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Wind-driven rain: A new challenge for soil erosion research

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Abstract

Soil erosion irreversibly destroys fertile top soil, causes huge ecological and socio-economical damage and is a main issue concerning ecosystem services and food security. The inherent complexity of soil erosion processes continues to be a great challenge to researchers, and a great proportion of global agricultural land, while producing the food for a growing population, is threatened to be lost forever. Quantification of global soil erosion by wind and water is still highly speculative and is impeded by a general lack of measurement and reliable data. Subsequently, computer models for erosion and risk assessment show results with very high uncertainties. Within this work, wind-driven rain is identified as one important reason for this uncertainty. Effects and processes related to the impact of wind on erosion by raindrops and shallow runoff are investigated by means of an experimental-empirical approach. To comprehensively assess this impact, experiments with the Portable Wind and Rainfall Simulator were conducted on different tempo-spatial scales. Experiments inducing the initial soil erosion processes raindrop splash and interrill erosion were conducted on a plot/ event scale, and a smaller scale was addressed by means of a special splash-test device on standardized substrates. The approach includes the development and formulation of research hypotheses, conception and conduction of experiments with the experimental device, sample processing, analysis and interpretation. Five articles comprise the main outcome of the work that is structured 1. Soil erosion experiments on autochthonous and semi-natural soil surfaces, 2. Experiments investigating particle transport due to (wind-driven) rain splash and 3. Synthesis from field and laboratory experiments.

1. Tests were conducted on autochthonous, highly degraded substrates in semi-arid Spain and on cohesionless sandy substrate. Since the applied experimental device was unique and new, implying the complete lack of experiences and comparative data, the first articles focus on method and method development as well as the investigation and quantification of the relative impact of wind-driven rain on soil erosion and runoff generation. Test equipment and performance proved adequate for reliable field measurements, simulating in a repeatable way the aspired conditions concerning wind, rain and wind-driven rain. The characteristic construction of the scientific device enabled a detailed process observation, so that a special emphasis was placed on process description. Most cases show an increased erosion output from wind-driven rain tests compared with windless rain, thus supporting the research hypotheses. Ambivalent results, particularly on strongly crusted, stony and patchily vegetated surfaces, underline the paramount importance of soil surface characteristics and *in-situ* experimental studies. They also indicate that a higher variability of involved factors (erosive agent, surface parameters) leads to a higher uncertainty of results.

2. A highly abstracted and specialized experimental design was developed and applied for explicit measurement of the impact of different erosion agents and soil surface characteristics on particle transport by rain splash erosion. The method proved adequate and could even be improved for a detailed study with an extended setup including a higher number of tested parameters. The measurements involved the erosion agents rain, wind-driven rain and wind, three inclinations, three levels of roughness and two substrates. The results very clearly show a wind-driven rain induced increase in particle transport of up to two scales for all tested factor combinations and concerning both, amount and distance of plashed particles. Rain splash erosion, which is generally of minimal erosive potential, becomes a powerful factor if under wind influence. Wind-driven rain is revealed to be a key factor concerning quantification of regional and global soil erosion, generation of sediment budgets and assessment of connectivity. The produced data are of a high quality (e.g. low standard deviation, three to five repetitions per set) and suitable for elaborate statistics and modeling.

3. A synthesis of field and laboratory work was pursued to appreciate the empirical data within a wider context. For that purpose, the data from both complementary approaches were compared and tested for coherency. All research information achieved investigating the wind-driven rain factor is valued by integration of the measurement data into an ecological context of a high scientific and societal interest. A careful projection on landscape scale allows for an insight into the relevance of wind-driven rain for soil erosion and hydrological risk assessment, particularly in connection with climate change induced increased frequency of rain storm events. Due to the potentially hazardous impact on soil erosion rates and runoff generation, the adequate integration of the wind-driven rain effect into hydrological and soil erosion modeling is strongly recommended.

The outcomes of the thesis generated valuable knowledge and data. It supported the understanding of processes and impact of single factors on soil erosion in general and the physical behavior of particles detached and transported by rain splash and wind-driven rain splash in particular. It was possible to investigate the relative impact of wind on water erosion and may assist an adequate assessment and interpretation of this impact on hydrological and soil management issues. It may promote improvement of traditional concepts and more realistic calculations of soil erosion rates.

I Scientific context of thesis

Section I includes an introduction to the topic of the thesis (1) with a structure of articles (1.1) and object of research (1.2). The articles are grouped. Each group (1.1.1, 1.1.2 and 1.1.3) is briefly characterized by approach and research hypotheses and each article (II, III, IV, V and VI) is summarized. Additional articles not included in the main work are mentioned (1.1.4). Wind-driven rain is highlighted as a relevant factor for evaluation of soil erosion (1.2.1) and the adaptation of the experimental design to the physical principles of soil erosion is explained (1.2.2). The experimental-empirical approach is addressed (1.3). A summary (2) shows conclusions and insights from the five single articles with respect to the research hypotheses (2.1) and gives an outlook about future challenges (2.2).

1. Introduction

The thesis was prepared within the project “Wind-Driven Rain as a new Challenge in Soil Erosion Research” (RI 835/15) funded by the Deutsche Forschungsgemeinschaft. The work approach was an experimental-empirical investigation of wind-driven rain and its impact on soil erosion. It is part of an ongoing research project that involved a first construction of a wind channel (Ries et al., 2000), which was further developed by Fister and Schmidt (2008) and finally equipped with a rainfall simulator (Fister et al., 2011, 2012). It was the worldwide first mobile device to measure erosion by wind, rain and wind-driven rain on autochthonous soils and substrates. The design corresponded to the premise that a comprehensive soil erosion assessment includes *in-situ* measurements on naturally developed soil surfaces (Ries et al., 2013). The Portable Wind and Rainfall Simulator (PWRS) is constructed according to the special requirements of the research topic *wind-driven rain* and was applied during several field and laboratory studies in southern and northern Spain, the Netherlands, Germany and Portugal. Besides the scientific application, it demonstrated its great benefit for didactical purposes. The initial processes of soil erosion by wind and water could be presented in a very catchy and comprehensive way, and the active manipulation of the device’s parameters strongly supports the understanding of involved processes and factors.

1.1 Structure of articles

The thesis comprises five articles (Figure 1). The grouping and order of presentation reflects the process of investigation: following tests on uniform substrates with simple characteristics (homogeneous sand with uniform surface conditions), tests are accomplished on varying substrates and surface conditions. During these studies, the complete complex of initial soil erosion processes (i.e. rain splash, sheet wash and initial rill development) is induced and measured. To further investigate the underlying mechanisms of detachment and transport causing the differences in erosion rates between windless rain and wind-driven rain, the process of rain splash transport is focused by means of a splash test device. In a first approach, tests were conducted with windless rain and wind-driven rain on standard sand without influence of other factors concerning the substrate surface. The next step was the introduction of additional factors such as inclination to derive the impact of wind on rain splash processes in combination with different surface conditions. The last article highlights the results of all tests including an unpublished set of field experiments and approaches an evaluation of the general impact of wind on rain erosion. Articles are numbered II-VI.

