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Switch on tunnel vision: Portable wind tunnels to understand and quantify aeolian processes

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ABSTRACT

A Portable wind tunnel is a highly specialized device capable of examining soil surfaces in their natural state and independently from naturally occurring wind events. The field experiments give valuable insights into wind-induced entrainment, transport, redistribution and emission of mineral and organic particles from surfaces in their original state to understand geomorphological, pedological, and ecological processes. Recent portable wind tunnel studies highlight a broad range of research objectives including the determination of threshold wind velocities, the quantification of wind-eroded sediment, the development of dust emissions, and wind-induced dynamics of nutrients and contaminants. Portable wind tunnels usually follow a straight tunnel design with a push or suction-type wind source, an air straightening section, and an open-bottom test area. Research groups developed and applied specific add-on features such as sediment feeders to simulate an erosive saltation layer, an integrated rainfall simulator for wind-driven rain studies, and miniaturized tunnels. A large variety of techniques is used to collect and count the entrained mineral and organic particles to allow for quantification and qualitative analysis. Validity, reproducibility, and reliability of the experimental setup and data application for extrapolation and modeling are discussed based on physical constraints of the tunnel and spatiotemporal characteristics of the data. The manuscript also summarizes experiences and recommendations for application and maintenance and proposes methods to compare results generated by different devices.

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Contents

1. Portable wind tunnels to study aeolian processes

1.1. Methodological approach

Aeolian processes include the movement of a large range of particle sizes and shapes in different transport modes (Bagnold, 1941). Detached substrate particles settle, drift, or rise size-dependently with local and regional air currents and turbulences, humidity and temperature (Shao, 2008). According to the characteristics of the particle, air, and surface morphology, the transport may lead to either a local redistribution, a regional transfer, or to global dispersion. Mobilization and emission of mineral dust affect soil health and food security (Goossens and Riksen, 2004; Goudie, 2014), air quality and human health (Achakulwisut et al., 2019), matter cycles including mineral and organic components on a local to global scale (Field et al., 2010; Mahowald et al., 2017) and the global climate (Kok et al., 2023; Schepanski, 2018). Because aeolian processes and forms comprise a great range of temporal and spatial scales, methods of investigation and observation include a broad spectrum of approaches such as on-site process observations and experiments, ground-based and satellite remote sensing techniques, and projection and modeling. While on-site and remote sensing observations as well as wind erosion and dust dissipation modeling have been increasing process understanding, the determination of wind-driven soil erosion is still associated with great uncertainties (Sherman, 2020).

Wind tunnels are an important link between laboratory and field experiments. The method comprises specific advantages and disadvantages regarding its application possibilities such as scaling laws, matching of non-dimensional parameters, and the development of a boundary layer as the main challenges (Funk, 2016). Laboratory wind tunnels have been used for a long time in aeolian sediment transport studies. For a broad range of research questions, a permanently installed laboratory setup including firmly installed and calibrated measurement equipment is a good option. This includes studies with repetitions with identical surface and air stream conditions, and basic research constituting generalized physical relationships such as interdependencies between wind parameters and particle behavior. The used sediment is usually of a simple and homogenous structure, in the range of fine to middle sand and often of single grain structure. The sediments are mostly prepared by drying and sieving to ensure comparable and reproducible conditions for test repetitions. However, if the surface structure increases in complexity, and features seals and crusts, vegetation, embedded stones, or other specific elements creating surface heterogeneity, the validity of the laboratory wind tunnel results decreases.

A portable wind tunnel (PWT) is a highly specialized device designed to investigate and to quantify wind-induced erosion processes on small spatiotemporal scales and focuses these surface complexities. The tunnel simulates an erosive event by producing a moving air stream with a velocity u exceeding the threshold velocity u_t needed for entrainment of substrate particles. The main difference between stationary and portable wind tunnels is the capability to be moved, mounted and dismantled in a relatively easy and fast way. While PWTs are applicable for field tests on-site, some parameters that are considered necessary for the validity, reliability and interpretability of results become less controllable compared with a stationary tunnel. At the same time, the representation of real soil surface conditions is more realistic because it offers the unique opportunity to test surfaces in situ and in an undisturbed state. They highlight the reaction of real soil surfaces to specific aeolian dynamics, fostering process knowledge and quantification of entrainment and transport of mineral and organic particles.

1.2. Portable wind tunnel applications since the 1930s

The first included reference is a study comparing results from a field tunnel and a stationary tunnel in the Soil Research Laboratory in Saskatchewan, Canada (Chepil and Milne, 1939). The authors state that wind erosion had become a ubiquitous problem of cultivated prairie soil, and investigation methods should offer controlled environmental parameters as well as independence from actual wind erosion events. The same scientific background, severe wind erosion particularly on agriculturally used soil, is stated in an early M.*Sc*.-thesis from Iowa State College (Thompson, 1948). The author investigated wind erosion after tillage with a variety of common tillage tools and constructed a PWT including a hay drier wind source and an open-top sediment collection section (Fig. 1).

During the following decades, singular studies were accomplished with a noteworthy peak in the 1950s and with a research hotspot in the USA, predominantly on agriculturally managed prairie environments and desert soils (Fryrear, 1984; Zingg, 1951a, 1951b) (Fig. 2a, b) and investigating the specific wind threshold velocity (Gillette, 1978). From Japan, an early construction is published to investigate wind effects on grain crops (Udagawa and Oda, 1967) (Fig. 2c). In China, the first tests were carried out in an Inner Mongolian Steppe environment (Zhu, 1987). PWT were developed and applied to derive information about soil erodibility in combination with physical and chemical analyses in Spain (Quirantes Puertas, 1987) and in Australia (Raupach and Leys, 1990). Besides the Australian tunnel with a square cross-section, a tunnel with a tent-shaped cross-section was constructed (Scott, 1995). From the late 1980s, there have been several new constructions in North America (e.g, (Houser and Nickling, 2001; Nickling and Gillies, 1989; Pietersma et al., 1996) (Fig. 2c)), Iran (Ekhtesasi, 1991, in Rostami et al., 2025) and Germany (Funk and Frielinghaus, 1997; Fister and Ries, 2009; Maurer et al., 2006). From the late 2000s, publications increased up to a higher average of publications per year. Nearly 25% of the total listed publications present the design, construction or testing of a wind tunnel device, which was not always followed by field applications. Total publications show a slight increase for the first half of the 2020s. The research topics have widened in terms of surface types from agricultural land over crusted and stone covered surfaces to humid environments, showing the generally growing interest in on-site investigations. A main cause is the increasing understanding of the crucial impact of specific surface characteristics on wind erosion and dust emission in contrast to the wind-focused research with standardized or disturbed substrate in laboratory tests.

A Clarivate core collection literature search including refined search commands with exclusion of unrelated research fields (Clarivate, 2025a), showed the quantity and relevance of PWT studies among other related key words “soil erosion”, “wind erosion”, wWind erosion model”, and “portable/ mobile/ field wind tunnel erosion” in global ISI-listed literature. The Clarivate search for “soil erosion” found 46,378 publications, “wind erosion” 9532 publications, and “wind erosion model” 3902 publications. The search with exclusion of unrelated research fields (Clarivate, 2025b) for key words “wind tunnel erosion” included stationary wind tunnels and found 729 results. The specified

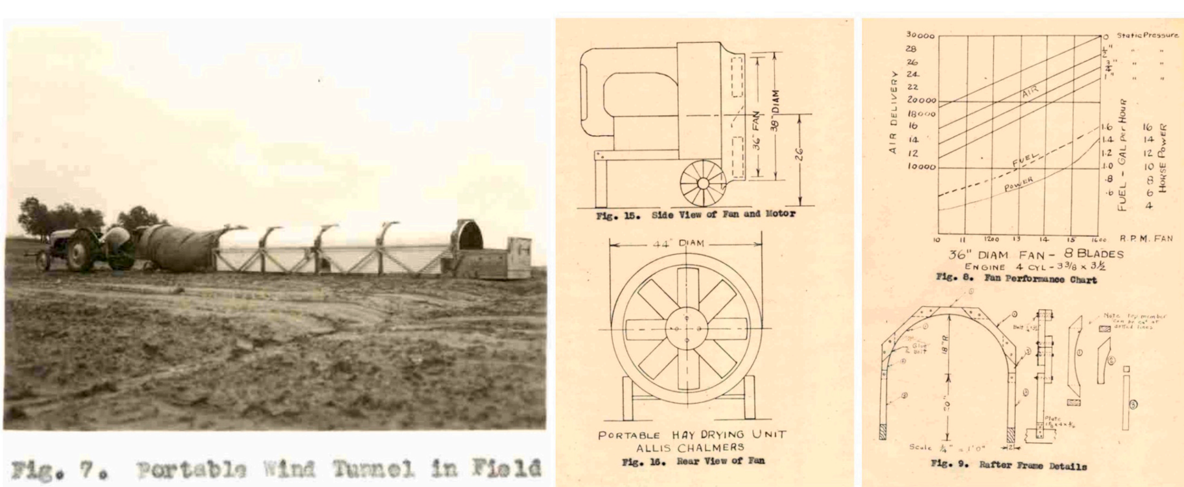

Fig. 1. Picture and construction details of a PWT, taken from the M.*Sc*. thesis “The effect of cultural treatments on wind erosion as determined by a portable wind tunnel” (Thompson, 1948).

search for “portable wind tunnel erosion” found 76 results with most studies categorized under “Physical Geography” (27) and “Environmental Sciences” (20) as well as “Geosciences” (21) and “Soil Science” (15). Exclusion of the device “Portable In Situ Wind ERosion Lab: PI-SWERL (PI-SWERL)” led to 64 results. While the number of yearly published PWT studies stayed on a similar level since 2011 with the exception of a maximum publication number in 2019 (8), the citations show an increasing trend until 2022. To include literature dated before 2002, we combined data from Web of Science search and Google scholar search with the same key words and checked each title for suitability (Fig. 3b). The results were classified as either reports on design, construction or validation of a portable wind tunnel (including one general method review paper) or an actual field study. Based on this search, study locations were visualized on a world map (Fig. 3a).

1.3. Portable wind tunnels

Basic features of PWT are a wind source, a transition section, an air straighter/ honeycomb to decrease uncontrolled turbulences, and an open-bottom test section. Possible adaptations are change of dimensions, shorter or longer wind run or test sections, or built-in sediment catcher systems. For the construction and setup of a PWT, scientists have always been focusing on the material and dimensions of the tunnel structure, the wind parameters, the conduction of the test, and the surface characteristics.

1.3.1. PWT structure

The PWT is a partly open system and simulates the natural wind conditions by means of the logarithmic wind profile and shear velocity, thus addressing the scale of the tested environment. Tunnel dimensions impact the formation of the boundary layer as well as transport characteristics (Owen and Gillette, 1985). Theoretically, based on the phenomenon of dynamic similarity, the dimensions of the experimental tunnel setup may be adapted to the scale of the tested processes by means of scaling parameters Reynolds number and Froude number (*Fr*) which characterize the relation between tunnel and airflow. The Froude number includes wind speed and tunnel height and is regarded of major importance for simulation of saltation, with an ideal *Fr* less than 20 (Owen and Gillette, 1985). The tunnel height has a reducing effect on the saltation flux if $Fr > 20$ (Hagen, 2001) which comes into focus if live plants or obstacles are placed inside the tunnel. To use the results for temporal and spatial upscaling and modeling, the scales and targeted processes involved must comply with tunnel specifics including measurement method. However, to develop certain phenomenon and related processes, the tunnel needs to reach specific dimensions.

