decided to place the inlet tube slightly higher (at 9 cm) in order to protect the instrument. However, as illustrated by MWAC 3, which is positioned at the same height, too little material was trapped at this height (Fig. 7). In retrospect, the inlet tube should have been positioned at the height of MWAC 1 or 2 (at respectively 0.5 and 3 cm) to be able to capture more material and thus have a more rapid increase in PM_{10} concentrations. This would have

Fig. 7. Average weights of trapped NS1 and DS1 in MWAC sampler 1 to 4.

Fig. 8. The average cumulative particle size distribution of the original substrates (NS1 and DS1), surface samples after the PI-SWERL and PWRS experiments, and the Dyson samples.

made quantification of the threshold friction velocity easier and probably more precise.

Another factor that might have caused the deviation of thresholds between devices for DS1 is that the PWRS experiments were performed on different days (NS1 on day 1, DS1 on day 2). Environmental conditions differed between the test days, with an average temperature of 16.5 °C and relative humidity of 58.8% on the first day. On the second day of the PWRS experiments, the average temperature was 9.3 °C and the relative humidity decreased to 46.0%. Temperature and relative humidity during the PI-SWERL experiment were similar to the environmental conditions of the first PWRS test day. Humidity directly influences the threshold friction velocity of a soil, as it strengthens the interparticle forces (Neuman, 2004). Temperature has an indirect effect on the critical value for particle entrainment. The drag force is proportional to air density, meaning that with low temperature the drag force on a soil particle increases, therefore reducing the threshold friction velocity (Kok et al., 2012). Also, with low temperature, the matric potential is low, weakening the interparticle cohesive forces, thus reducing the threshold friction velocity (Neuman, 2004). Because of these deviating environmental conditions, we would expect that the threshold friction velocity of DS1 would be lower during the PWRS experiments, compared to the PI-SWERL tests. However, the opposite was observed. Therefore, the differences in environmental conditions do not explain the deviating threshold friction velocities for DS1. On the second day, DS1 was tested by a different operator, who might have manually controlled the fan slightly different, leading to variations in wind velocities and thus different threshold friction velocity during the experiment. This explanation is supported by the larger variation in observed PM₁₀ emission patterns for DS1 replicates. Based on these assumptions, it is likely that the actual PWRS measurements on both substrates are

valid. However, the increased variability between DS1 replicates, due to operator change, could have also resulted in inaccurate identification of the threshold friction velocity for DS1.

Lastly, some alterations should be made to the test set-up of the PWRS experiments to make it as similar as possible to the experimental design of the PI-SWERL. The PWRS tests lasted 190 s, while the PI-SWERL tests were much longer with 420 s. However, maintaining the PWRS test for 420 s was not possible because the sample tray in the tunnel floor would have been highly depleted in material before the end of the test. Increasing the size of the sample tray does not solve this problem. As soon as the material is below the rim of the tray, aerodynamic conditions change and material is emitted differently. This change in procedure would improve the comparability of the total dust flux between the instruments but not the issues with detecting the certain threshold friction velocities.

Based on the observed experimental issues, it is important for future research to focus on reducing these factors from the PWRS experiments. Most importantly, the regulation of the fan's speed must be done by a single observer or automatically. Ideally, both substrates should be tested on the same day to ensure repeatable environmental conditions between measurements. Furthermore, multiple DustTrak II monitors should be added to the PWRS' experimental set-up. In the current design, it was not possible to measure dust emissions over a vertical profile and calculate vertical PM₁₀ emission fluxes. In comparison, the study by Sweeney et al. (2008) used four DustTrak II monitors at 0.05, 0.10, 0.17 and 0.25 m above the tunnel floor.

When more DustTrak II monitors are added to the PWRS set-up, comparison of measured dust fluxes by both instruments would be possible. When comparing such results, underestimation of dust emission by the PI-SWERL should be considered. Due to the rotating

movement of the blade, the PI-SWRL behaves like a cyclone separator (Etyemezian et al., 2019). Particles will be separated based on their particle size, and smaller particles are likely to follow the airflow and will be removed from the chamber by the exhaust pipe. However, larger particles remain in the chamber due to the cyclonic movement of the airflow. Etyemezian et al. (2019) suggest that this is the case for particles larger than 5 μm and that the effect strengthens with increasing particle size. In other words, PM_{10} dust emissions are likely to be underestimated. However, this potential underestimation needs further clarification and explanation because Sweeney et al. (2008) did not find such systematic variations. For NS1, 2.7% of its mass consists of particles with a diameter up to 10 μm (PM_{10}), while for DS1 this is 8.6%. In addition, 0.7% of the particles of NS1 have diameters between 5 and 10 μm , while for DS1 3.9% of the particles are within this size category. According to Etyemezian et al. (2019), we would expect slight underrepresentation, especially for DS1, of the PM_{10} emission during the PI-SWRL experiments. As a result, it is likely that the dust flux measurements of the PI-SWRL will systematically differ from the PWRS findings.

5. Conclusion

In previous research, the PI-SWRL has been successfully used to study the dust emission potential of various surfaces. In this research, we aimed to explore if the PI-SWRL can be used to quantify threshold friction velocities for PM_{10} emission by comparing its findings to those of a wind tunnel: the PWRS of the University of Basel. Two substrates were used during the experiments: NS1 and DS1. For NS1, threshold friction velocities of 0.33 m s^{-1} were found by both instruments. In contrast, the observed thresholds for DS1 were different. A threshold friction velocity of 0.25 m s^{-1} was quantified by the PI-SWRL, while the PWRS experiments yielded a different speed of 0.39 m s^{-1} . The good comparability of thresholds for NS1 indicate that the PI-SWRL can be used to assess threshold friction velocities for PM_{10} dust emission. However, the rather large difference for DS1 shows that experimental issues need to be improved, before reliable results and a definite answer to the hypotheses can be formulated.

The different threshold friction velocities can possibly be explained by the experimental design of the PWRS tests and also by the instrument's operation by different persons. Lowering the inlet tube of the DustTrak II monitor should result in higher observed PM_{10} concentrations, making the identification of threshold friction velocities easier. The lack of a rapid increase of PM_{10} and highly variable emission patterns make precise quantification of the threshold velocities difficult. Furthermore, operation of the PWRS by different persons could explain the difference in PM_{10} emission patterns between substrates. The mechanical regulation of the push-type fan made precise control of the wind velocity between operators difficult.

Furthermore, to improve quality and reliability of results, multiple DustTrak II monitors should be included in the experimental set-up and the duration of the PI-SWRL experiments should be shortened to increase similarity between experiments. Although our research did not yield a 1:1 correspondence in threshold friction velocities for both substrates, we believe that with an improved and more comparable test set-up, the comparison of thresholds between the two methods can be achieved. This would indicate that the PI-SWRL could be used in future research to supplement and even substitute threshold friction velocity datasets based on wind tunnel experiments, in the laboratory and, most importantly, in the field.

CRediT authorship contribution statement

C.C.E. van Leeuwen: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft. **W. Fister:** Conceptualization, Investigation, Methodology, Supervision, Writing - original draft. **H.C. Vos:** Conceptualization, Investigation,

Methodology. **L.H. Cammeraat:** Conceptualization, Supervision. **N.J. Kuhn:** Conceptualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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