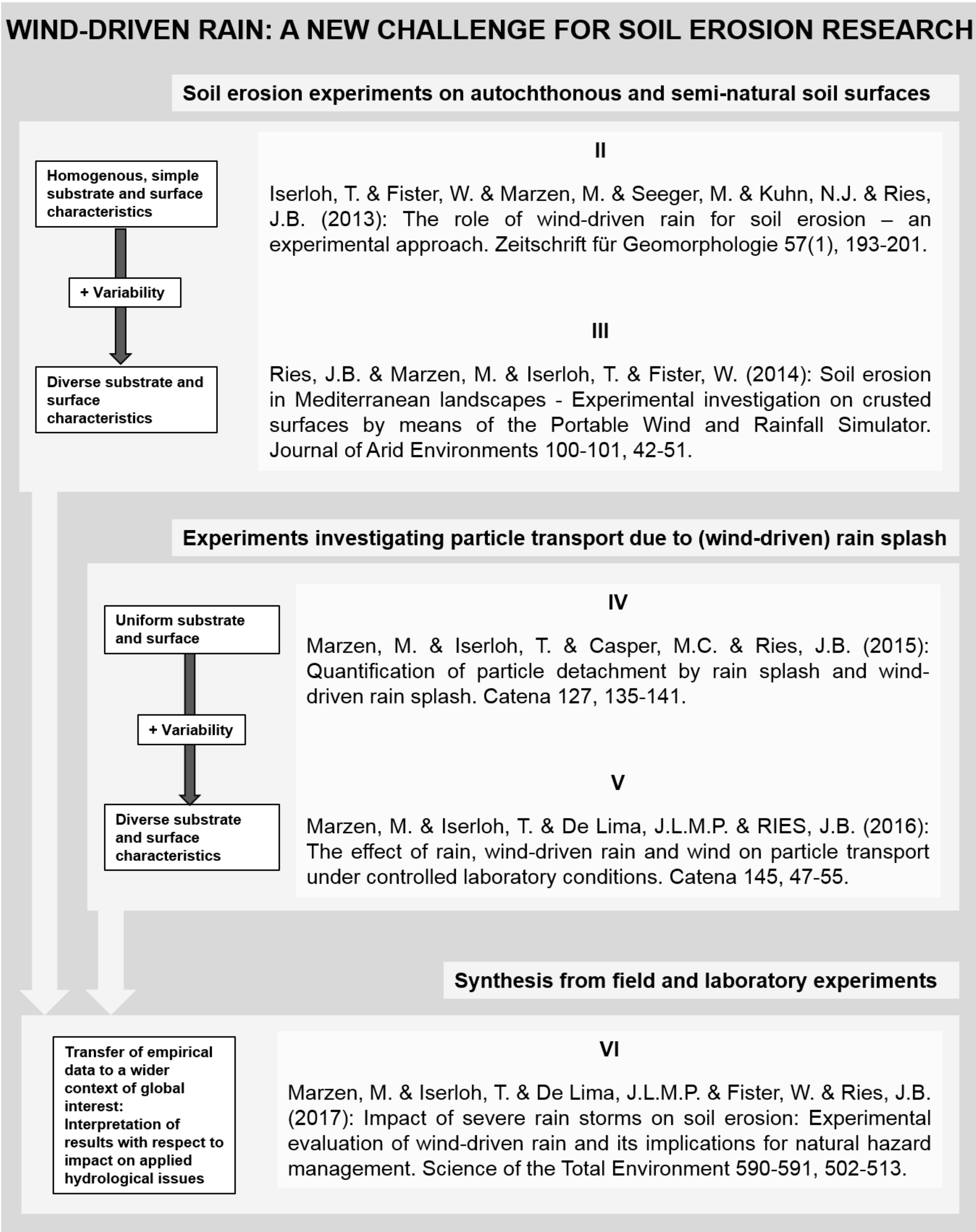

Figure 1. Structure of articles.

1.1.1 Soil erosion experiments on autochthonous and semi-natural soil surfaces

Research hypotheses:

- *Wind has an impact on water erosion*
- *Wind-driven rain intensifies soil erosion compared to windless rain.*
- *The test device and procedure are adequate to investigate wind-drive rain erosion*

Soil erosion experiments with the Portable Wind and Rainfall Simulator were conducted on autochthonous soil surfaces and semi-natural substrates following a fixed sequence. Since the applied experimental device was unique and new, implying the complete lack of experiences and comparative data, the first articles focus on method and method development as well as the investigation and quantification of the relative impact of wind-driven rain on soil erosion and runoff generation. The test sequence was established to allow for comparison of wind erosion, rain erosion and wind-driven rain erosion rates without the uncertainties of changing the test plot. The characteristic construction of the scientific device enabled a detailed process observation, so that a special emphasis was placed on process description. The method proved adequate to reliably measure the aspired processes related to the impact of applied wind to rain erosion.

II

Iserloh, T. & Fister, W. & MARZEN, M. & Seeger, M. & Kuhn, N.J. & Ries, J.B. (2013): The role of wind-driven rain for soil erosion – an experimental approach. *Zeitschrift für Geomorphologie 57(1), 193-201*.

Workshare: 25% (Iserloh 35%, Fister 25%, Seeger 5%, Kuhn 5%, Ries 5%)

The first published data obtained with the Portable Wind and Rainfall Simulator were measured on homogenous sandy substrate in a semi-laboratory setup inside an irrigation tunnel. The objectives of this study were quantification of soil erosion under wind-driven and windless conditions and qualitative observation of the differences in processes between windless and wind-driven simulations. The research hypotheses were supported. Under uniform substrate conditions, wind-driven rain intensified in all cases the processes of particle detachment and transport and strongly increased soil erosion compared to windless rain. Wind influenced shallow surface flow showed to be of major importance for high erosion rates.

III

Ries, J.B. & MARZEN, M. & Iserloh, T. & Fister, W. (2014): Soil erosion in Mediterranean landscapes - Experimental investigation on crusted surfaces by means of the Portable Wind and Rainfall Simulator. ***Journal of Arid Environments 100-101, 42-51.***

Workshare: 40% (Ries 40%, Iserloh 15%, Fister 5%)

The influence of diverse substrate and surface conditions was included during the tests conducted on autochthonous, highly degraded substrates in semi-arid Spain. Study sites featured surface aspects typical for large parts of the region such as strong crusts, patchy vegetation and embedded stones. The research hypotheses could not be clearly retained. Most tests showed an increased erosion output from wind-driven rain tests compared with windless rain, but some tests showed opposite rates. These ambivalent results underline the paramount importance of soil surface characteristics and *in-situ* studies including the natural diversity of an autochthonous soil or substrate. They also indicate that a higher variability of involved factors (erosive agent, surface parameters) leads to a higher variability and thus uncertainty of results, which is particularly important for erosion modeling. Besides the investigation of the research topic wind-driven rain, the article is strongly related to the particular geographic location and covers aspects of regional interest.

1.1.2 Experiments investigating particle transport due to (wind-driven) rain splash

Research hypotheses:

- *Wind-driven rain splash is a major factor controlling soil erosion by wind-driven rain*
- *Wind-driven rain splash transports more particles than windless rain splash*
- *Wind-driven rain transports particles over a greater distance than windless rain splash*
- *Test device and procedure are adequate to measure splash erosion by windless and wind-driven rain*

The articles present test device and results obtained with a highly abstracted and specialized experimental setup. It proved adequate to explicitly measure the impact of wind on rain splash erosion. By comparing amount and travel distance of particles, the relative impact of diverse erosion agents and soil surface characteristics on particle transport by rain splash erosion could be derived. The research hypotheses were strongly supported. Wind-driven rain splash could be highlighted as a considerable factor affecting soil erosion processes and rates.

IV

MARZEN, M. & Iserloh, T. & Casper, M.C. & Ries, J.B. (2015): Quantification of particle detachment by rain splash and wind-driven rain splash. *Catena 127, 135-141.*

Workshare: 70% (Iserloh 20%, Casper 5%, Ries 5%)

The article focuses on method development and quantification of rain splash and wind-driven rain splash under the given conditions concerning rainfall and wind generation. The first set of experiments was conducted to assess the general applicability of the splash test device as well as the measurability of the differences in transport rates. The research hypotheses were supported. Test device and procedure proved adequate for measurement of particle transport by rain splash. On uniform sandy substrate, the impact of wind on rain splash erosion showed to be of a significant extent.

V

MARZEN, M. & Iserloh, T. & De Lima, J.L.M.P. & Ries, J.B. (2016): The effect of rain, wind-driven rain and wind on particle transport under controlled laboratory conditions. *Catena 145, 47-55.*

Workshare: 55% (Iserloh 30%, De Lima 10%, Ries 5%)

The method applied in the first tests was further developed to meet the requirements of a refined elaborate measurement including the erosion agents rain, wind-driven rain and wind, three inclinations, three levels of roughness and two substrates. The results very clearly showed a wind-driven rain induced increase in particle transport of up to two scales for all tested factor combinations and concerning both, amount and distance of plashed particles. Rain splash erosion, which is generally of minimal erosive potential, becomes a powerful factor if under wind influence. Wind-driven rain was revealed as a key factor concerning quantification of regional and global soil erosion, generation of sediment budgets and assessment of connectivity. The data were produced in a quality suitable for elaborate statistics and modeling.

1.1.3 Synthesis from field and laboratory experiments

Research hypotheses:

- *Wind-driven rain has the potential to become a natural hazard.*
- *The impact of wind driven rain differs according to the respective landscape unit*

VI

MARZEN, M. & Iserloh, T. & De Lima, J.L.M.P. & Fister, W. & Ries, J.B. (2017): Impact of severe rain storms on soil erosion: experimental evaluation of wind-driven rain and its implications for natural hazard management. *Science of the Total Environment 590-591, 502-513.*

Workshare: 60% (Iserloh 25%, De Lima 5%, Fister 5%, Ries 5%)

A synthesis of field and laboratory work was pursued to appreciate the empirical data within a wider context. One objective of the work was to obtain interpretability for applied hydrological methods and questions particularly concerning soil management and risk assessment strategies. For that purpose, the data from both complementary approaches were compared and tested for coherency. Included are a not yet published set of field experiments and a further statistical processing. The whole of results achieved within the strand of research investigating the wind-driven rain factor is valued by integration of the measurement data into an ecological context of a high scientific and societal interest. The results were to some degree theoretically simplified, particularly regarding the introduction of a “wind-driven rain coefficient”: a careful projection on landscape scale allows for an insight into the relevance of wind-driven rain for soil erosion and hydrological risk assessment, particularly in connection with climate change induced increased frequency of rain storm events. The negation of the potential impact of wind-driven rain on soil erosion rates and hydrological processes may lead to hazardous consequences. Due to the potentially hazardous impact on soil erosion rates and runoff generation, the adequate integration of the wind-driven rain effect into hydrological and soil erosion modeling can be recommended.

1.1.4 Additional peer-reviewed articles not included in the main work

- *Rodrigo Comino, J. et al. (2016): Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. Science of the Total Environment 565, 1165-1174.*

Vineyards in Spain and Germany were compared in terms of sediment and runoff output using the same method and equipment. Tested were old and young vineyards with conventional and ecological management. The results allow for identification of the main factors related to soil properties, topography and management, controlling soil erosion processes in vineyards.