Recent PWT designs (Fig. 4) follow a general elongated shape based on the physical restrictions to develop the specific wind parameters without the option of a circulation system which would hinder transportation and on-site mounting. The material must be robust and lightweight, so most tunnels are constructed with aluminum, often including perspex windows. The square tunnel design usually includes cross-sections in the range of 0.5 × 0.5 m − 1.0 × 1.0 m width * height, and a length of 10.0–12.0 m (Table 1). The structure is composed of individual components that are assembled and adjusted on-site. The construction is often transported (and stored) on a trailer. An important and specific aspect of the PWT is its correct installation and assembly. The larger the tunnel is, and the more sophisticated equipment is involved, the more representative it will be of natural processes, but the more elaborate are transportation and mounting. Some research groups report an increase of functionality and applicability over time based on field experiences.

1.3.2. Wind parameters

The airflow is the centerpiece of all wind tunnel investigations. At the same time, it is particularly sensitive to disturbances caused by the setup or environmental conditions during field tests. Most tunnels run with wind velocities between 8.0 and 18.0 m s − 1, single devices up to 22.5 m s − 1, and use test durations from 5.0 to 15.0 min. The wind is usually temporally and spatially homogeneous, which is not a natural condition but meets the requirements of experimental work, repeatability and interpretability of the test setup. Homogeneity is assured by a variety of operations, such as the rectification of the fan blades-induced wind swirl by means of a flow straightener (honeycomb structure), and roughness elements to create uniform and controlled turbulences in the laminar flow. Wind sources are mostly fans with rotor blades that push or suck the wind over the surface (Fig. 5). The rotation of the blades leads to a swirl which would interfere with the aim of a homogenous wind profile. While devices using the push-type fan rely on the transition section and the honeycomb structure, the application of a suction-type fan is used to increase the homogeneity of the airflow. Since the air does not pass through the rotating blades before meeting the test section, the air mass is considerably less affected by the rotational swirl compared to a push-type wind source.

The airflow is adjusted to comply with the particular research question or environmental conditions. This includes one specific or a range of applicable wind velocities, a logarithmic wind profile and the spatial and temporal homogeneity of the wind field at the test section. These properties of the wind field may be affected during field application. The wind velocity may be disturbed by either the setup of the fan or by gusts from outside the wind tunnel leading to temporally limited increases. To prevent impact from wind from outside the tunnel, the push-type fan may be screened, either by the trailer walls or from specific wind shields that must still not interfere with the air intake of the fan. Velocity measurements are mostly integrated in the tunnel setup for checking the airflow during tests. These measurements can be recorded and used for interpretation, which may be mostly feasible for a steady sediment monitoring with a small measurement interval. The logarithmic profile is affected by surface roughness originating from the natural soil surface including depressions, stones, and plants. If placed on a vegetated or otherwise rough surface, an aerodynamic ‘noise’ is established due to the lack of a stable seal between the soil surface and the tunnel (Maurer et al., 2006). On agricultural land, clods and ridges create a great disturbance resulting in great changes in the dynamic characteristics of airflow even for slight differences in height and alignment (Zingg and Woodruff, 1951). Most designs now use flexible transition sections since they ease levelling and increase fixing to the

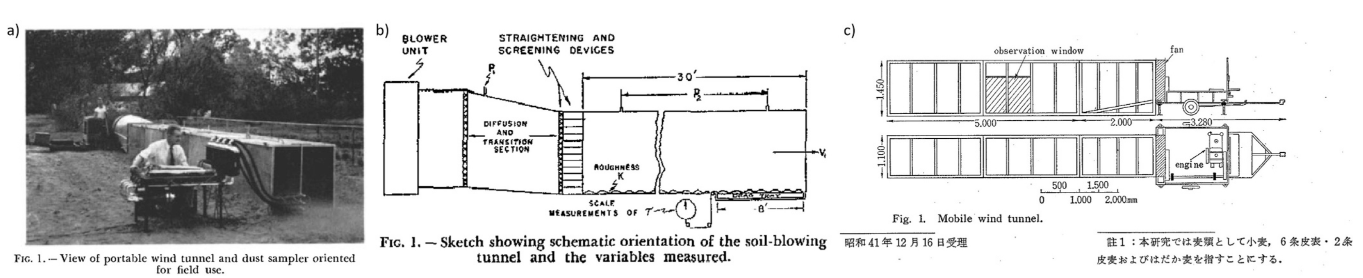

Fig. 2. PWT construction details a) (Zingg, 1951a), b) (Zingg and Woodruff, 1951), c) (Udagawa and Oda, 1967).

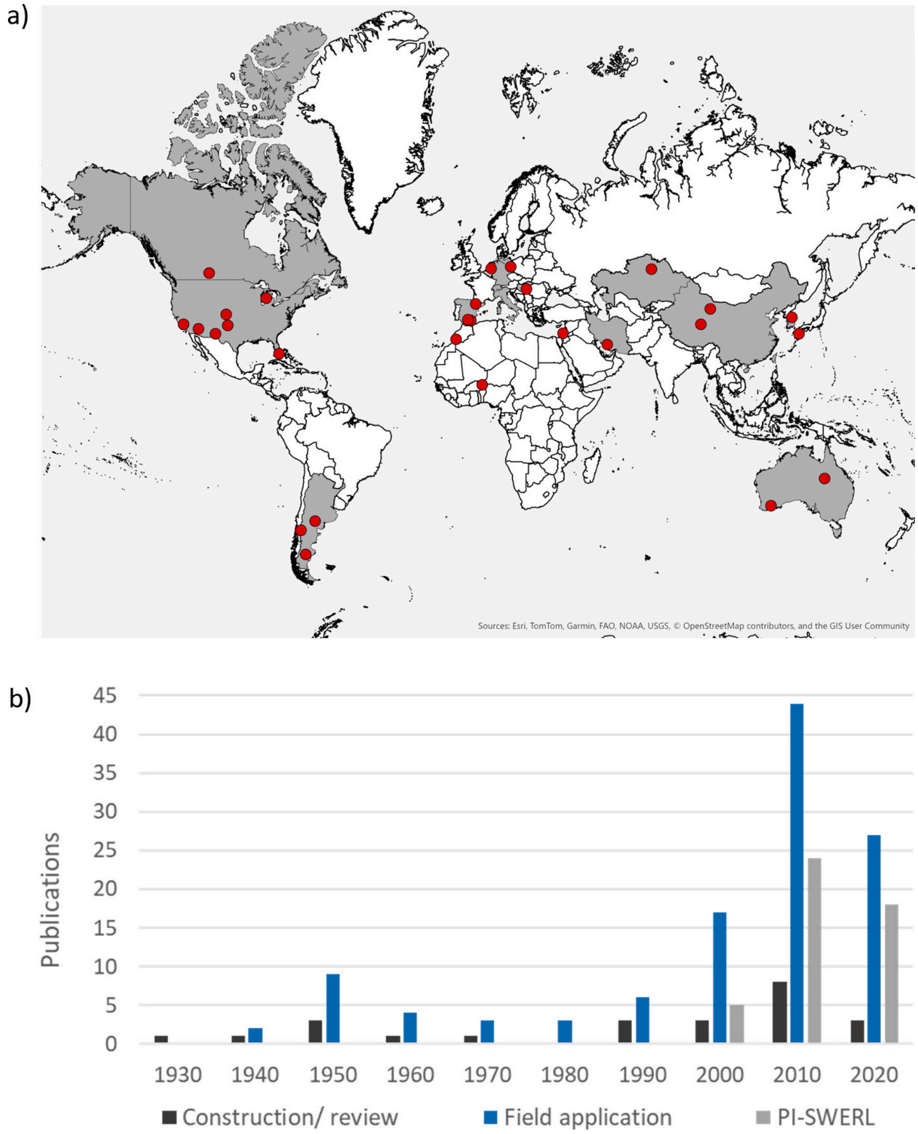

Fig. 3. a) World map with countries with constructed tunnels (gray) and conducted test locations (red dots), b) Publications of portable wind tunnel studies for soil erosion research based on Clarivate and Google scholar.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

roughness of a given natural surface. The INCITAP wind tunnel was difficult to level due to its S-shaped section, so the Patagonian wind tunnel, based on the INCITAP tunnel design, was equipped with a flexible transition section (Fig. 4k). Ideally, the boundary layer and logarithmic wind speed profile should be appropriately thick. Some authors deem half the tunnel height optimal to ensure initiation of vertical particle lift (Maurer et al., 2006).

1.3.3. *Conduction of experiment*

Test procedures with PWT mostly follow a general routine including choice of test plot and securing of the original surface at the test area, tunnel and equipment installation, and testing of wind parameters. Sediment flux and wind speed are often measured simultaneously with a high temporal resolution to investigate interrelations between surface and wind parameters and respective particle entrainment. Most research groups apply test durations of 5–15 min. Since the wind erosion processes are mostly not linear with time, the choice of test duration is of particular importance. The test duration should be based on a prior estimation of erosion rates based on surface characteristics including eroding obstacles and supply-limitation. Longer test durations may be beneficial to collect larger amounts of material. The reasonable calculation of site-specific wind erosion rates is related to an appropriate choice of test duration. During the test, environmental parameters are monitored and often recorded to increase the interpretability of the PWT derived data.

To prevent the fan from drawing in erodible particles that may interfere with the measurements, the soil surface underneath the fan should be covered (e.g. tarpaulin) or the fan elevated above the soil surface. Since the air is not filtered prior to the application on the test area, it may contain suspended particles that interfere with the measurements. This is of particular importance for dust measurements by means of aerosol monitors. Comparative measurements without artificial wind (background values) are needed for correction. Mean wind velocities are mostly controlled during the experiment. The velocity profile may be tested after the regular test sequence or at another plot, and changes may be included in the interpretation. Wind velocity measurements on-site are also used to derive the roughness length (z0). Surface characteristics and inclination should be uniform across the tunnel length.

Fig. 4. Portable wind tunnels: a) University of Almeria, Spain, b) Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (CAS), China, c) Shiraz University, Iran, d) Martin Luther University Halle-Wittenberg, Germany/ Barayev Research and Production Center for Grain Farming, Kazakhstan (MLU/ BRP), e) University of Basel, Switzerland f) Istituto Nazionale di Geofisica e Vulcanologia (INGV), Italy, g) University of California, USA, h) Trier University, Germany, i) United States Department of Agriculture–Agricultural Research Service (USDA-ARS), USA, j) Ben-Gurion University of the Negev (BGU), Israel, k1) + k2) National Council for Scientific and Technical Research (CONICET)/National Institute of Agricultural Technology (INTA), Argentina.

Table 1
Recently applied tunnels and device specifics.

PWT, Country	University/ Institute/ Working group	Test section, length (m)	Test section, height x width (m)	Total Length (m)	Logarithmic wind profile height (m)	Fan type	Velocity range ($m\,s^{-1}$)	Special features
Argentina	National Institute of Agricultural Technology	4.0	1.0 × 0.5	11.0	0.6	Push	Up to 22.5	Windows for optical observation
Argentina	Institute for Earth and Environmental Sciences of La Pampa (INCITAP)	4.0	1.0 × 0.5	11.0	0.6	Push	Up to 22.5	Abrader hopper (sand feeder)
China	Dunhuang Gobi Desert Research Station, Chinese Academy of Sciences	6.0	0.6 × 0.6	11.4	0.2	Push	Up to 16.0	Windows for optical observation
Germany/ Kazakhstan	Martin Luther University Halle-Wittenberg/ Barayev Research and Production Center for Grain Farming	6.0	0.8 × 0.8	13.0	0.4	Push	Up to 19.0	Windows for optical observation and easy surface access
Germany	Trier University	4.0	0.7 × 0.7	10.0	0.2	Push	Up to 8.0	Rainfall simulation unit (➔ wind-driven rain), Windows
Iran	Shiraz University, Shiraz	2.5	0.3 × 0.3	10.0	–	Push/ suction	0.5–22.0	Integrated particle collector (plastic tube)
Israel	Ben-Gurion University of the Negev	10.0	0.5 × 0.5	11.5	0.4	Push/ suction	Up to 18.0	Changeable fan type
Italy	Experimental volcanology research group, HPHT lab, INGV	1.1	0.1 × 0.1	2.5	–	Suction	Up to 22.5	High speed cameras
Spain	Department of Agronomy, University of Almería	2.4	0.8 × 0.8	5.0	0.2	Push	10.0	Laser scanner
Switzerland	Physical Geography and Environmental Change Research Group, University of Basel	4.0	0.6–0.8 × 0.8	11.0	0.4	Push	Up to 15.0	Rainfall simulation unit (➔ wind-driven rain), Windows
USA	USDA-ARS-WEWC, Wind Erosion and Water Conservation	2.0–6.0	1.0 × 0.5	12.0–14.0 depending on fan and trailer orientation	0.5	Push	Up to 18.7	Flow conditioning section with sand hopper, vertically integrating slot sampler, Sediment Recovery and Sorting system
USA	Department of Geography, University of California	10.0	0.5 × 0.5	11.5	0.4	Push/ suction	Up to 11.0	Abrader Hopper, IR Particle Counters, PM Monitor

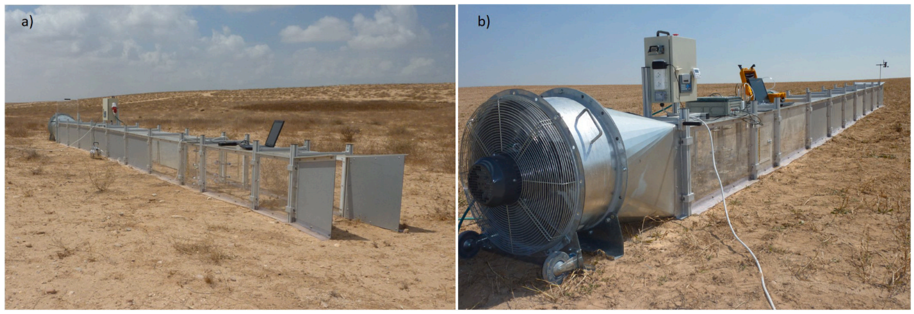

Fig. 5. BGU-tunnel with a) push-type and b) suction type wind source with respective measurement installations.

1.3.4. Surface and topsoil characteristics

The characteristics of the in situ tested surface are crucial information for interpretation of PWT study results. While stationary wind tunnels mostly work with easily erodible sand to allow a separation of the research target from other influencing factors, the testing of the unique and delicate structure of cohesive substrate surfaces is the basic research goal towards which PWT tests are oriented. Specific roughness or surface elements such as physical or biogenic crusts and embedded stones are hardly reproducible in laboratory and the main reason why a portable and not a stationary tunnel is preferred. The quality of the experimental study including validity, repeatability, reliability and interpretation consequently are based on the exact and thorough characterisation of the surface.

The characterisation focuses on the first mm of the soil surface to understand present processes and may include deeper soil layers to deepen the understanding of processes on-site over time. Percentages of surface cover (e.g. stone and crust cover, aggregates, vegetation, litter) are determined by visual observation including on-site estimation, photos, and laser scans.

Surface roughness can be measured by chain method after (Saleh, 1993), or derived from UAV photos or laser scanning and computed as the ratio of true surface area to planimetric area (Jenness, 2013) which corresponds to the chain method coefficient but may be biased towards rougher surfaces in case of a rougher resolution. A laser scanner is quick and accurate method for characterisation of roughness as well as detection of microtopographic changes of the soil surface during the tests in order to quantify soil wind erosion (Asensio et al., 2019). The surface roughness can also be calculated from the wind profile and used to evaluate roughness length (z0).

The weight percentage of soil particles with a diameter less than 0.84 mm is the erodible fraction (EF) of the soil (Chepil, 1960; Colazo and Buschiazzo, 2010) which may be measured by either dry rotary sieving, or dry flat sieving (López Sánchez et al., 2007). The resistance to wind shear and abrasion is measured by a vane test device or a pocket penetrometer e.g. (Marzen et al., 2022; Mina et al., 2022). Focused basic properties that relate to cohesivity and aggregate stability and major factors for soil erodibility to wind forces include contents of organic matter, soil water and clay particles. The tested soil is sampled per site or plot for laboratory analyses of the physio-chemical properties of the upper soil layer.

1.3.5. PI-SWERL®

While it is not considered a wind tunnel, the Portable In Situ Wind Erosion Laboratory (PI-SWERL®) is applied in close relationship with the research topics targeted by straight wind tunnels. Noting the difficulty of satisfying boundary layer, Reynolds number, and Froude number similarity criteria, Etyemezian et al. (2007) proposed a different approach to characterizing wind erodibility of soils. The PI-SWERL® device transfers friction from a suspended (6 cm above the test surface), flat, rotating annular disc (outer diameter 25.4 cm, inner diameter 17.8 cm) to the test surface. The rotation of the disc is controlled by a motor and can be varied to simulate friction velocities from 0.15 $m s^{-1}$ to >1.0 $m s^{-1}$ depending on the roughness of the test surface (Etyemezian et al., 2014). The device components are housed in a cylindrical chamber (ID 30 cm) that is actively vented, and dust concentrations within the chamber are measured with a real-time particulate matter (PM) monitor. This allows for estimation of a dust flux at varying simulated friction velocities. Use of optical gate devices (Etyemezian et al., 2017) within the PI-SWERL body is helpful for identifying incipient movement of sand grains and sustained sand movement under varying conditions of simulated shear stress, though there is no accepted method to calculate a saltation flux.

The advantage of the PI-SWERL is that it is highly portable, is easy to set up and operate in the field, and provides for highly controlled test conditions. The drawback is that it does not recreate the interaction of atmospheric conditions and the soil surface with fidelity. Nevertheless,

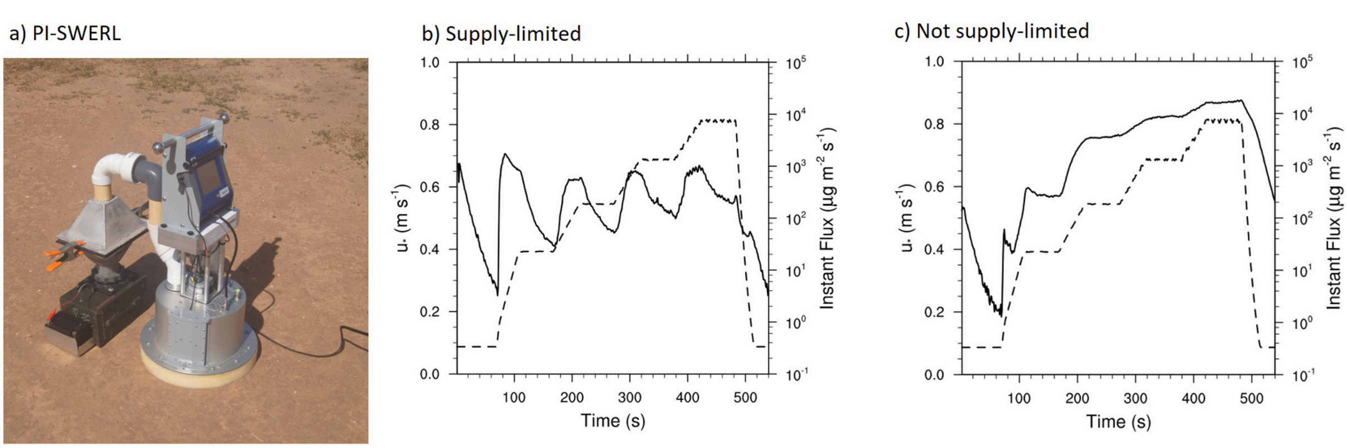

Fig. 6. a) PI-SWERL with dust recovery system, b) supply-limited surface with limited emissivity, c) not supply-limited, highly emissive surface.

numerous studies have used the instrument to infer information that is meaningful for understanding aeolian sediment systems. Sweeney et al. (2008) performed a side-by-side comparison of the PI-SWERL with a large field tunnel developed by the University of Guelph (Houser and Nickling, 2001), showing generally good agreement across several landforms in the Mojave Desert, USA. Another cross-comparison of threshold friction velocities and PM_{10} emissions between a portable straight-line wind tunnel and the PI-SWERL was accomplished by van Leeuwen et al. (2021) at the University of Basel, with similarly good agreement between obtained results for two types of soil substrates. Since then, the PI-SWERL has been used by investigators for quantifying and comparing across locations the dust emissions from arid regions around the world (Cui et al., 2019b; King et al., 2011; Munkhtsetseg et al., 2017, 2016; Salawu-Rotimi et al., 2021; Sweeney et al., 2016, 2011; Sweeney and Mason, 2013; Vos et al., 2022, 2021), investigating aeolian dust, soil properties, and interactions in various contexts (Cui et al., 2019a; Gillies et al., 2022; Goossens and Buck, 2009; Kavouras et al., 2012; Mejia et al., 2019; Sankey et al., 2012; Smits et al., 2024; Sweeney et al., 2023; Van Pelt et al., 2020; Wang et al., 2015), and better characterizing the instrument and its measurement properties (Etyemezian et al., 2014; von Holdt et al., 2021).

Recent configurations of the PI-SWERL testing system include an aerosol spectrometer yielding the number of particles in 31 diameter ranges from 0.253 μm to >35 μm and nine regulatory measures of aerosols for each 6 s period of the test. In addition, an aspirating filter that filters the PI-SWERL exhaust to yield a physical dust sample for chemical and biological analyses was designed and built (Fig. 6a). One of the advantages of the PI-SWERL is the rapid characterisation of supply limited and unlimited surfaces (Van Pelt et al., 2020). During the execution of the test, when dust emissions initially increase as the shear force is increased and then falls to previous levels under the increased steady state shear force, the surface is supply limited (Fig. 6b). When dust levels increase with increased shear force and do not drop with time, the surface is not supply limited (Fig. 6c).

1.4. Portable wind tunnel research objectives

Portable wind tunnel work is conducted because the specific structure of the tested surface is acknowledged crucial for soil surface response to wind. Wind is a primary mechanism for transport and redistribution of sediments, soil organic matter, SOC, seeds, and nutrients (Larney et al., 1998; Li et al., 2007; McTainsh and Strong, 2007). The initial effect of the agent wind is the movement of particles. One of the most basic research aims for PWT applications is the determination of shear stresses required for particle entrainment over a surface under specific natural field conditions (Gillette, 1978; Rezaei et al., 2022). Thus, the threshold wind velocity is a crucial parameter to determine potential wind erosion and dust emission and a basic variable for modeling approaches. PWT work has been associated with more complex surfaces often in agricultural or semi-arid environments. The range of research objective spans from determination of erodibility indices and quantification of transport rates of sand and dust over on-site dynamics of mineral and organic material including redistribution of carbon and nutrients, to landscape development.

1.4.1. Impact of wind erosion on landscape and environment

Wind is one of the most important geomorphological agents (Lancaster, 2023). While PWT are mostly used for plot level analysis, they may be deployed to investigate the effects of landform development, landscape functionality, and ecological services. To use the plot scale data for a larger scale, the tunnel's aerodynamic parameters should comply with the aerodynamic standards (e.g. logarithmic velocity profile). The PWT-derived data may be used for interpreting aerodynamic parameters as well as eroded and emitted material regarding specific environmental conditions.