- *Iserloh, T. et al. (2013): European small portable rainfall simulators: a comparison of rainfall characteristics. Catena 110, 100-112.*

The artificially generated rainfall of simulators used at the Universities Basel, La Rioja, Malaga, Trier, Tübingen, Valencia, Wageningen, Zaragoza, and at different CSIC (Spanish Scientific Research Council) institutes (Almeria, Cordoba, Granada, Murcia and Zaragoza) were measured with the same methods (Laser Precipitation Monitor for drop spectra and rain collectors for spatial distribution). The comparison represents a good data-base for improvements and provides a consistent picture of the different parameters of the simulators that were tested.

- *Wirtz, S. et al. (2012): Soil erosion on abandoned land in Andalusia – a comparison of interrill- and rill erosion rates. ISRN Soil science, Volume 2012, Article ID 730870, 16 pages; DOI: 10.5402/2012/730870.*

Rill and interrill area of several Spanish test sites were mapped and rainfall simulations evaluated concerning the relation between total sediment delivery and type of area. It was found, that rill erosion makes up for a considerable part of measured erosion compared to interrill area.

1.2 Object of research

The object of research, besides the investigation of wind-driven rain processes and impact, was also method and method development. The results presented within this thesis were derived from the first experiments accomplished with the Portable Wind and Rainfall Simulator. The work with and further development of the specific method enhanced learning about experimental-empirical approaches in general. A special emphasis always was laid on the reliable measurements and a high accuracy of conduction, while the structural and basic problems implied by this kind of method was always reason to consider and examine the approach. These circumstances lead to the incorporation of a more or less detailed description of method including a brief discussion of general limitations (e.g. natural variability and scale, measurement of single processes, transferability of results to natural conditions) into each article.

Furthermore, considerations concerning some basic physics of soil erosion by wind-driven rain are stated in the context of method development: *How had the experiment to be planned to enable the measurement of the focused process or factor respectively the impact of the focused process or factor on particle transport?*

1.2.1 Wind-driven rain as a relevant factor for evaluation of soil erosion

Although strong rain events are more often than not accompanied by wind (Visser and Sterk, 2007), hydrological processes related to the wind-driven rain complex have generally been excluded from studies investigating soil erosion and runoff generation. Among the reasons might be a general strict differentiation between zones of prevailing water erosion and wind erosion (Mc Tainsh et al., 1992; Visser et al., 2004), the elaborate requirements of experimental design and procedure as well as a general underestimation of wind impact on rain erosion. But a profound understanding of soil erosion processes as well as the presentation of reliable data of soil erosion amount and potential is basis for the implementation of soil conservation strategies into general environmental measures, which is urgently necessary since the non-renewable resource soil is subject to increasing damage and scarcity (Brevik et al., 2015). Knowledge of actual processes and soil erosion rates could rise the awareness by stakeholders and soil managers and support development of solution strategies. De Vente et al. (2008) state that policy makers need to know the effect of land use and climate changes on erosion rates. How wind influences the falling and impacting raindrop and subsequent processes of detachment and transport certainly needs to be clarified beyond theoretical considerations (Blocken et al., 2006).

The impact of wind-driven rain seems to be most effective if high kinetic energy rainfall coincides with low wind speeds regarding both absolute and relative impact (Cornelis et al., 2004) and particularly in situation where no wind erosion can take place due to a high soil water content (van Dijk et al., 1996), one reason possibly being the disruption of raindrops by high wind speeds, thus minimizing their impact and kinetic energy. Climate change is supposed to regionally induce weather conditions highly favorable for intense impact of wind-driven rain, such as a very likely increase of high precipitation events (e.g. de Lima et al., 2015, 2013; Kovats et al., 2014; Santo et al., 2014) and a decrease in wind storms (Nissen et al., 2014).

For soil erosion and hydrological modeling approaches, the inherent complexity of erosion processes continues to be a great challenge. A significant lack of data and understanding leads to a wide variability of model outputs and considerable uncertainty of risk assessment associated with land use and climate change (Bryan, 2000; Nearing et al., 2004; Valentin, 1996). As a major source of uncertainty, the potential impact of wind-driven rain on erosion has been identified (Breshears et al., 2003; Bullard and McTainsh, 2003; Field et al., 2009; Visser et al., 2004). To close these gap of knowledge, detailed process studies of wind-driven rain associated detachment and translocation processes are necessary. The quality of model simulations might thus be considerably improved by a deepened process understanding, possibly enhancing the development of a wind-driven rain-module basing on empirical data.

1.2.2 Adaption of experimental design to physical principles of soil erosion

Soil erosion is defined as detachment, transport and accumulation of soil material including organic matter and nutrients by water and wind (Blume et al., 2010) on agricultural sites (Ahnert, 2015) considerably triggered by human impact (Bork, 1988; Richter, 1965). Soil erosion irreversibly destroys fertile top soil, causes huge ecological and socio-economical damage and is a main issue concerning ecosystem services and food security. It includes a geomorphological aspect that affects adversely cycles of water and substances (Ries, 2011).The physics of soil erosion processes have been subject to many scientific works both by water (e.g. Auerswald, 1998; Brodie and Rosewell, 2007; Bork, 1988; Le Bissonnais et al, 2005; Roth, 1995) and wind (Bagnold, 1941; Chepil, 1945; Funk and Frielinghaus, 1998; Hassenpflug, 1998). Morgan (2005) names the factors controlling soil erosion erodibility (of soil), erosivity (of agent), slope and vegetation coverage. Substrate specific parameters determine shear strength and resistance to detachment. Since the design of the experiment determines the scope of possible measurements (see 1.3), experimental devices and procedures were carefully adapted to their respective purpose. In the following, selected factors concerning the erosive forces of the agent and inherent substrate parameters controlling the processes of particle detachment and transport are named and it is explained, how the design of experimental setup and procedure corresponds to their measurement.

Water and wind, the main eroding agents, both are fluids that are capable to detach and transport particles by surpassing the surface specific critical shear stress (Visser et al., 2004). This is achieved within an air/ water flow by lifting force and drag, by slaking or anisotropic swelling during rapid wetting and by splash/ bombardement (Toy et al., 2002; Visser et al., 2004). Possible interactions of wind and rain are manifold- depending on specific situation and tempo-spatial scale, the mutual interferences might support or hamper erosion rates over periods of hours, years or geological time scales (Düwel et al., 1994; Funk and Frielinghaus, 1998; Holcombe et al., 1997; Jiongxin, 2000; Mc Tainsh et al., 1992; Offer and Goossens, 2001). The effect of wind-driven rain depends on micro- to macroscale variations in atmospheric conditions, causing raindrops that enter an area under influence of local wind vectors to be redistributed in a specific pattern (Blocken et al., 2006).

This thesis investigates the impact of wind driven rain on a smaller scale, highlighting the effect of wind on soil erosion by raindrops and shallow overland flow at a small plot scale.

The term “wind-driven rain” thereby is understood as the possibly profound modification of physical properties and erosivity of the main eroding agent raindrop by the action of wind (Marzen et al., 2015).

There are two main components of water erosion that can be identified as potentially influenced by wind:

- **Raindrop splash**
- **Shallow sheet flow**

Raindrop splash is the initial detachment of soil particles by surface-hitting raindrops (Figure 2). It is generally not assumed a considerable erosion process but effects sealing, crusting and compaction of soil surface (Govers and Poesen, 1988; Morgan, 2005). The impacting raindrop disrupts aggregates and ejects the downsized parts or single particles outwards from the point of drop impact (Auerswald, 1998; de Lima, 1989; Le Bissonnais, 1996; van Dijk et al., 2002a, 2002b). Detachment and transport (D) occur when the forces of a raindrop impacting on the surface (e) overcome a critical threshold of resistance (e_0). An intrinsic empirical factor of soil detachability (*k*) is used to describe the soil resistance:

$$D = k\,(e - e_0) \qquad \text{(equation 1)}$$

Transport amount and distance of detached particles vary as a result of drop-surface interaction, such as the kinetic energy of an individual drop and the behaviour of the surface upon drop impact (de Lima, 1990; Kinnell, 2005; Legout et al., 2005; Leguédois et al., 2005; Riezebos and Epema, 1985). Furbish et al. (2007) and Dunne et al. (2016) estimate splash relevant for levelling of surfaces of micro- to macrotopographical ranges. Few experimental studies were carried out minutely investigating splash patterns by windless raindrops (Furbish et al., 2007; Dunne et al., 2010), but none for wind-driven raindrops.

Erosivity of wind-driven rain differs significantly from rain without wind (Lal et al., 1980) and wind without rain (de Lima et al., 1992). Theoretical considerations and few experimental studies indicate that wind increased the drop fall and impact velocity and lead to partly larger drops, a flatter impact angle (~45° on level ground) and thus to a higher erosive potential (Disrud et al., 1969; Erpul et al., 2000; Fister et al., 2012; Marzen et al., 2015, 2016; Sharon, 1980; Umback and Lembke, 1966; van Heerden, 1964).