In a dryland environment, a range of typical surfaces including desert scrub and patchily vegetated river terraces were adequately classified by means of the threshold wind velocity u_t (Nickling and Gillies, 1989). Redistribution of soil material by wind occurs on plant-interspace scale, the patch-landscape scale, and the regional-global scale including deposition of nutrients in downwind ecosystems (Okin et al., 2006). In agropastoral argan environment, erosion was found related to small-scale variations in land use and roughness, and crusted surfaces were not eroded by wind and act as a sediment cache for subsequent transport, while roughness elements act as local traps (Marzen et al., 2022). Wadis may function as sediment and organic carbon source or sink depending on variabilities on a very small temporal and spatial scale (Marzen et al., 2022). In a similar dryland environment in Israel, PWT tests showed a strong impact of agricultural activity on wind erosion and dust emissions (Katra, 2020). The study highlighted the crucial impact of herding, because greatest total emissions were measured on surfaces that were impacted by grazing and subsequently caused intense destruction of physical crusts and pulverization of the aggregates (Katra, 2020). On a plot scale, PWT tests in combination with soil analysis pointed to wind-driven dynamics of SOC which is released as litter from local vegetation before being transported across the soil surface to be reduced to smaller particles by the scouring winds and sand particles (Marzen et al., 2020). In the northern Kazakhstan Steppe environment, severe soil and organic carbon loss occurred immediately after the destruction of the native grass vegetation and seedbed preparation for crop cultivation (Koza et al., 2024a). On a landscape scale, portable wind tunnel experiments were used to investigate how changing wind patterns and hill shapes affect the distribution and deposition of dust (Offer and Goossens, 1995). Spatial deposition patters were associated with a greater accumulation of dust on the windward side and near the summit of conical landforms (Offer and Goossens, 1995).

1.4.2. Physical and biological crusts

Soil resistance to the eroding action of wind is strongly altered by physical (Chepil, 1953) or biological crusts (Marticorena et al., 1997). The specific reactions from surface crusts to wind and wind-driven sand flux are two of the most highlighted subjects for PWT studies. In situ measurements on the naturally developing crusts are critical to obtaining accurate and reliable data on the effects of wind impact on erosion and potential dust emissions, because crusts can hardly be recreated in a laboratory setting (Pietersma et al., 1996). It has long been understood that a crusted surface layer significantly reduces soil erodibility by wind (Belnap, 2003; Belnap and Gillette, 1998). Mechanical crusts, on undisturbed arid soils, help minimize soil erosion and keep dust emission at low levels (Edri et al., 2016). The authors found this effect on sandy soil, including rock fragments, as well as vegetation covered soil (Edri et al., 2016). The strength of the crust varies with the composition and distribution of the binding media (Zaady et al., 2017). Tests on strongly crusted, lightly crusted, and tilled surfaces in close proximity to each other showed that even a slight (probably dew-induced) physical crust considerably increased shear resistance and decreased the intensity of wind erosion (Marzen et al., 2020). A loose gravel mulch cover was shown associated with a linear increase in shear stress and threshold wind velocity and a decrease in sand transport rate (Zhang et al., 2015). The precise characterisation and historical development of these natural crusts remain a challenging subject to assess. It is evident that the integration of the Pi-SWERL with a rainfall simulator provides a valuable opportunity to analyze crust specification and development in a highly effective manner, primarily due to its small plot size (Vos et al., 2020).

Without the constant scouring action of saltating grains, erosion-prone substrates are strongly supply-limited and show a minor dust emission after a first very intense peak during the first seconds (Houser and Nickling, 2001). A PWT equipped with a sand feeder can provide a cascade of sand impacting the crusted surface to investigate and quantify an increased dust production from resulting abrasion of the crust (Van Pelt et al., 2013).

Fig. 7. Preparation of surface: a) levelling and reducing roughness for comparable surface, b) use of hammer to simulate hoof impact, c) animals led over the test plot prior to mounting the tunnel.

Biocrust disturbances have been assessed by measuring the sediment flux rates on three disturbance-levels (Leys and Eldridge, 1998). It demonstrated the important role of cryptogamic crusts in binding and providing roughness after moderate disturbances. On loam soils, sediment fluxes strongly increased after a severe disturbance, but undisturbed crusts maintained surface stability. Crust cover was associated with high emissions on sandier soils, and a disturbance caused an increase of up to 6.7 times the erosion control target. The crust removal decreased the threshold wind velocity and resulted in an increase of erosion risk from <5% to 20% (Leys and Eldridge, 1998). By applying a micro PWT, cyanobacterial soil crusts in Australian drylands were analyzed for their reaction to rainfall and the ensuing impact on wind erodibility (Bullard et al., 2022). The authors found that key parameters concerning the natural biocrust were more adequately represented by field experiments, in contrast to cultured, microbial communities in previous laboratory tests. The tests supported findings of previous studies, stating biocrusts very effectively stabilize the soil against wind erosion. The authors also noted that the duration of this effect must be newly assessed for climate change impacted landscapes, because dehydration decreased the crusts' resilience to disturbance (Bullard et al., 2022).

1.4.3. *Effects of mechanical surface disturbance*

Mechanical impacts generally lead to the destruction of a naturally developing surface structure including surface crusts, soil aggregates, vegetation and stone coverages. With the loss of preserving cover and the destruction of aggregates, the susceptibility to detachment and transport is increasingly dependent on soil properties texture, aggregation, and moisture. External forces from anthropogenic activity including tillage, grazing and driving are considered main driving forces for aeolian processes and affect entrainment and emissions either directly or indirectly (Katra et al., 2016). The indirect impacts of agriculture are creation of bare, susceptible soil surfaces and destruction of stabilizing soil texture or crusts. PM emissions occur due to field cultivation and consecutive wind erosion from agricultural land (Funk et al., 2008), and the direct effects of land use and management operations have been found to strongly impact wind erodibility. Wind erodibility was compared between non-tilled and tilled cropland and (trampled) rangeland in the farming–pastoral ecotone in northern China as well as local to regional dust inventory (Chen et al., 2015). The testing of agricultural soil surfaces has been the objective of numerous field studies (Fig. 7 a, b). Past and present research aims address the erodibility of soil surfaces related to specific crops, soil types and tillage methods (Zingg, 1951a). A multitude of different tillage devices is applied globally with according impacts on wind erosion and dust emissions: Disk-tillage application was related to a higher soil loss than cultivator-tillage, and stubble grazing was found to be associated with a stronger aeolian erosion than mechanical tillage (Tanner et al., 2016). In addition, disturbance of the surface was found to increase the potential for multiple emission events, which may affect the temporal accumulation of atmospheric dust (Macpherson et al., 2008). The impact of herding and trampling has been tackled by passing over a cow (Baddock et al., 2011), goats (Ries et al., 2014), or artificial hooves (Van Pelt et al., 2017), over the test surface (Fig. 7c). In general, dust emissions increased with the degree of disturbance (Baddock et al., 2011). The interaction between soil surface, transported sand and aggregation is critical for total aeolian soil erosion and the potential of dust emission over time (Swet and Katra, 2016). Stones or large aggregates have been

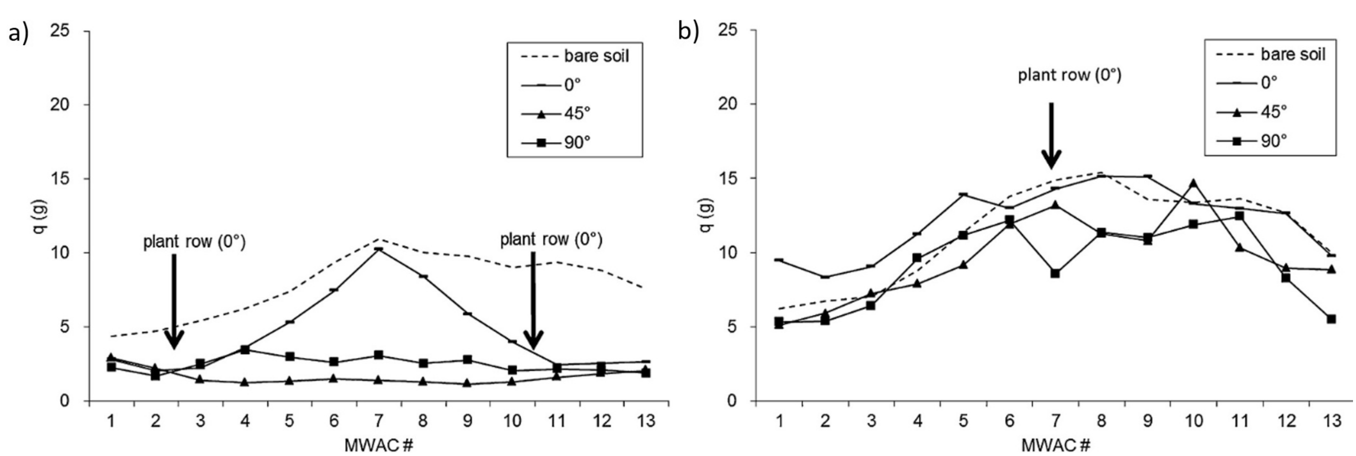

Fig. 8. Sediment flux over the wind tunnel width of 0.7 m for a) beet and b) maize (Funk and Engel, 2015). The distinct impact of plants on horizontal sediment flux has also implications for the choice of the adequate sampling spot and interpretation of results from heterogeneous surfaces, particularly for test plots containing plants.

in use for a long time as emergency dust control measure (Fryrear, 1984). The rough surface controls erosion by providing shelter angle protection of the surface behind the clods (Potter et al., 1990). Dirt roads and field tracks are considerable sources of wind erosion (Koza et al., 2024b, 2024a) and fugitive dust emissions (Etyemezian et al., 2003). Since they are subject to fluid impact by surface wind as well as the direct impact by vehicle travels, they may be considered a substantial contribution to mass transfer and air pollution (Katra, 2019).

1.4.4. Plant-wind interaction and effects on erosion

On a meso scale, plants increase the surface roughness, the aerodynamic roughness length considering the logarithmic wind profile, and decrease the wind velocity related to an obstacle-specific height and fetch length. On the micro scale, complicated interactions between air stream, specific plant and surface may lead to temporally and spatially very small-scale increases in wind velocities and generation of turbulences. Element height, width, shape, spacing, and arrangement alter the form of the wind profile within the roughness sublayer and change the flow regime (Wolfe and Nickling, 1993). In an ecological and economic context, these small-scale variabilities are of particular interest because of their impact on abrasion by saltating particles, also called sandblasting. It mainly affects young plants, and possibly biocrusts, and consequently may lead to significant crop damage and economic losses to farmers (e.g. (Hagen and Casada, 2013; Skidmore, 1966). Stationary wind tunnel studies with live plants showed complicated interactions between moving leaves and development of small-scale turbulences (Burri et al., 2011). The partial blocking by the plants enhanced wind speed and sand flux above and within planted areas, and the fluttering of leaves was found to increase sand flux even under a low vegetation density (Miri et al., 2019). In few PWT studies, the effects of plants on wind patterns and related sand flux have been studied for plants suitable for the tunnel scale. Comparisons between surfaces with and without young maize *(Zea mays)* plant rows supported the results concerning a profoundly changed wind field including a reduced mean wind velocity at the direct plant area, and an increased velocity at the vicinity (Farsang et al., 2013). Consequently, the total soil erosion was higher from plots with vegetation in rows compared with plots without rows in various environments (Farsang et al., 2013). On a particularly erodible sandy soil, a comparative study showed that vegetation cover of maize and beet (*Beta vulgaris*) led to a reduction of soil erosion only if 40% or more soil was covered (Funk and Engel, 2015) (Fig. 8). Maize plants with a percentage of <10% covered soil led to a higher soil loss in comparison to a bare plot (Funk and Engel, 2015).

Niu et al. (2023) investigated the ecophysiological effects of sandblasting (sediment flux) on arid grassland vegetation. The results from the experiment showed that C_4 vegetation (grasses) is more susceptible than C_3 vegetation (shrubs) to wind-driven sediment transport in a dryland environment.

1.4.5. Particulate matter

Dust is a key driver of ecosystem and environmental conditions because it connects all components of the Critical Zone on local, regional, and intercontinental scales (Brahney et al., 2024). Wind erosion processes lead to the emission of dust and fine dust by either direct aerodynamic entrainment, or by the action of saltating sand-sized particles (Bagnold, 1941; Shao et al., 1993). While aerodynamic entrainment is generally considered to provide a minor contribution to total dust emission budget (Shao et al., 1993), there is evidence that it may be of major importance under specific soil conditions (Kjelgaard et al., 2004), or during convective turbulences (Klose et al., 2014). Laboratory tunnel studies have investigated this relationship based on saltation or emission efficiency (Avecilla et al., 2016a, 2015; Panebianco et al., 2022). A PWT study on the relative aerosol production potential found differences for a range of surfaces including abandoned agricultural land, desert scrub, dunes, and a sparsely vegetated river terrace (Nickling and Gillies, 1989). In supply-limited environments, a PWT study found primarily aerodynamic-resuspension driven PM_{10}-emissions (Macpherson et al., 2008). They found emission rates directly influenced by wind shear and mechanical disturbance, and indirectly by soil texture. Another PWT-study concludes that dust emission efficiency is high and strongly correlated with frictional velocity because saltation bombardment maintains surface renewal and dust supply (Liang et al., 2024). They also found if the surface sand supply is insufficient, dust emission efficiency gradually decreases with the increase of the frictional velocity, and the correlation gradually weakens until irrelevant (Liang et al., 2024). Recent dust and fine dust dynamics are of high interest regarding ecological, agricultural, and economic considerations since they contain a disproportionally high amount of SOC and plant nutrients 13/01/2026 06:09:00.

For a great range of soil surfaces and environments, the actual output of dust and adhesive aerosols has not been comprehensively quantified yet. Among them are post-fire aeolian processes, since burned soils have been found mayor sources of atmospheric particulate matter (Meng et al., 2025; Wagenbrenner et al., 2013), and anthropogenic dust emissions, which are still related to a great uncertainty (Chen et al., 2023). PWT applications of site-specific natural surface conditions may provide crucial information on processes and rates.

1.4.6. Contaminants and microbes

Feedlots represent a continuous point source of particulate matter into the atmosphere, encompassing organic components and pollutants highly relevant for environmental and land use planning, and human health (de Oro et al., 2021). Laboratory wind tunnel tests with a steady low wind velocity found the release of PM and adhering contaminants and microbes from manure related to manure type and moisture content (Kabelitz et al., 2020). A PWT study found not only high enrichment factors for two investigated pesticides but also an increase of this enrichment after specific soil management after pesticide application (Csányi and Farsang, 2022). The impact of scratching and sandbathing of hens from outdoor runs on PM emissions was investigated by means of a specifically modified PWT (Maffia et al., 2021). Small portable wind tunnels have also been applied for quantification of field losses of ammonia (Lockyer, 1984) and carbon dioxide (Loubet et al., 1999).

PWT was applied to investigate the wind-driven dynamics of microbial communities in situ. The source soils could experience significant reductions in their bacterial diversity as a consequence of wind erosion (Gardner et al., 2012), and considerable levels of bacterial diversity were found in the eroded coarse sediment and finer dust particles (Acosta-Martínez et al., 2015). A PI-SWERL study highlighted relations between source soil microbiome and emitted dust and found considerable differences between microbiomes from different agricultural soil surfaces (Salawu-Rotimi et al., 2021). The findings are of particular importance for soils or soil surface layers that are specifically rich in organic matter. These soils can be susceptible to wind erosion when dry due to their low density. In addition, they are typically associated with intense cultivation, which can increase their wind erosion risk.

Transport of microplastics by wind was revealed for the first time using a PWT in Iran (Rezaei et al., 2019). The light density microplastics were shown to be preferentially eroded (Bullard et al., 2021) and effectively shred by wind impact (Bullard et al., 2023). PWT-studies on semi-arid arable land supported a considerable enrichment of microplastics in wind eroded sediment (Rezaei et al., 2019).

1.4.7. Resuspension of volcanic ash

Volcanic ash contains fine abrasive particles including silica and poses a significant health risk, damages ecosystems, and alters soil chemistry. In contrast to coarser mineral particles, volcanic ash can remain airborne longer, increasing potential risks to aviation and urban infrastructure, including the damage of systems and electronics. Since its physical properties are highly variable, its behavior is difficult to predict (Del Bello et al., 2018). Specifically focused research is necessary for hazard management. First laboratory wind tunnel studies found that volcanic ash particles of similar sizes are resuspended at a range of threshold friction speeds, due to their highly variable shape and density (Del Bello et al., 2018). Irregular, low-density particles resuspend at lower wind friction speed than dense, uniform particles. Ash resuspension showed to be only reduced under very high humidity conditions with >90% RH (Del Bello et al., 2018). These results were supported by PI-SWERL (Etyemezian et al., 2019). A mini PWT for ash resuspension (PoWAR) was constructed and calibrated to investigate the impact of site-specific natural deposit conditions on threshold friction speed (Del Bello et al., 2021). Local deposit conditions were found to be a minor factor compared to the particles' physical properties.

1.4.8. Prevention of wind erosion and dust emission

The prevention of wind erosion and dust emissions has been the main aim of PWT-studies from the beginning of soil erosion research (Zingg, 1951a, 1951b). Anthropogenic activities such as agricultural management, quarrying, mining, and off-road vehicles, have been major targets for wind erosion and dust emission control. The application of synthetic or natural stabilizers is preceded by an exhaustive evaluation of their effectiveness. The testing of different soil stabilizing products and comparisons of their effectiveness have been carried out using wind tunnels (Avecilla et al., 2016b). By manipulation of wind speeds and soil surface conditions with specific respect to soil texture, the necessary concentrations for effective control and application procedures are determined. PWT were applied for a broad variety of stabilizing vegetative and nonvegetative materials (Chepil et al., 1963; Lyles et al., 1974) and manure (Woodruff et al., 1974). A range of stabilizers was applied as aqueous dilutions which were sprayed with coarse-spray industrial nozzles, or as undiluted material with fine-spray agricultural nozzles finding wind erosion reduced to 0.4 t/acre (Lyles et al., 1969). An evaluation for heavily stressed surfaces such as unpaved roads included a wide range of dust control products such as Lignin, Resin, Bitumen, PVA, and Brine (Katra, 2019). The stabilization of mobile sand dunes was aspired by application of coal fly-ash and bio-inoculants which supported the rehabilitation of disturbed biocrusts (Zaady et al., 2017).

2. Extensions for specific applications

2.1. Sand feeder

The impact of saltation on entrainment is a paramount factor in wind erosion (Raupach and Leys, 1990). The fetch effect is an increase in the sediment transport rate (Q) with distance downwind which generates an (increasingly saturated) saltation layer (Gillette et al., 1996). Because of the crucial impact of the wind-driven bombardment and in-air collisions on dust generation and emission, a well-developed steady-state saltation layer is a valuable feature. Experimental results indicated device-specific minimum length required for studying the saltation process in its equilibrium state, as well as the order of magnitude of the measurement errors if the tunnel is shorter (Shao and Raupach, 1992). The additional input of sand at the inlet of the test section has the function to compensate for the missing fetch distance and derive a given saltation flux rate by means of adjustable saltation feed rates (Pietersma et al., 1996; Strong et al., 2016; Van Pelt et al., 2010). (Van Pelt et al., 2010) constructed and tested a sand feeding option for a PWT with an orifice-controlled gravity-fed saltation initiator that drops the sand abrader into inclined tubes for acceleration before striking a sandpaper surface and bouncing into the flow stream. This hopper design works well in the field and has been copied by several wind tunnel builders. A similar sand feeding device was developed and used in studies carried out by the INCITAP wind tunnel (Argentina) to evaluate the effect of increasing the flow of particles mobilized by saltation (additional saltation) with materials of different composition (+/− proportion of aggregates; +/− proportion of sands) (Avecilla et al., 2016a, 2015). The development and operation are related to a range of uncertainties, e.g. the quantity of introduced material and a realistic application in the airflow.

2.2. Rainfall module for wind-driven rain

During storm events, wind and rainfall display various interactions which consequently lead to specific effects on rain drop and wind erosivity (de Lima et al., 1992; Erpul et al., 2000) and total soil erosion (Marzen et al., 2017). Wind alters angle and kinetic energy of falling and impacting rain drops from the vertical and influences the overland flow by direct acceleration (Iserloh et al., 2013) which is a considerable challenge for rainfall simulation experimentation (Ries et al., 2010). A PWT equipped with a rainfall module Trier Portable Wind and Rainfall Simulator (Fister et al., 2012) was applied to investigate the impact of wind-driven rain on undisturbed substrates (Fig. 9). The PWRS was used to quantify the impact of wind on raindrop splash (Marzen et al., 2015) and to compare the wind influence with influence of substrate and slope (Marzen et al., 2016). The same erosion-increasing effect was found on crusted Mediterranean soils (Ries et al., 2014) and on arable land (Marzen et al., 2017).

2.3. Mechanical impact during a wind event

Mechanical impact includes tillage, driving and trampling. In contrast to herding or tillage prior to or after a wind event, the mechanical disturbance during the actual wind event has not been systematically addressed yet by PWT studies. For mechanically triggered

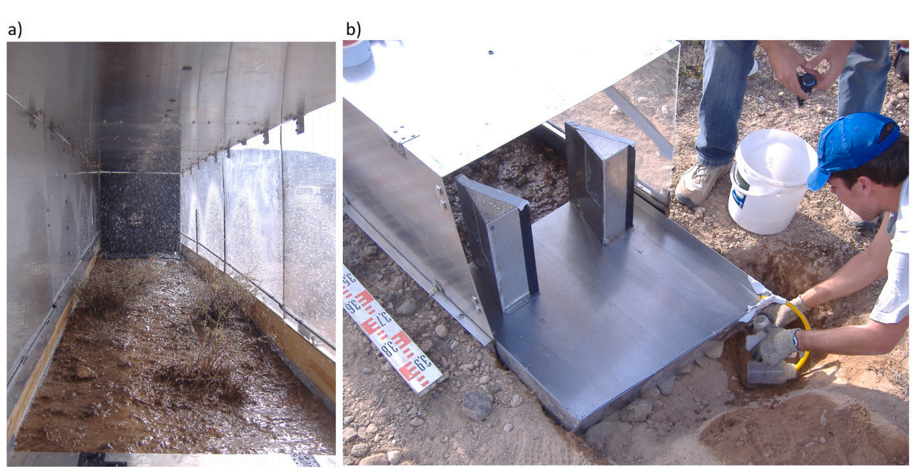

Fig. 9. Trier Wind and Rainfall Simulator with a) applied rain, b) during wind-driven rain test with combined runoff and splash trap.

erosion events, the threshold velocity is not the limiting factor for particle entrainment and total particle flux: the active hauling of particles leaves them floating for a shape- and density-dependent time, where much lower wind velocity is sufficient for transport compared to detachment (Marzen et al., 2022). Larger and more particles may be potentially released into suspension than by solely wind erosion without mechanical impact. Soil tillage was found to have a considerable impact on wind erosion and fine dust emissions (Chen et al., 2015; Funk et al., 2008; Goossens et al., 2001). The investigation of the effects on mechanical impact during a PWT test may give key insights particularly on surfaces where no wind erosion is measured by the common experimental procedure without external impacts (Marzen et al., 2020). The only simulation of animal trampling during a wind test (Fister and Ries, 2009) found a strong increase in wind erosion during the simulated trampling compared with no impact (Fig. 7b). A variation of tools was used to manipulate the surface during wind tests. The application of tillage tools inside the PWT during a run adds uncertainties which greatly affect validity, interpretability and repeatability of the experiment. Mechanical stress exerted by the simulated "hooves" (hammer) needs quantification, and the procedure should be developed to offer a standardization.