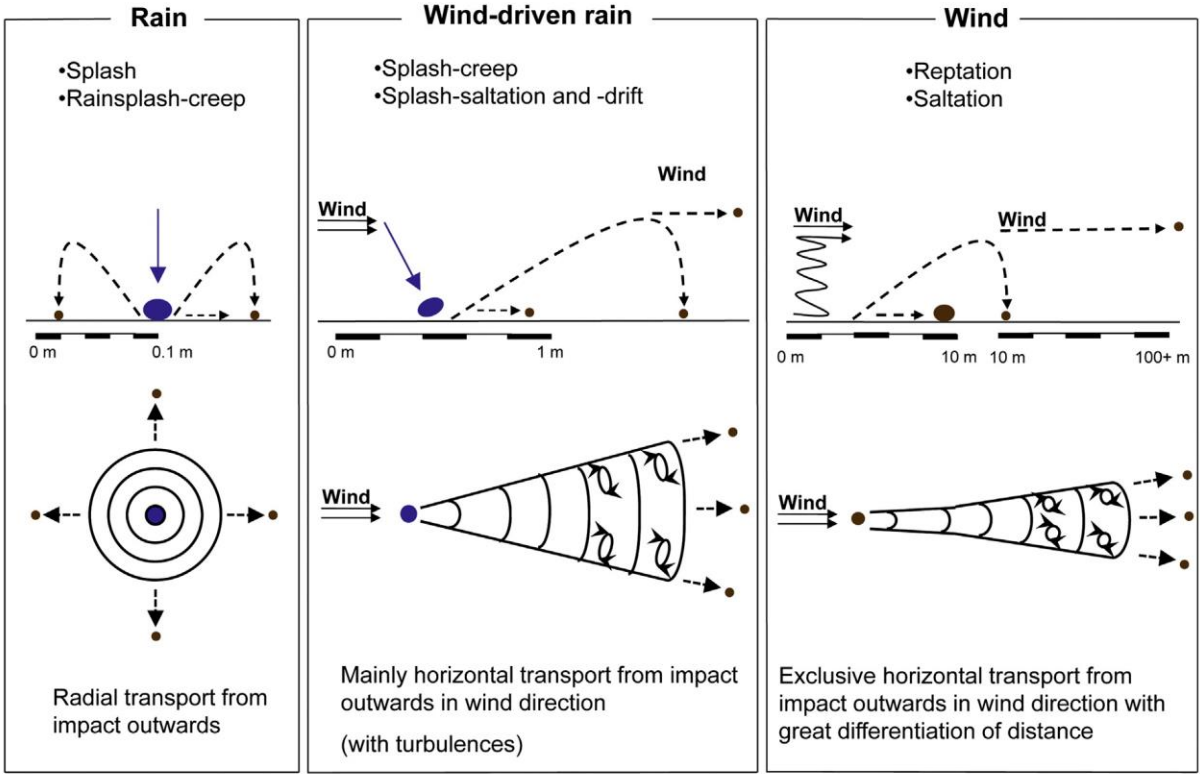

Figure 2. Sketches of initial soil erosion processes by rain, wind-driven rain and wind (Marzen et al., 2016).

One of the most important aspects is the deviation from the vertical axis by the lateral component introduced by wind. Sharon (1980) found the relationship between wind velocity (u; m s^{-1}) and angle of falling raindrop deviating from vertical course (I):

$$I = 7.13u - 0{,}270 \sqrt{u} \qquad \textit{(equation 2)}$$

indicating that a wind velocity of 10 m s^{-1} induces oblique angles of already 40 – 60°.
Resulting from this deviation are an altered intensity as well as spatial distribution of the raindrops correlating with wind velocity and direction (Visser et al., 2011).
Erpul et al. (2011) propose for WDR a raindrop impact velocity vector (RIVV) consisting of impact angle, slope and aspect for calculation of rainfall. For slopes they derived:

$$I_{wdr} = I \cos (a \; {}^{+}/_{-} \; O) \qquad \textit{(equation 3)}$$

with I_{wdr} = Intensity of wind-driven rain on slopes; I= Intensity of rain on a plane surface regarding the vector of falling raindrops, a= angle of impact of raindrop; O= slope ${}^{+}/_{-}$ ($^{+}$ facing wind, $_{-}$ leewards).

Besides these rather conceptual approaches, more elaborate equations were given by concerning splash ejection by windless raindrops are available by Wright (1986), Planchon et al. (2000) tested a possible application of the diffusion equation and Furbish et al. (2007) derived a numerical model by means of a thorough empirical study.

The experimental device PWRS is capable of simulating this influence of wind on the falling and impacting raindrop. From Table 1 can be derived, that the applied wind slightly decreases the rainfall intensity (due to a drift of raindrops beyond the test and measurement area) and increases drop size, drop fall velocity, an thus kinetic energy of the rain. The wind impact also leads to the typical oblique impact angle of the rain drop. Following the above stated remarks, all parameters assumed to be influenced by wind impact are accordingly influenced within the experimental setup, thusly enabling the measurement of wind-driven rain and the comparison of rain erosion with wind-driven rain erosion.

Table 1. Main wind and rainfall characteristics of the Portable Wind and Rainfall Simulator (source: (Iserloh et al., 2013): Presented are mean wind velocity [v_w], mean Intensity [I], mean volumetric drop diameter [d_{50}], drop fall velocities for drops of the size d_{50}, mean kinetic energy expenditure [KE_R], and mean kinetic energy per unit area per unit depth of rainfall [KE] for windless and wind-driven rain.

	v_w [m s^{-1}]	I [mm h^{-1}]	d_{50} [mm]	v_r [m s^{-1}]	KE_R [J m^{-2} h^{-1}]	KE [J m^{-2} mm^{-1}]
windless rain	0	96	1.5–2.0	2.2–2.6	270.8	5.21
wind-driven rain	7.5	88	1.75–2.5	3.4–4.2	1590.8	8.08

To exclusively measure the impact of wind on raindrop splash erosion, a very abstracted experimental design was developed (Marzen et al., 2015). For the detailed study of splash transport by windless rain and wind-driven rain, a specialized measurement device was built ("gutter system") and a strict procedure was specified.

The splash test device was designed to receive a fine resolution of particle transport, restricted by the requirement of practicability, i.e. a limited number of processible single samples per repetition (Figure 2a). It was integrated into the PWRS setup (b). The first type was a gutter system made from plastic U-channels that worked well but were difficult to handle and not solid enough for a higher number of repetitions. The second type, used for the second data set regarding the splash tests, was built from stainless steel, solid and easy to handle (Figure 2b).

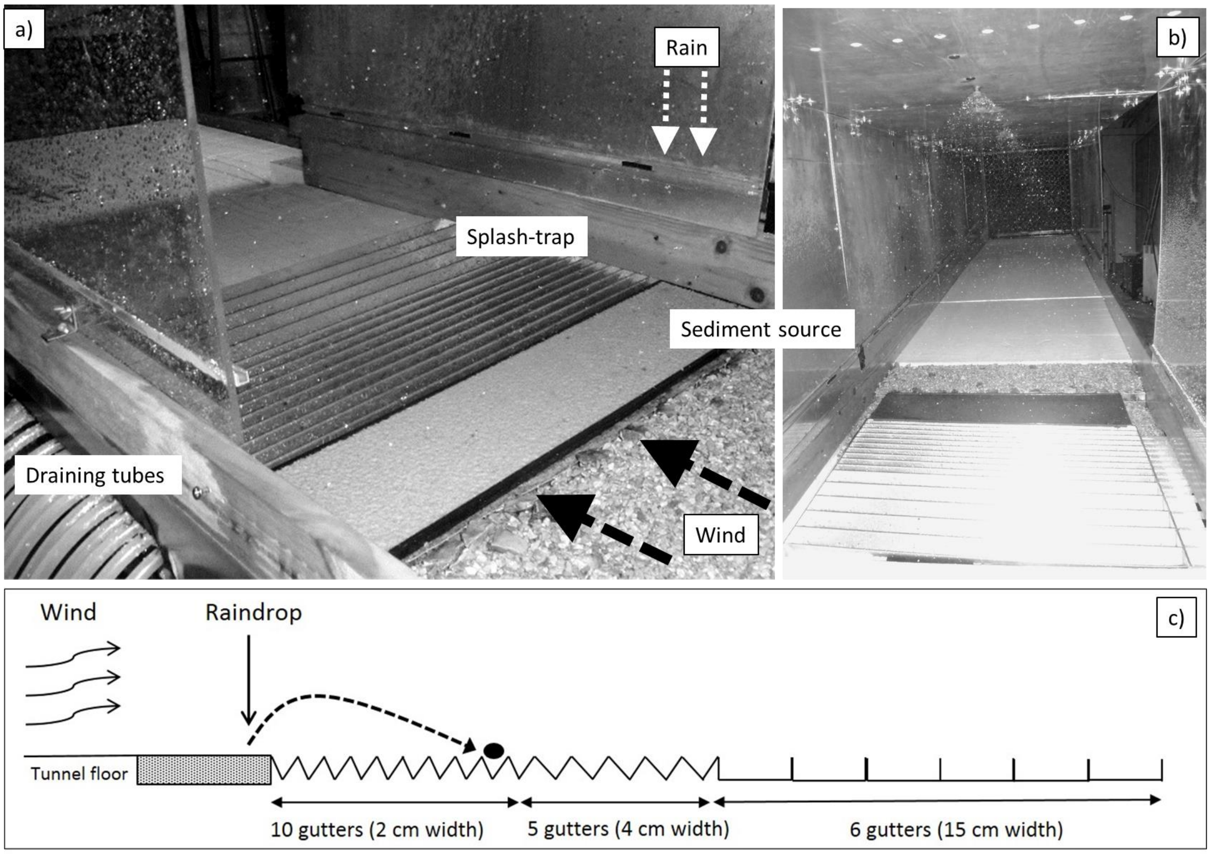

Figure 2. Photo and sketch of splash test device.