2.4. Gusts

Wind tunnel tests and wind erosion models mostly work with a concept of uniform wind velocity, but a steady wind is rarely found in nature since it usually fluctuates (Li and McKenna Neuman, 2014). Velocity peaks have been found associated with highest horizontal flux (Baas and Sherman, 2005; de Oro and Buschiazzo, 2009; Jackson and McCloskey, 1997; Pfeifer and Schönfeldt, 2012) and suspended particulate matter (Siegmund et al., 2022). Sediment entrainment during singular and defined gusts may considerably differ because of the specific characteristics of a gust including a defined velocity difference and a rapid acceleration. The transferred momentum fluxes to the surface may be local but many times the average (Klose and Shao, 2013). Gusts have two potential impacts that suggest application in PWT, an extreme capacity for particle entrainment which may start a subsequent erosion cascade and the direct emission of dust without establishment of a saltation layer. Raupach and Leys (1990) tested gusts in their PWT setup to address hysteresis regarding the higher shear stress needed for initiation compared to sustaining erosion but did not approve the application. A simple setup for simulation of strong singular gusts in a PWT produced one reliable and reproducible gust (with increasing uncertainty for three and five consecutive gusts) and underlined the great impact of gusts on entrainment of sand and loam substrate (Marzen, 2024).

2.5. Miniature wind tunnels

Mini and low-cost PTW have been designed to gain access to remote areas and relatively small and complex surfaces as well as enable greater number of repetitions. An early construction to determine threshold velocities was a tunnel with working section dimensions of 15.24 × 15.24 cm and a length of 300.5 cm (Gillette, 1978). A recently applied micro tunnel is a duct-type design with a cross section of 0.05 m × 0.1 m with a 1.0 m long working section (Strong et al., 2016). The suction wind source reaches velocities from 5.0 to 18.0 m s^{-1} with high reproducibility, but it produces no logarithmic profile due to the dimensions. Wind velocities are laterally uniform and shear velocity values are comparable with larger PWT. There is also a sediment feeding option and it is easy to be operated on slopes up to 10° (Strong et al., 2016). For application on deposited volcanic ash, another small PWT was constructed including a commercial combustion engine fan equipped with a fine-tuning power setting (Del Bello et al., 2021). Flow distortion is prevented by suction mode and a flow straightener. Transparent perspex at the test section enables recording resuspension with high-definition camcorders and high-speed cameras (Del Bello et al., 2021).

3. Data acquisition and application

3.1. Data acquisition

Target information for PWT studies are qualitative and quantitative data of material entrained and transported by the action of wind. Measurement options include collection of transported material, electronic particle sensing, video recording for particle tracking, and surface-change detection. The methods are used individually or combined and need to be chosen consistent with spatial and temporal scale of observed processes, on-site test conditions, focused particle size, and aspired laboratory analyses. The complementary use of sampling and measurement devices enables the comprehensive investigation of particles of different sizes and different forms of transport.

3.1.1. Sediment samplers

Sediment samplers include active and passive traps. Active samplers suck the air in at a similar velocity as the surrounding wind velocity and adapted to the respective pressure conditions, creating an isokinetic state at the inlet, while passive samplers rely on the material transported into the trap by the flowing airstream. Most used sediment samplers are i) wedge-shaped traps and ii) conical traps. Scientists also use iii) filters and sticky paper, iv) collect total eroded material, use a v) integrated approach, or vi) particle tracking. Traps are potentially applicable to all size classes. Collected material is quantified and qualitatively analyzed if sufficient material is collected. The trap itself creates an obstacle to the air flow that that blocks and distracts the transporting air stream as well as the particle itself. Thus, the used traps are designed as aerodynamic as possible including a relatively small directly wind-facing area and low roughness and are placed outside the tunnel. The greatest share of wind eroded particles travel in the saltation layer with 90% in the first 0.3 m (Chepil and Woodruff, 1963), so collection of particles in this height enables representative quantification of total mass flux. For application inside or at the outlet of a tunnel, the actual size of the passive sampler and its effect on the collection efficiency may be considered highly device-specific because it relates to the created airstream for every wind source device (Goossens et al., 2000). The sampler body is designed as a deceleration chamber which promotes deposition of transported particles into the container. The quantification of eroded material should include an estimation of the impact of the trap on respective particle characteristics. While large saltating particles may be trapped with high efficiency, the lighter-weight fraction of eroded sediment including nutrient-rich dust and SOC are less efficiently collected. These unequal efficiencies subsequently may result in an underestimation of nutrients and SOC loads in the wind-eroded material and enrichment compared with parent soil material (Webb et al., 2013).

3.1.1.1. Wedge-shaped traps. Wedge-shaped traps collect a large amount of material but also may create a relatively large measurement error. They are a greater obstacle to the air stream, causing a higher stagnation pressure and a decreasing fluid flux through the sampler inlet with a subsequent decrease in trap efficiency (Goossens and Offer, 2000). Particularly very small particles with small inertia tend to flow around the collector instead of entering the sampler (Goossens and Offer, 2000). One of the most widely used traps is the Big Spring Number Eight (BSNE) sampler (Fryrear, 1986). The BSNE very efficiently collects saltation material >100 μm (~90%), but severely underestimates dust <10 μm (~40%) (Goossens and Offer, 2000; Shao et al., 1993). Traps with a large vertical vent (e.g. (Nickling and McKenna Neuman, 1997; Van Pelt et al., 2010) allow for continuous measurement of the entire or a representative area of the wind profile to derive mass transport without extrapolation and mathematical estimation. Wedge shaped traps are still being developed and modified (e.g. (Cornelis and Gabriels, 2003, Fister and Schmidt, 2008). The Bagnold trap included several heights and has been adapted to act as an isokinetic trap (Stetler et al., 1997). The mounting of the traps needs specific attention. Wedge-shaped traps have been shown to react very sensitive to incident wind angle with deviations >5° by significantly reducing the sampling efficiency and promoting scour around the trap inlet (Nickling and McKenna Neuman, 1997).

3.1.1.2. Conical traps with inlets. A modified Wilson and Cooke sampler (MWAC, (Wilson and Cooke, 1980)) includes bottles made from plastic, glass, or aluminum with inlet and outlet tubes with a small wind facing area. They collect smaller amounts of eroded material but have a higher efficiency in greater heights and for smaller particles and higher wind speeds compared to wedge traps (Goossens et al., 2000). Trap efficiency was tested 110–120% (mean grain diameter 126 μm) for wind speeds between 7.0 and 14.0 m s^{-1} against an isokinetic probe reference system (Goossens et al., 2000). Generally, several collectors are mounted vertically at a beam and the point measurements are integrated to obtain the total horizontal mass (Dong et al., 2003; Gillette et al., 1997; Koza et al., 2023; Shao and Raupach, 1992). The horizontal installation of MWAC can help to identify the variability of the sediment transport across the wind tunnel width and is useful when obstacles such as row crops with a certain arrangement are examined (Funk and Engel, 2015) (Fig. 8). A new trap with a high trapping efficiency was recently tested against MWACs and BSNE (Mendez, 2022). The Suspension Sediment Trap (SUSTRA, Janssen and Tetzlaff, 1991) has a large opening allowing for the collection of higher quantities of eroded material for qualitative analyses and provides maximum trapping efficiency for particles of medium to fine sand. The inlet flow velocity is adjustable by varying a slot on the backside of the vertical tube, thus providing near-isokinetic conditions. While the wind vane for alignment to natural wind is not removable, it may be fixed for PWT applications and the substructure may be buried (Funk and Engel, 2015; Koza et al., 2024a). The cyclone sediment trap (BEST) has a cyclone separator by design and collects also finer particles with a high efficiency between 75 and 100% from stationary wind tunnel experiments (Basaran et al., 2011).

3.1.1.3. Filter and sticky surfaces. Filter papers are common in fine dust observation and often included in aerosol monitoring devices. The filters are used for quantitative and qualitative analyses by a range of microscopy approaches. Stationary tunnel tests used vaseline-coated slides (Basaran et al., 2010; Youssef et al., 2007). Adhesive plates were successfully used in combination with image processing (Asensio et al., 2016). Sticky surfaces may be used in PWT applications, but the surfaces are easily contaminated under field test conditions.

3.1.1.4. Collection of total eroded material. Some sediment collectors have been aiming to collect the total amount of eroded material in contrast to an aliquot sampling by traps. An 8-m-long two-layer cyclone collector was attached at the end of the wind tunnel and allows for collection of total detached particles from the open surface area inside the PWT (Sirjani et al., 2019). The wind flows with the detached material from the working section into the inner tube and deposits the eroded material at the bottom before the air is pushed over to the external tube and exits “clean” through the holes (diameter: 0.1 m) on top. (Fister and Ries, 2009) used a tarpaulin to build an open-top sedimentation area at the tunnel's outlet. For a mini wind tunnel setup, the sampling bottle was connected to the airflow outlet, where a collection vial could be swapped during the ramp-up experiment (Del Bello et al., 2021). The method was estimated to capture nearly all material except fine dust fraction (approximately smaller than 30 μm) which was lost with the airflow.

3.1.1.5. Integrated sampler. The vertically integrating slot sampler USDA-ARS-WEWC Sediment Recovery and Sorting (SRS) system collects sediment in the lower 0.1 m at the end of the tunnel (6 m downwind). The entry of the SRS is rectangular in shape and has a subtending settling chamber where soil aggregates and coarse sand are deposited (Fig. 10a). The aspirated flow then transitions into a large volume (0.3 m^3) settling chamber with a subtending pan that captures the medium sand before allowing the finer sediment to be captured on glass fiber filters. Samples from the respective sections are representative of aeolian sediments deposited on the edge of an eroding field, several meters downwind, and possibly entering long-range transport.

vi) Particle tracking/ Particle image velocimetry.

Particle tracking is an option for larger particles during stationary wind tunnel tests (O'Brien and Neuman, 2023) and has been applied for PWT- tests with particle detection by high-speed (HS) or high definition (HD) camcorders (Del Bello et al., 2021). For large particles, moving particle counts were estimated automatically using particle image velocimetry; when particles were too small or poorly contrasted, the gray tone variation of images was used (Del Bello et al., 2021) (Fig. 11 c).

3.1.2. Electronic particle sensing

3.1.2.1. Optical sand detection. In addition to electronic measurement of dust, real-time measurement of sand movement is also increasingly applied in wind tunnels. These fall broadly into two classes, impact-based sensors (e.g.,(Baas, 2004; Ellis et al., 2009; Jackson, 1996)) and optical based sensors (e.g., (Butterfield, 1999; Davidson-Arnott et al., 2009; Hugenholtz and Barchyn, 2011; Mikami et al., 2005). Saltation impact sensors may primarily be applied to study temporal or spatial saltation patterns rather than quantification for total saltating particles but can be calibrated for event-specific soil and wind condition (Van Pelt et al., 2009). Optical based sensors are more promising for use inside of

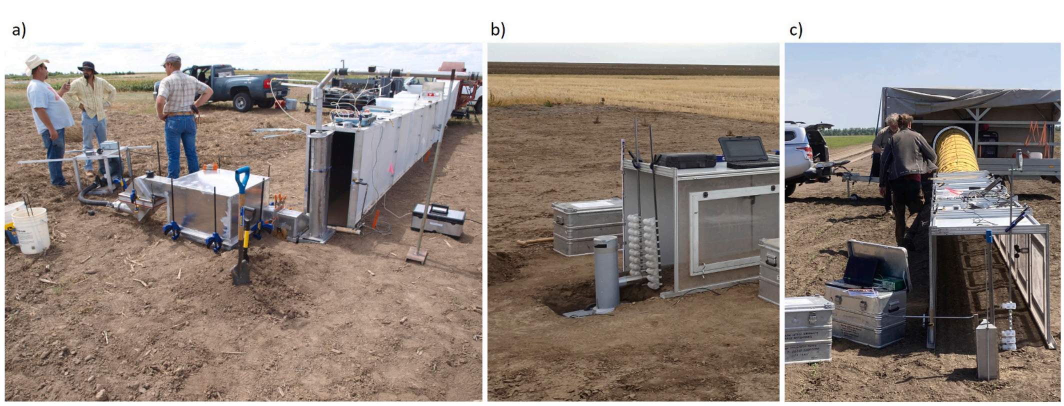

Fig. 10. Sediment collection: USDA-PWT with Sediment Recovery and Sorting system (SRS) and the vertically integrating slot sampler, b) MLU/ BRP tunnel with SUSTRA trap, c) MLU/ BRP tunnel with MWACs, alu-wedge trap for microplastic analysis, and aerosol monitor.

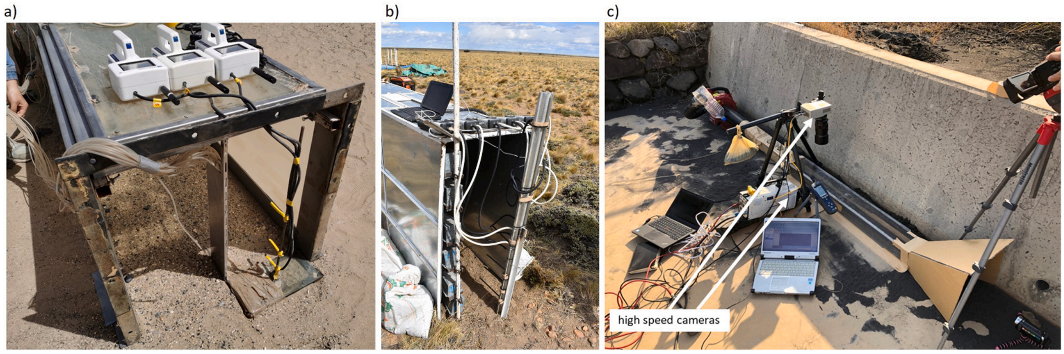

Fig. 11. Optical particle detection a) CAS tunnel with handheld laser airborne particle counters, b) INTA tunnel with handheld airborne particle counters, c) INGV High-speed camera setup.

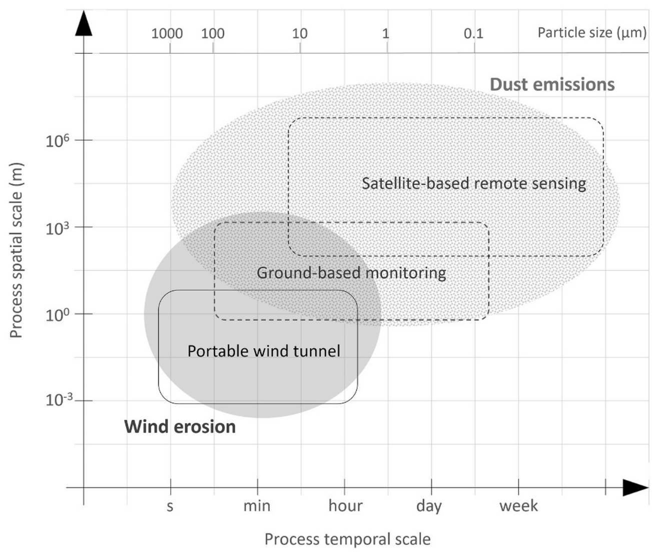

Fig. 12. Conceptual comparison between temporal and spatial scale of wind erosion and dust emissions, and methodological approaches to measure related processes and particles. PWT applications predominantly comply with wind erosion and dust emissions on small temporal and spatial scales, capturing processes related to particle detachment and transport, mass of total erosion, and initial dust emission. PWT share methods with ground-based monitoring sites, which also relate to larger temporal and spatial scales but share a strong connection to local to regional processes. Satellite-based data emphasize wind erosion and dust emission processes on larger scales, including continental to global tracking. The particle sizes are related to the time scale indicating processes of detachment and transport.

wind tunnels as they are generally smaller and less susceptible to electronic noise. In addition, because optical devices essentially count sand grains that cross through a known volume, it is in principle possible to use them to calculate a sand flux directly (Etyemezian et al., 2017).

3.1.2.2. Optical dust detection. Optical particle sensors and monitors allow for obtaining detailed information about the behavior of coarse and fine dust in the range of ca. < PM 30 µm under different experimental and surface conditions. Optical particle sensors enable the measurement of particles that cannot be reliably captured by passive or active collectors. They give the particle number per size class, and/or the concentration of a range of size classes in µg per m^3 air mass at the measurement point within the tunnel profile (Fig. 10c). Some devices offer a simultaneous filter collection of particles. This enables the correction of mass related to the actually measured particles independently of the device-specific assumptions concerning particle density and size class distribution, as well as qualitative analysis of the measured particles. The simultaneous application of handheld sensors in different heights enables the measurement of dust flux profiles (Fig. 11 a, b). The measurement of PM is strongly dependent on climate parameters and measurement specifics including the device-specific sensor calibration.

3.1.3. Surface change detection

The total amount of eroded material from the PWT test surface may be calculated by comparison of surface before and after the experiment, particularly on erodible sediments. A low-cost laser scanner was used to measure the volume of eroded soil during experiments by laser scanning the surface at a resolution of 0.1 cm × 0.1 cm before and after the test and calculating the difference based on bulk density (Asensio et al., 2019). Combined with dust samplers located at the end of the tunnel, image processing allowed for quantitative and qualitative analysis with high precision (Giménez et al., 2019). A recent PWT construction comprises a photogrammetry approach as a cost-effective and accurate method for creating 3D models of the test surface prior and following the wind test (Rostami et al., 2025).

3.2. Application of portable wind tunnel data

Aeolian processes and the methods of investigation and measurement are extremely scale-dependent, and results derived by different approaches are assumed divided between laboratory, field, and modeling studies (Sherman, 2020). The temporal and spatial scale of the PWT method suggests a primary use of the data as basis for qualitative evaluation of aeolian processes on-site, and a sight specific comparison (Fig. 12). It has been often used to assess the wind erodibility of soil, rather than total erosion, but results often show very good correlation with data from particle samplers and provide fast results. One of the driving questions for the application and analysis of PWT data therefore is how the point-data of the very specific method setup may be used for upscaling to area and quantification and spatial analysis on a local to regional scale. To derive quantitative information, the PWT data must be interpreted based on the knowledge about the characteristics of airflow inside the artificial device and the dynamics of airflow in the open (Zingg, 1951a). Validity, reliability and repeatability of test setup and results must be ensured. Therefore, the test setup and artificial wind of the test setup must meet a range of requirements to represent wind dynamics in the open (“natural wind”) (Van Pelt et al., 2010; Zingg, 1951a, 1951b). The crucial characteristics of wind must be represented adequately to reach test conditions that enable the phenomena of “natural” initiation of particle detachment and transport. Repetitions of tests (e.g. per surface type) increases the reliability of results particularly for complex surfaces.

3.2.1. Experimental quality of tunnel setup

Compared to laboratory wind tunnels, accurate quantitative measurements using PWT can be challenging due to their relatively small scale and possibly reduced flow control, for example in flow-straightening and turbulence control. To some extent, careful laboratory calibration of PWT can compensate for such drawbacks, specifically for factors such as non-uniformity, spatial/ temporal instability or poor flow alignment. Calibration typically involves accurate wind flow measurements relating the wind tunnel flow control (e.g. fan rotation rate) to parameters such as the mean central wind velocity, turbulent velocity and surface shear stress / friction velocity. This can be achieved using accurate wind velocity sensors such as a Laser Doppler Velocimeter for single point multi directional absolute velocimetry. Single measurements with pitot tubes or hot wire anemometers applied over the total cross section give information about complete wind field and particularly boundary layer characteristics. Techniques such as particle image velocimetry might also be used for quantifying uniformity of air flow. Once the setup is calibrated in the laboratory, measurements with portable airflow monitors such as mechanical velocimeters, pitot tubes, hot wire anemometers, sonic anemometers are used for wind control on site. To increase the suitability of PWT data for upscaling, laboratory calibration of PWT may also be performed following field measurements and using actual samples of particulate material (sand/ dust/ ash) for resuspension and remobilization studies.

The upscaling on the temporal scale calls for great circumspect in determination of the used test duration and modeling application due to the great variations in total flux and emissions. Based on the highly dynamic processes, data are given for short time periods such as seconds, minutes, or hours. The duration of tests often ranges between 5 and 15 min. The amount of eroded mass is usually given as mass rate or mass flux, as a mean or sum for a given time under a range of wind speeds, or interpolated/ extrapolated from a regression curve based on measured values in different heights. The temporal upscaling is based on a comprehensive dataset of environmental and surface conditions including occurrence and duration of erosive wind events and supply of erodible surface material.

3.2.2. Application of portable wind tunnel data for modeling

The main subjects touched by the method PWT is the entrainment and horizontal transport of soil material including mineral and organic components. The associated processes are tackled by wind erosion models based on temporal and spatial data about soil, soil surface and climatic conditions (Jarrah et al., 2020). The Wind Erosion Equation (WEQ) and Revised Wind Erosion Equation (RWEQ) as well as single event model (SWEEP) based on the wind erosion prediction system (WEPS) have been applied for PWT studies. RWEQ predicts mass transport as average annual soil loss from a wide, unsheltered, bare and non-crusted smooth surface in mass per area per year if wind speed exceeds the threshold speed (u-u_t) (Woodruff and Siddoway, 1965). Besides empirical components, RWEQ includes process-based components and calculates wind erosion by field and climate data and is often combined with GIS applications. PWT tests were conducted on a dry field to derive input data for a short-term WEQ-based model of wind erosion, which was furthermore coupled with Computational Fluid Dynamics (CFD) modeling (Hong et al., 2014). The SWEEP model simulates the same erosion processes as WEPS and gives sub-hourly results based on input parameters field geometry (field length, width, orientation, and barriers), plant material (flat dead biomass, height, leaf and stem area index), soil (particle and aggregate size, rock content, stability), soil surface (crust and loose material cover, crust stability, roughness, and surface moisture), and wind speed and direction (Tatarko et al., 2016). Comparison of SWEEP and RWEQ- results with results from PWT-tests showed that the SWEEP inadequately simulated soil loss for minimum and no-tillage, and PM_{10} loss from all tillage treatments, but simulated soil loss adequately for the case of minimum tillage (Pi and Sharratt, 2017). The dynamics of dust and fine dust involve mostly vertical transport and are focused by schemes that model the generation of dust by saltation. The horizontal orientation and the point-scale of the PWT-studies are in contrast to the modeling-scale of dust emissions, but a multitude of parameterizations have been developed to predict wind erosion based on field and wind tunnel experiments in which streamwise saltating mass flux and associated vertical dust flux are expressed via wind shear stress (e.g., (Gillette et al., 1974; Marticorena and Bergametti, 1995; Zender et al., 2003)).

The small temporal and spatial scales of plot data are not easily applicable for upscaling to larger scales and may lead to great under- or overestimation of erosion and emissions. On the other hand may PWT studies support the improvement of model performance because they focus the surface conditions and their specific reaction. The applicability of most models depends on a generalization of soil and surface parameters for larger areas which are not always justified from a process-understanding point of view. Dust emission models in particular are not optimized for complex soil properties and smaller scales, which may significantly affect dust budget estimates (Klose et al., 2019).