The impact of wind on **shallow sheet flow** is assumed to increase its erosivity, but has not been measured yet. Possible effects are a higher velocity and increased turbulences, both increasing the transport capacity of runoff, and also an indirect effect via wind-driven raindrops impacting the water covered surface (Kinnell, 2005; Samray et al., 2011; Yoon and Wenzel, 1971). Torri et al. (1987) estimated the effect of a (not moving) layer of water on splash detachment as

$$D \approx e^{-1.5h} \qquad \textit{(equation 4)}$$

where D is the rate of splash detachment (g min^{-1}), and h is the depth of flow (mm). As runoff depth increases, splash decreases. However, there are manifold approaches of varying degree of precision, and different authors suggest varying values as a threshold where the positive and negative effects balance (e.g. Auerswald, 1998; Guy et al., 1987; Moss and Green, 1983; Mutchler and Larson, 1971; Poesen and Savat, 1981). Since even the concept of transport capacity itself is currently under review (Wainwright et al., 2015), the alteration of shallow sheet flow's erosive potential is highly speculative.

Within the experimental setup on autochthonous substrates, both main components (splash and sheet flow) are induced at plot size and their joint impact on soil erosion rates measured.

Within the laboratory setup, the splash processes are quantified exclusively, leaving the impact on shallow runoff as a future research topic to be integrated into e.g. mechanistical diffusion models (Furbish et al., 2017) (see 2.2).

Soil water content is one of the most important factors controlling erosion by wind (Chepil, 1956; Cornelis and Gabriels, 2003; Funk and Frielinghaus, 1998; Wiggs et al., 2004) and water (Blume et al., 2010; Duttmann, 2001; Poesen and Savat, 1981).
Thus, to investigate rather the impact of erosion agent than of soil water content on soil erosion rates, this factor had to be levelled as far as possible for test conditions. This problem was tackled by establishment of a test sequence, where a first run was established to moisten the soil. That is assumed to level the water content for following test runs which could then be used for comparison. For laboratory tests, the substrate was moistened prior to each test to prevent the substrate to be blown away by the airstream (Fécan et al., 1999; Funk and Frielinghaus, 1998). Cappelle and Lüders (1981) show for sandy substrates stabilized conditions for a water content of >10 Vol%, while saltation is only prohibited by much higher water content (Cooke et al., 1993). If it comes to raindrop splash, a high water content can possibly inhibit any transport (Figure 3), so that a lowest possible water content as well as an approximate uniformity of water content is a paramount test condition. Thus, the substrate source was thoroughly drained and the test duration was kept very short (5 minutes) to prevent substrate from waterlogging.

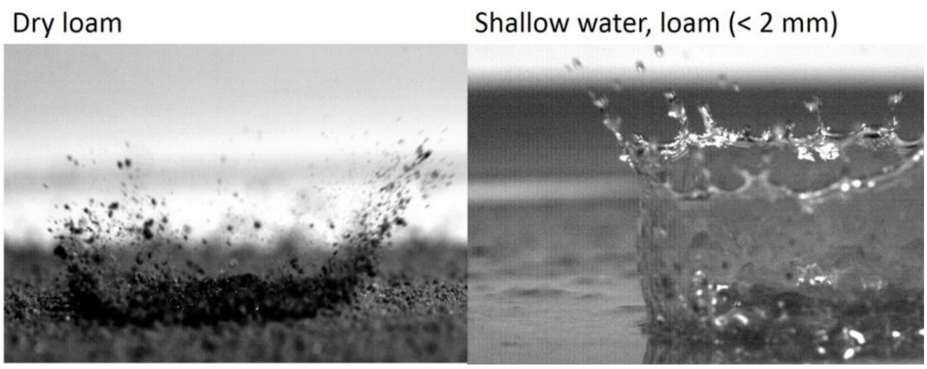

Figure 3. Comparison of drops hitting dry (left) and moist (right) substrate.

Grain size distribution can be generally correlated to susceptibility of substrate to erosion (Bork, 1988; Hassenpflug, 1998) as well as specifically to splash erosion (Leguédois et al., 2005; Poesen and Savat, 1981). Fine sand (63-200µm) and coarse silt (20-63 µm) are particularly prone to erosion by wind and water (additional middle sand 200-630 µm). Coarser (> 2 mm) and smaller particles (< 65 µm) are less easily eroded due to weight, cohesive force or agglomeration. Accordingly, the substrate for laboratory tests was chosen so as to gain as much material as possible during the simulations.

A **surface crust** can act as a protection against the erosive forces of wind and water (Belnap and Gillette, 1998) or, particularly if it is destroyed, as a source of readily erodible substrate (Gillette et al., 1980; Offer et al., 1992; Roth, 1992). A large part of the tests were conducted on autochthonous soils including strong surface crusts. The design and procedure of tests was adapted to the specific requirements of this kind of surface structure in some respects, e.g. the substructure was only slightly introduced into the soil and afterward sealed again with water to prevent the crust from generate additional sediment output. Furthermore, the sediment trap was installed in such a way, that the “rim effect” of these destroyed crusts was not collected.

1.3 Experimental studies in soil erosion research

Experimental studies are of great value to geosciences. Paola et al. (2009) observe “a consistency between experimental and field systems despite large differences in governing dimensionless numbers” and call it “unreasonable effectiveness”, presumably arising from the fact that natural processes often seem to develop independently from scale.

Due to their temporal or spatial scale, many processes of geoscientific interest are hidden or impossible to measure *in actu*. In the case of soil erosion, the related processes happen either continuously on a low level, or suddenly, such as due to an extreme rainfall event. The first would lead to a gradual loss of productive top soil by splash and sheet wash processes, the latter to an abrupt heavy wash including the formation of rills and gullies. In both cases, the process is not plannable observable and the amount of eroded material is nearly impossible to assess. Scientists, stakeholders and planning offices work with sediment loads derived from receiving waters to establish sediment budgets and erosion rates, a method known to create huge errors for several reasons (e.g. Cammeraat, 2004; de Vente et al., 2007; de Vente and Poesen, 2005). The fact that assessments of erosive potential are currently generally generated by means of computer simulations that are calibrated with these inaccurate data aggravates the situation. As a result, models lead to high variabilities of simulation output and risk assessments are highly uncertain (Poesen et al., 1996). This situation might be a reason that experimental approaches including rainfall and wind simulations currently gain more approval again among German researchers, and they have been worldwide applied and constantly developed since decades. They are used to investigate fluvial or aeolic processes and simulate mainly the initial stages of particle entrainment and translocation. They can be used for both, *in-situ* measurement of autochthonous soil surfaces and laboratory studies. Experimental research is of a high importance for knowledge generation and data collection, thus being a crucial basis for hydrological and soil erosion modeling (e.g. Stroosnijder, 2005; Toy et al., 2002).

The presented thesis includes a complementary approach combining studies on autochthonous substrates and laboratory studies to coherently investigate the focused topic. All tests were carried out with the Portable Wind and Rainfall Simulator (PWRS). The experimental setup's physical limitations are addressed in (Fister et al., 2012; Iserloh et al., 2013; Marzen et al., 2016). The concept of this empirical approach includes the idea that reality is approximated and partly represented by the experimental device and procedure (Figure 4). To which extent this is even possible is an unsolved problem, one big issue being the fact that highly variable natural processes are standardized for the sake of reproducibility and reliability. The quality of an experimental setup depends on various aspects, among others the adequate representation of involved factors and a precise execution. Instead of absolute values, a comparison of local conditions is derived, and the data of one experimental device cannot be compared to other devices. However, paramount achievements of experimental work prove the merits and the great value for geosciences. Furthermore, a wide data basis can partly eliminate the effects of systematic and random errors of single measurements (Fiener et al., 2011).

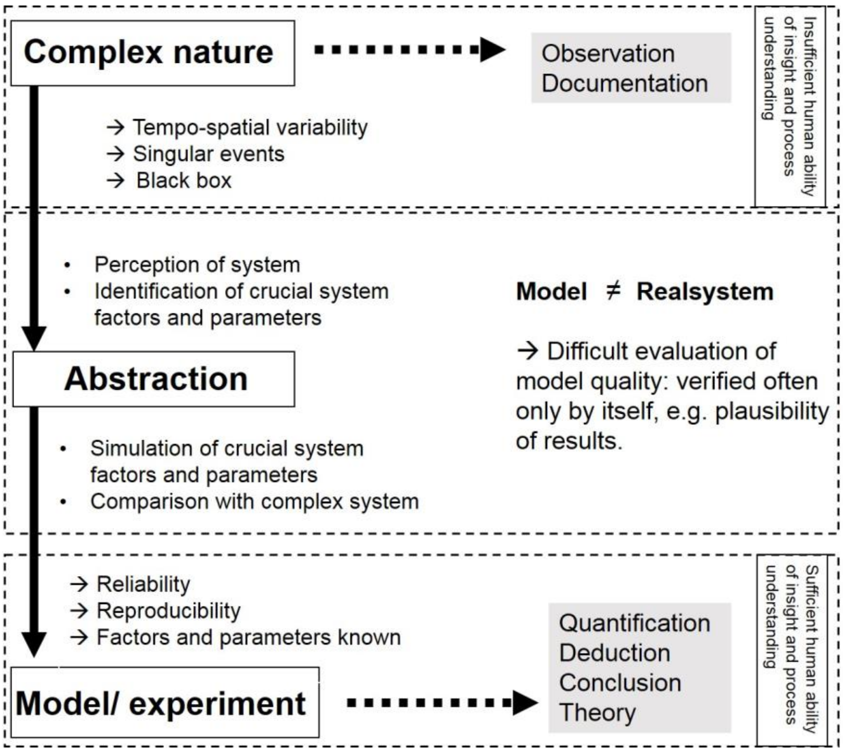

Figure 4. Development of model/ experiment.

One of the most important aspects is the strict adaption of the experimental design to research question and aspired results.

The exact formulation of the research question is as necessary as the careful choice of experimental components and the adaption of the interpretation to the degree of abstraction (Kuhn et al., 2014). Within the thesis, the complexity of the experimental system was several times adapted to the changing level of complexity of the aspired results, corresponding to the specification of the research topic. The different levels of abstraction are shown in Figure 5. In the case of erosive processes, there is a great difficulty to derive information about the system by observation or measurement of the real natural system itself due to a high spatio-temporal variability of erosive processes and their impact (a). A higher level of abstraction as in field tests (b) involves a higher level of control, while the complexity of the system is reduced. This allows for a detailed process observation and an association of acting factors and processes to measured or observed results. The range of processes and the quality of data corresponds to scale, test equipment and procedure. An intermediate position would be larger stationary plots that produce data assumed to be closest to natural values but require permanent maintenance.

Most control was possible during laboratory tests, where the involved factors and processes were reduced to a minimum level (c). This allows for a precise measurement of focused processes and factors, but at the same time, the high degree of abstraction causes a problem of interpretation due to a difficult transferability to the natural phenomenon. The interpretation must be tackled with great care.

Scale is a great issue in experimental geomorphology (Cammeraat, 2004; Lal, 1990). The research focus applied within this thesis ranged from a small tempo-spatial scale (“event scale”) including the impact of wind-driven rain on soil erosion processes on plot scale to a to a micro scale (impact of wind-driven raindrop splash on particle transport) and, finally, approaches a large scale on a theoretical basis, transferring findings to a level of global hydrological assessments.The experimental device Portable Wind and Rainfall Simulator and the related procedures are trade-offs between controllability and authenticity: the more complex the experimental setup is chosen, the more natural it is, but the less controllable (and thus interpretable) are procedure and output. The awareness about merits and limits of such an experimental method are basis of an adequate handling of the device and the processing of data. One result of this awareness is the consistent avoidance of an otherwise common practice of upscaling of total rates, either temporal or spatial. Instead, for transferring the data from the point measurement to a field scale, comparative analyses are performed.

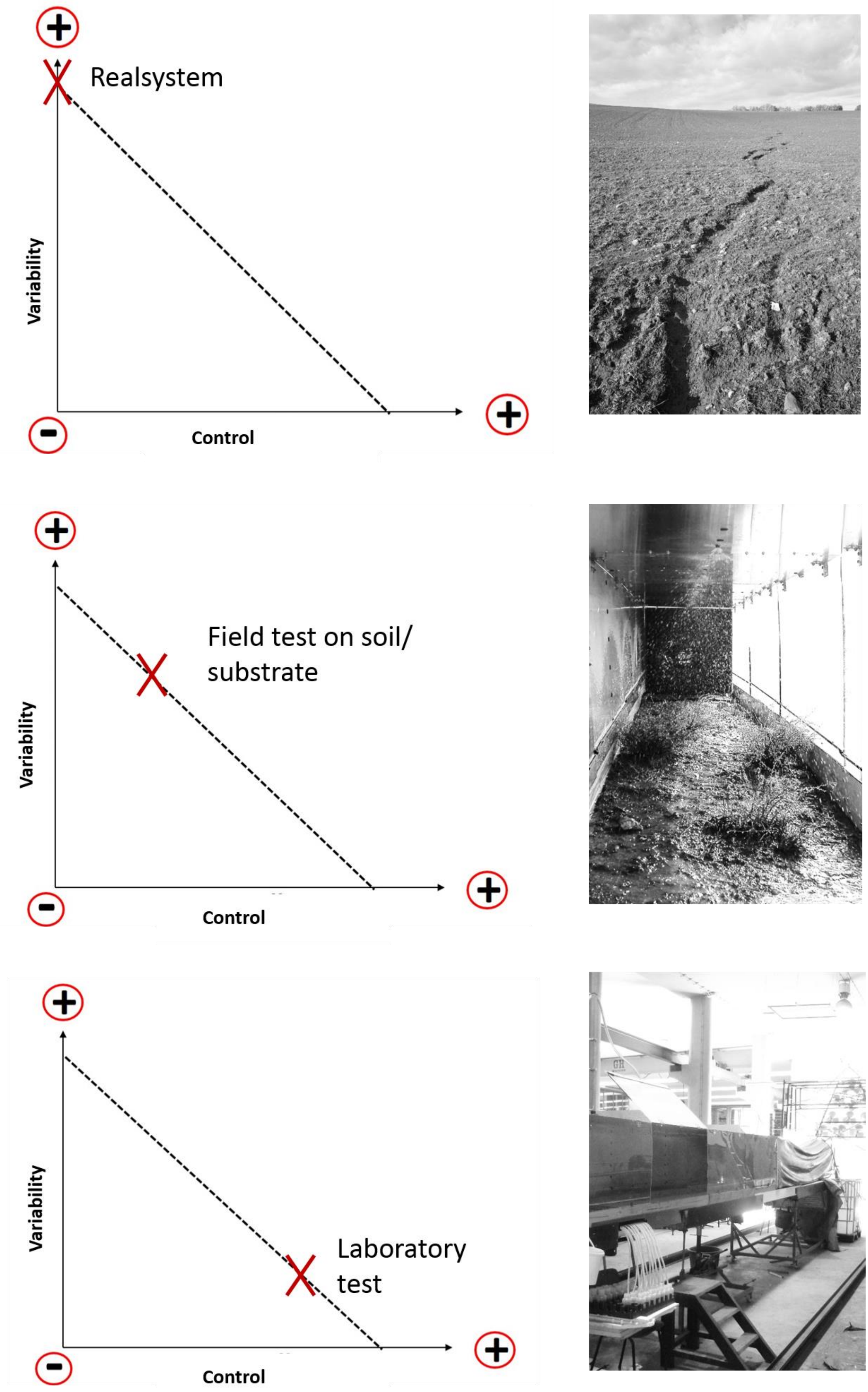

Figure 5. Model complexity vs. controllability.

2 Summary

The summary concludes research aims/ hypotheses and their supporting results derived from the experimental investigations and their statistical analyses presented in the articles. The outlook contains the transfer of findings into conceptual models and numerical models. Furthermore, it contains research questions concerning the controlled investigation of impact of a shallow runoff and interactions with impacting raindrops with and without wind influence.

2.1 Conclusions and insights from the five single articles

Each study involved development and formulation of research hypotheses and objectives, conception and conduction of experiments with the experimental device, sample processing, analysis and interpretation. The experimental design was tested for its applicability. Wind-driven rain was tested for its erosive impact. Wind-driven rain is shown a key factor for understanding and analysis of soil erosion.

The outcomes of the thesis generated valuable knowledge and data. It supported the understanding of processes and impact of single factors on soil erosion in general and the physical behavior of particles detached and transported by rain splash and wind-driven rain splash in particular. It was possible to investigate the relative impact of wind on water erosion and may assist an adequate assessment and interpretation of this impact on hydrological and soil management issues. It may promote improvement of traditional concepts and more realistic calculations of soil erosion rates.

- **Quality of test device and procedure for tests on autochthonous substrates as well as for splash tests setup**

During several measurement campaigns including units under laboratory and field conditions, the PWRS proved adequate for measurement of the aspired processes and factors. The test device showed to be of a robust design suitable for work under field conditions. The impact of wind, rain and wind-driven rain could be quantified via amount of soil erosion on a plot scale. The particular impact of wind-driven rain was assessed by comparison of rainfall simulation and WDR-simulation. The experimental setup allowed for detailed qualitative and quantitative observation of runoff and erosion processes. The splash test design was adequate for isolation of sub-processes splash and wind-driven rain splash from the diverse processes of detachment and transport, and it was possible to quantify an compare detached and transported material with and without applied wind on various substrates, slopes and levels of roughness. Test devices and test sequences met the requirements of validity as well as reproducibility.