4. Comparability between data derived from different wind tunnel designs

4.1. The need for comparison and scaling methods

Diverse designs are applicable to investigate, quantify and upscale results based on a site-specific comparison, if the device meets valid, reliable and reproducible test conditions. To increase the overall informative value of the method, either the test device can be standardized, or devices and results acquired by other devices based on the same aerodynamical principles need to be comparable by means of correction factors.

Portable wind tunnels have been employed in soil erosion and aerodynamic studies on sediment and dust emissions for decades. Over time, a multitude of devices have been developed, partly built with specific options and for a variety of research questions. The recent tunnels show a range of shapes, lengths, and wind sources (Table 1). To adequately compare the data obtained between wind tunnels, it would be ideal to standardize their dimensions at the time of their construction. This would avoid making corrections and minimize the use of correction coefficients. A single type of design based on an international standard could be derived from already existing designs, which are sophisticated, well adapted to the research questions, and still mobile. However, the differing designs reflect different approaches and questions of the respective research groups that often relate to their geographical location. Since most PWT-designs share many similarities, but are not completely identical, the options include correction factors based on comparison of device as well as measurement results. We propose a standard test for wind tunnels including a standardized test procedure and uniform test substrate. Comparison is possible based on the aerodynamic parameters of the tunnels, and the measurement results under similar soil surface and wind conditions. The establishment of correction factors will enhance a more reliable and uniform application of results for greater scale application and modeling.

4.1.1. Correction factors for aerodynamic parameters

Crucial aerodynamic parameters are the wind velocity at a certain height, wind velocity profiles with height, the development and thickness of an equilibrium boundary layer, the threshold friction velocity, the Reynolds number, and the Froude number (Raupach and Leys, 1990; Van Pelt et al., 2013, 2010). It is assumed that sufficiently similar aerodynamic properties lead to comparable soil loss rates and fluxes. The dimensions of the tunnel, i.e. height, width and length, are key for possible comparisons between devices. The height influences the Froude number and the development of an equilibrium boundary layer, while the length influences the saltation capacity due to the avalanching effect, which depends on the fetch distance (Delgado-Fernandez, 2010). Dimension problems are one of the main reasons why results obtained with different PWT may be difficult to compare and require correction factors. A method for comparing wind erosion data from devices with varying dimensions involves applying empirical corrections.

To ensure valid comparisons, the fetch effect, which significantly influences both vertical and horizontal sand flux profiles over sandy surfaces, must be addressed. Studies in large laboratory wind tunnels have demonstrated that this effect intensifies with wind velocity. Empirical models, such as those developed by Dong et al. (2004), suggest that total blow sand flux increases with fetch length according to a power function, albeit with a diminishing rate of increase as fetch lengthens (Eq. 1). The use of this empirical coefficient derived from this relationship could potentially standardize results from different test section lengths, reducing variability and facilitating direct comparisons.

$$Q = C\,(1 - ut/u)^2 u^3 \left(\frac{\rho}{g}\right)$$

$$C = 0{,}000306\ L^{2/3}$$

where, Q is the total transport rate (g cm^{-1} s^{-1}), u and u_t are wind velocity and threshold wind velocity (cm s^{-1}) at the centerline height of the wind tunnel, respectively, g is gravitational acceleration (981 cm s^{-2}), ρ is the density of air (0.00125 g cm^{-3}), and C is a proportionality coefficient that increases with the fetch length with L being the distance from the upwind boundary to a point of interest (Delgado-Fernandez, 2010).

Since the equation was developed for sandy surfaces (Dong et al., 2004), the applicability for complex soils should be tested. It may be a good alternative for correcting the fetch length effect among tunnels and could be included in a general scaling and calibration procedure. Regarding test section width, observed values range from 0.3 to 0.8 m. When comparing results across these variations, the accounting for sidewall effects is essential for data consistency. Research indicates a linear increase in sand transport from the sidewalls (Hong et al., 2018). An appropriate correction factor could be established to mitigate these boundary influences, as well as for comparison between different devices.

Wind tunnel height, which varies from 0.1 to 1 m in the listed PWTs, profoundly affects boundary layer development. Taller tunnels facilitate the establishment of more extensive and realistic boundary layers, enabling better matching of parameters like the Froude number. The explicit report of the boundary layer depth enables a selective comparison of data from wind tunnels with similar boundary layer characteristics to enhance the reliability of comparative analyses. As long as a boundary layer exists, it can also be used to scale the results to derive empirical corrections for height variations.

CFD simulations have been conducted to characterize wind tunnel specifics (Shen et al., 2003). They serve to accurately model the boundary layer, correct the fetch and the sidewall effects caused by tunnel dimension variations (Bai et al., 2023). It can also support the detection of spatial variation of variables, challenging to measure with sufficient accuracy without surface disturbance such as shear velocity. Precise measurements of the airstream ensure the reliability and applicability of CFD simulations (Gartmann et al., 2011).

4.1.2. *Correction factors for measurement results*

Comparison of measurement results includes all aeolian processes and eroded or emitted quantities such as eroded sediment rate or dust flux at a given wind or friction velocity. Comparing the magnitudes between two different devices of dust emissions at comparable shear conditions is a good indicator that they are providing a comparable measurement. In supply-limited systems, it may be beneficial to compare the integral of the dust flux to determine comparability. This is analogous to comparing dust fluxes, but also incorporates the influence of surface behavior over time in response to applied shear stress. Such an emission-based approach also allows for the comparison of straight line PWTs with the PI-SWERL (Sweeney et al., 2023; van Leeuwen et al., 2021), where a comparison of aerodynamics is not feasible. In the case of crust cover, the energy per area (or maximum shear stress) needed to destroy the crust and expose underlying erodible sediments may give valuable insides to tunnel performance and comparability. The threshold wind/ friction speed, although the concept of threshold is itself a bit fuzzy, is a useful metric for intercomparison of instruments with a relatively easy way of assessing if the devices measure the same thing. Leys et al. (2002) measured the erosion rate of a surface in conjunction with particle-size analysis of the eroded sediment to successfully determine the relative dust emission of a mini-wind tunnel in comparison to a large PWT. By conducting analogous measurements with both tunnels, a correlation and correction factor could be established, enabling the calculation of indicative emission values for different soils.

There are very few direct comparisons between dust emissions and sand transport measured with a PWT and field-measured. In a similar approach to the one described by (Leys et al., 2002), Avecilla et al. (2018) developed a correlation between PM_{10} emission measurements of the same soil by a laboratory wind tunnel, a dust generator and an open-air plot. The PM_{10} emissions showed notable discrepancies between the methodologies employed. Further experimentation is considered to foster accurate determination of field emission values through standardized wind tunnel experiments in the future.

4.2. *Standardized procedure for comparison of different tunnels*

To compare the results obtained from different wind tunnels, we propose the development of a standardized procedure to derive basic information on the respective tunnel and its characteristics concerning aerodynamics and erosive characteristics. The here presented procedure includes the most crucial points and is proposed as a general basis to adapt it for specific purposes.

a) Mounting of the tunnel in a sheltered environment to exclude interferences. The setup should be completely alike to the outdoor setup including all components, measurement devices, and energy supply.
b) Measurement of aerodynamic key characteristics (Pitot tube, hot-wire anemometer)

- Wind speeds at different heights/ complete wind field measurement at two locations at least
- Boundary layer depth at two locations at least
- Friction velocity u*
- Roughness length z0 from logarithmic wind profile

c) Standard test procedure involving similar procedure, sediment, and collection and monitoring devices

- Standardized test substrates (three separated size classes, not rounded)
- Standardized substrate position (complete test section)
- Application of standard wind velocities (6, 10, 14 ms^{-1}) for standard durations (1, 5, 10 min)
- Standard erosion collectors: MWAC, BSNE at standard position(s)
- Aerosol monitor for fine dust measurement at standard position(s)

d) Standard weighing procedure

- Collection of material in PET-Bottles (from MWAC-setup)
- Collection of material in containers (from BSNE)
- 24 h in climate room
- Weighing on precision scales

The results obtained by this type of standardized comparison procedure will give valuable insights in the functioning of each device. Based on these results and comparisons, correction factors can be derived.

5. Conclusions: opportunities and challenges of portable wind tunnel applications

5.1. Closing research gaps with portable wind tunnel investigations

The entrainment of substrate by wind depends on a range of characteristics of particles, surface and airflow and interactions between them. The testing of not-manipulated surfaces in situ may be an underestimated factor for process understanding and upscaling, and the comprehensive investigation of its reaction will likely be key to approaching existing uncertainties. Research highlights for the near future comprise complex surface reactions, drought-stressed humid environments, post-fire soil surfaces, and anthropogenic dust.

Wind erosion and dust emissions have been predominantly investigated in arid and semi-arid environments, where complex surfaces increase the variability of surface reactions. The surface complexity increases with heterogeneity of surface comprising e.g. (embedded) gravel, vegetation, seals and crusts. The impact of aeolian processes on landscape dynamics and ecology can be considered increasing in humid environments within the context of climate change with increasing likelihood of heat and drought events, but investigations of potential flux dynamics are scarce. The impact of fire can change the structure of the surface as well as their reaction to wind, including the post-fire mobilization of mineral and organic material. Since the partially combusted organic material is very susceptible to wind drift and emissions, on-site studies are necessary to investigate nutrient dynamics particularly in temperate forests and for soils including organic horizons.

The extent of anthropogenic dust has not been comprehensively assessed yet, and several anthropogenic dust sources have not been quantified yet. Wind erosion and dust emissions are important components of human-environment interactions on several spatial scales. PWT tests in semi-arid environments showed strong connections between aeolian transport, nutrient availability and anthropogenic impact. Considering regions with intensifying land use and agricultural management, there is great potential for increase in wind erosion and dust emission on a short-term - medium term level. Typical surface-related variations include source- and sink interactions that may be strongly impacted by anthropogenic activity. Changes in management measures such as climate-change adaptation strategies may lead to a fast change in erosion and deposition dynamics and dust emission potential. PWT provide small-scale assessments that give valuable information on dynamics hidden from methods ranging on a greater temporal and spatial scale.

5.2. Check list for decision-making: portable wind tunnel application

The scope of application may be considered a compromise depending on the weighting of parameters that need thorough evaluation. An investigation with PWT is based on a case-individual evaluation of research questions, equipment, and specific test site conditions.

Advantages of PWT

- It is possible to examine surfaces in their natural state.
- PWT can initiate wind erosion, dust emissions, and emissions of adhesive nutrients or contaminants on a plot scale with implications for larger scales.
- PWT are applicable to investigate aeolian processes independently of the occurrence of erosive wind events.
- PWT are relatively easy to transport and convenient to store between campaigns.
- Remote areas are accessible with many devices.
- Since experiments are conducted on real surfaces and under standardized wind conditions, they are also valid with a lower repetition rate, number and frequency of experiments compared to laboratory wind tunnels.
- Comprehensive approaches can be fostered by combination of field tests with synoptic weather data and modeling.
- PWT can be used as a hands-on teaching instrument.

Disadvantages PWT

- While tunnels are portable, in some cases they require considerable logistical support for actual application in the field, such as specific vehicles and trailers for transportation, access to the site by e.g. well-developed roads.
- Environmental conditions may limit the possible uses and may change during tests.
- The test campaigns often require complex planning and several persons for field work.
- Open system at the end usually does not allow for collection of total eroded material but aliquots.
- Some aeolian processes are difficult to simulate at the PWT scale, such as variability of wind including wind direction and gusts, and a fully developed saltation layer.

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Declaration of competing interest

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Miriam Marzen reports was provided by University of Trier. If there are other authors, they 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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Data availability

Data will be made available on request.

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