In a greater context, the work with the experimental device increased process understanding and general knowledge about soil erosion processes. The work with the PWRS allowed for development of a deeper understanding of relevant factors, processes and interactions. It proved not only a valuable tool for scientific investigation but also for didactical purposes, since the driving factors are to be observed while they are happening, and the manipulation of the device’s parameters concerning artificial wind and rainfall induces a much deeper learning than mere theory. Experimental erosion studies are a very worthwhile field of soil science and a source of knowledge and data.

- *The test device and procedure are adequate to investigate wind-drive rain erosion*
- *Test device and procedure are adequate to measure splash erosion by windless and wind-driven rain*

- **Impact of wind on processes of erosion by water in general and raindrops in particular**

The objectives of the studies were quantification of soil erosion under wind-driven and windless conditions and qualitative observation of the differences in processes between windless and wind-driven rain simulations.

In all studies, an impact of wind on rain erosion could be supported. Tests on autochthonous soils and substrates showed ambiguous results, sometimes even on the same site. This shows the great influence of surface conditions as only featured by *in-situ* test conditions. Splash tests produced very homogenous results all presenting the strong impact of wind on raindrop detachment and transport regardless of the surface conditions, but the surface conditions here too changed general rates.

In a greater context, the first systematic investigation of wind-driven rain on soil erosion and runoff generation was conducted. The work could strongly increase process understanding and generate urgently required data for the assessment of relative impact of WDR.

- *Wind has an impact on water erosion*
- *Wind-driven rain intensifies soil erosion compared to windless rain.*
- *Wind-driven rain splash is a major factor controlling soil erosion by wind-driven rain*
- *Wind-driven rain splash transports more particles than windless rain splash*
- *Wind-driven rain transports particles over a greater distance than windless rain splash*

- **Impact of wind-driven rain on a regional scale**

Wind-driven rain is found an important factor controlling soil erosion and runoff generation and can be assumed a crucial factor for natural hazard risk assessment. A wind-driven rain coefficient was introduced to depict that total soil erosion is severely underestimated for all types of tested soil surfaces including different substrates and surface characteristics. The enhanced runoff generation should be acknowledged an important factor adding to the general increase in erosive potential of wind-driven rains. Furthermore, wind-driven rain might lead to erosion rates exceeding those obtained conventionally by means of experimental studies or numerical models. That is caused by the fact that the erosive effect of wind-driven rain is not accounted for sufficiently by simply applying a higher kinetic energy as is generally the case in models simulating soil erosion and runoff generation.

- *Wind-driven rain has the potential to become a natural hazard.*
- *Wind-driven rain generally increases soil erosion and runoff generation*
- *This increase differs according to the respective substrate and landscape unit*

2.2 Outlook about future challenges

Wind-driven rain is shown to be a key factor for soil erosion assessment. Its impact seems to extent to surface hydrological processes, particularly concerning generation and development of shallow overland flow. A coordination between experimental procedures and theoretical approaches for both rain-splash transport and shallow overland flow dynamics must be achieved. Therefore, the future challenges include measurements as well as the development of theoretical frameworks and model simulations and are briefly discussed as two research topics.

Research topic 1: Development of modeling approach of particle transport by (wind-driven) rain splash

Basing on the here presented results, a theoretical formulation can be conceptualized to comprise the different effects of wind-driven rain on particle transport under diverse surface conditions. Key points for discussion and adaption to computer models are *drops* (single drop vs. heterogeneous drop population), *wind* (constant wind velocity vs. gusts; wind stream parallel to surface vs. wind stream “hitting” surface) and *substrate* (standard grain size vs. grain size mix).

Research topic 2: Wind influence on (raindrop-impacted) shallow sheet flow: Experiments and model simulation

The problem of wind influence on shallow runoff has to be tackled. Due to its small dimensions, shallow overland flow is strongly influenced by the boundary conditions (bed and air). The bed surface has many variables that can either increase or decrease flow parameters such as velocity, depth and turbulences. The new aspect is the influence of wind on the shallow flow as well as on impacting raindrops. Compared with a water free soil surface, shallow flow might lead to either an intensification or a decrease of the erosivity of an impacting raindrop. A threshold value is not yet found and different authors suggest varying values. On the basis of investigations of sediment transport by turbulent flow, fundamental assumptions can be adapted to the specific case of a shallow runoff. Theoretical concepts of shallow surface flow dynamics have to be developed with special emphasis on the influence of wind and raindrop impact. Depending on the aspired and possible richness of detail, following factors are included into the model:

- Shallow flow hydraulics (velocity, depth, turbulence)
- Wind (velocity, direction relative to topography, steady or gusts, boundary layer)
- Impacting (wind-driven) rain drops (velocity, size, kinetic energy/momentum, impact angle, number)

Corresponding to the achieved results and workflow of theoretical considerations, an experimental design can be developed including parameters identified as relevant to test the developed hypotheses. A special device for generation and exact control of a steady uniform runoff has to be developed. The water flux and depth can be measured by means of a laser. A sediment trap for measurement of the transported sediment (splash and runoff) is probably the biggest challenge. Model formulations and experiments thus support a mutual development.

II

Iserloh, T. & Fister, W. & **MARZEN, M.** & Seeger, M. & Kuhn, N.J. & Ries, J.B. (2013):

The role of wind-driven rain for soil erosion – an experimental approach.

Zeitschrift für Geomorphologie 57(1), 193-201.

Note: Because of authorization issues, the original article is replaced by a working manuscript. This version may differ from the original article. For citing, the original article must be used.

The role of wind-driven rain for soil erosion – an experimental approach

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with 3 figures and 2 tables

Abstract. Recent research has shown that wind can have a significant influence on velocity, impact angle and kinetic energy of raindrops, and subsequently increases soil erosion. The aims of this study were to 1) quantify the influence of wind on water erosion, 2) specifically observe the difference in processes between windless rain (WLR) and wind-driven rain (WDR) simulations and 3) test the device's and test sequence's practicability.

The Portable Wind and Rainfall Simulator (PWRS), recently developed at Trier University for plot-scale *in situ* assessment of differences in soil erosion with and without the influence of wind on raindrops, was used. To facilitate extraction of the influences of WDR on soil erosion, to avoid systematic errors, and to reduce variability between test plots, a defined order of four consecutive test runs was established: 0) wind simulation, 1) WLR simulation on dry soil, 2) WLR simulation on moist soil, 3) WDR simulation. The tests were conducted on homogenous sandy substrate deposited on an area of 15.2 m x 60 m with uniform and smooth surface and low inclination (1°) in the Willem Genet Tunnel of Wageningen University. The results show an increase of eroded sediment ranging from 113 % up to 1108 % for WDR simulations in comparison to WLR simulations. The increase in runoff was considerably lower (15 % to 71 %), resulting in an increase of sediment concentration between 56 % and 894 %. The results indicate an immense impact of WDR on soil erosion of sandy cohesionless substrate. The experimental setting and measurement proved reliable and reproducible and enables a clear process observation and quantification in the field.

Keywords: Water erosion, wind erosion, soil erosion, wind-driven rain, Portable Wind and Rainfall Simulator (PWRS), rainfall simulator, wind tunnel

1 Introduction

Natural rain events often occur as rainstorms, where wind adds a driving component to the falling raindrops as well as to the shallow overland flow. Due to limitations of experimental field equipment and the difficulties of simultaneous assessment of soil erosion processes via both eroding agents (VISSER ET AL. 2004), wind and water erosion have been mainly studied separately in the past. In this study, we overcome the neglect of natural complexity by investigation of wind influenced rain and its impact on soil erosion on a natural body of cohesionless substrate.

Interactions of wind and rain are considered very complex, as laboratory research in Gent (e.g., CORNELIS ET AL. 2004 a, b, ERPUL ET AL. 2000, 2002, 2005, 2011), Coimbra (e.g., DE LIMA ET AL. 2003, 2009, DE LIMA 2011) and other institutions (e.g., LYLES ET AL. 1969, UMBACK & LEMKE 1966) has shown. The influence of wind on falling and surface-hitting raindrops is potentially very effective considering the detachment and transport of soil particles (CORNELIS ET AL. 2004 b, ERPUL ET AL. 2011, VAN HEERDEN 1964). These effects regard (i) a considerable increase in velocity, exceeding the natural terminal velocity of falling rain drops without wind acceleration, (ii) the deviation from the vertical course of fall, resulting in an oblique impact angle and (iii) a modification of size and number of drops. Furthermore, the wind itself might fetch and transport single particles and small aggregates. This alteration of physical properties of drops plus the direct transport by wind (splash-drift) is recently found to be much more accentuated than detachment and transport by raindrops that are not wind-influenced (splash) (CORNELIS ET AL. 2004 b). Concerning the detachment via shallow overland flow, wind might effect its detachment and transport capacity directly by acceleration and indirectly by modification of the impacting raindrops, again in flume studies found to increase soil erosion rates (ERPUL ET AL. 2011, KINNELL 2005).

So, recent scientific laboratory work seems to have reached a consensus concerning a potential intensification of sediment supply and soil loss as mentioned above, while a comprehensive empirical approach on natural soil surfaces is still missing. Laboratory results need to be reassessed by investigation of natural surface-water interactions concerning shallow overland flow and raindrops: experimental investigation of the impact of wind-driven rain (WDR) on net-soil erosion is imperative for process understanding and development and adaption of soil erosion models, and it has repeatedly been stated that this considerable gaps of knowledge urgently need to be filled (e.g., RAVI ET AL. 2010, VISSER ET AL. 2004).

Results of preliminary field measurements with Trier's Portable Wind and Rainfall Simulator (PWRS) on *autochthonous* soils in Spain show highly variable signals of WDR on erosion (ISERLOH ET AL. 2009, RIES ET AL. 2010). For this study, we used an experimental approach to reduce the amount of influencing parameters and to extract specific influences that are assumed to affect erosion by WDR and enlighten these variable results. We conducted tests on four sandy substrate plots in the Willem Genet Tunnel of Wageningen University that provide more reproducible and controllable conditions than the highly degraded and crusted soils in semi-arid Spain. The objectives of this study are: (1) quantification of soil erosion under wind-driven and windless conditions, and (2) qualitative observation of the differences in processes between windless and wind-driven simulations. In this way, the experiments present a link between field measurements on variable soil conditions and real laboratory measurements. Finally, we verified the practicability of applied test sequence and the usability of the PWRS (3).

2 Material & methods

2.1 Experimental setup

To accomplish measurements of the effect of WDR on soil erosion, we developed a device (Fig. 1a) at Trier University that is capable of producing single wind and single rainfall events (windless rain = WLR), rainfall events with the influence of wind on falling raindrops, and a sediment collector that is able to catch runoff as well as detached sediment (FISTER 2011, FISTER ET AL. 2012). The PWRS is specially adapted for this application in the field and consists of four sections:

a) A push-type fan as the wind source
b) A transition section and honeycomb to reduce turbulences
c) The working section with a plot size of 2.2 m², including the rainfall simulator
d) A sediment trap for wind- and water-eroded material

The analysis of wind and rainfall characteristics showed good results regarding reproducibility of air-stream and rainfall conditions and therefore allow for comparative measurements of different surfaces in the field. Furthermore, with this setting we achieve the typical impact of wind on falling raindrops (i.e. acceleration, partly enlargement, oblique impact angle of drops and an increase in number of drops per unit area) when the wind source is applied (Table 1). A detailed description of the PWRS (Fig. 1a) is given in FISTER ET AL. (2011, 2012), the combined sediment trap is described in FISTER AND SCHMIDT (2008).

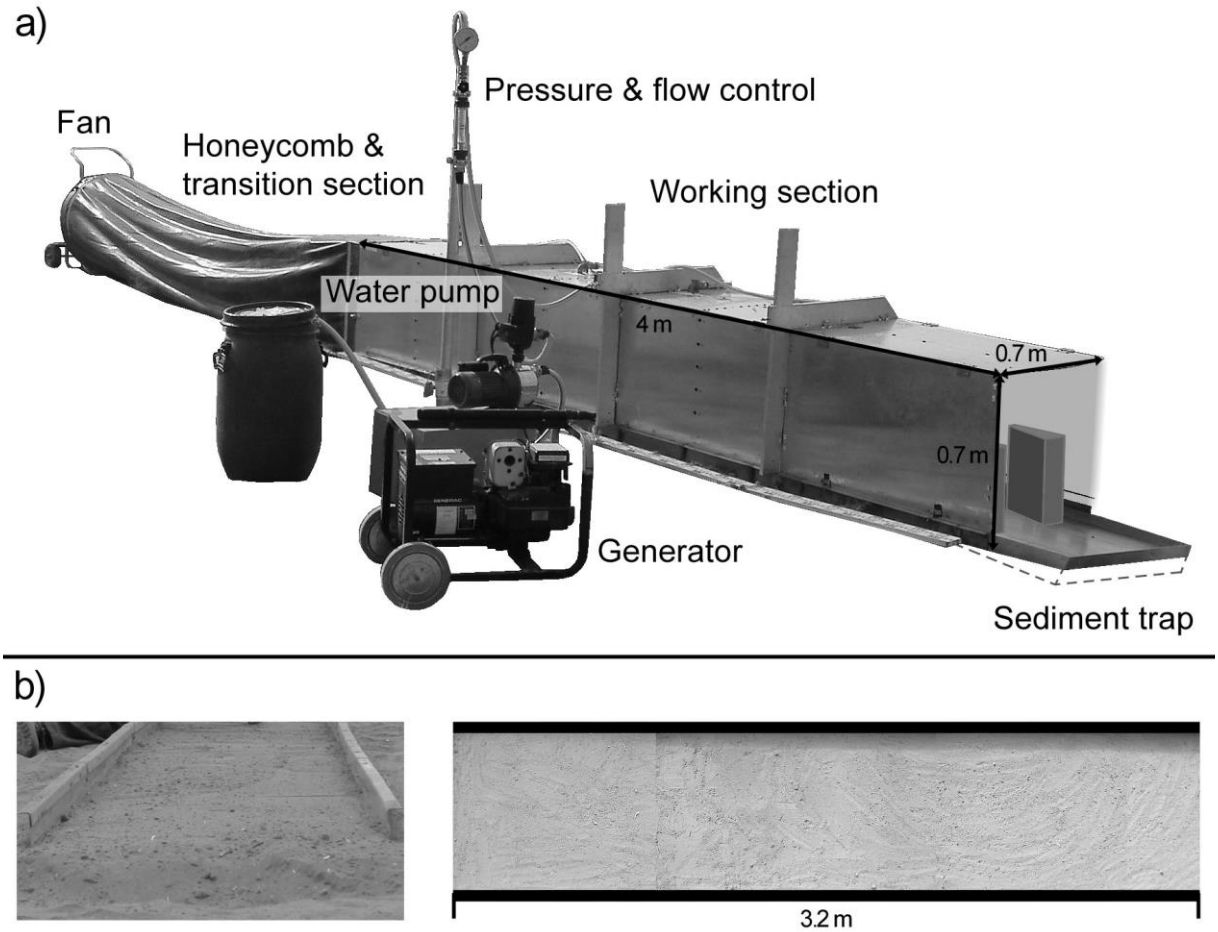

Fig. 1. Instrumentation and experimental setup: a) Portable Wind and Rainfall Simulator (PWRS), b) exemplary 2.2 m² test plot (left: front view, right: plan view).

Table 1. Main wind and rainfall characteristics of the Portable Wind and Rainfall Simulator (based on FISTER et al. 2012) which are mean wind velocity [$\mathbf{v_w}$], mean Intensity [I], mean volumetric drop diameter [d_{50}], drop fall velocities for drops of the size d_{50} [v_r], mean kinetic energy expenditure [KE_R], and mean kinetic energy per unit area per unit depth of rainfall [KE] for WLR and WDR simulations.

	v_w [m s^{-1}]	I [mm h^{-1}]	d_{50} [mm]	v_r [m s^{-1}]	KE_R [J m^{-2} h^{-1}]	KE [J m^{-2} mm^{-1}]
windless rain (WLR)	0	96	1.5–2.0	2.2–2.6	270.8	5.21
wind-driven rain (WDR)	7.5	88	1.75–2.5	3.4–4.2	1590.8	8.08

2.2 Test sequence and procedure of sediment collection

To facilitate extraction of the influences of WDR on soil erosion, to avoid systematic errors, and to reduce variability between test plots, a defined order of four consecutive test runs was established. All test runs were conducted on the same plot forming a test sequence. At first, a wind test run of 10 min duration is performed to allow for assessment of susceptibility of the substrate and the soil surface to wind erosion. This preliminary test is followed by a WLR simulation on dry soil (1) of 30 min duration. This simulation can answer the question of susceptibility of soil to an extreme rain event, and is also conducted to moisten the soil surface for the next test run: because water content of the soil surface is a major parameter influencing soil detachment, for the sake of comparing WDR with WLR this parameter is therefore levelled for both test types. 30 minutes after this “moistening-run”, a WLR simulation on now moist soil (2) is conducted. This test without the influence of wind acts as control sample for the deduction of the impact of wind on water erosion, when compared to the next and last test run (3), a WDR simulation: Additionally to the artificial rain, wind is applied that induces WDR erosion on the plot. By comparing results of rainfall simulation (2) with that of WDR simulation (3), the impact of wind on water erosion can be assessed.

Each rainfall simulation lasts for 30 minutes followed by a 30 min break allowing for initial drainage of the soil as well as sampling and remounting of the sediment catchers. The complete test sequence was conducted four times on accordingly four plots (Plots A-D). After each test sequence, the PWRS was moved to another plot and the test sequence was repeated. We collected total runoff and total amount of sediment detached from the 2.2 m^2 test area with 0.5 L bottles filled into 10 L buckets in 2.5 min intervals. After sedimentation, decanting, filtering (Munktell©, Prod.-Nr. 3.104.185, <2 μm mesh-width) and drying (105 °C), we weighed the amount of sediment for every 2.5 min interval and plotted it against runoff for the same interval.

2.3 Test site

We accomplished the experiments in the Wageningen University’s Willem Genet Tunnel. The facility provides a very homogenous soil surface, while still representing a complete body of soil considering physical and chemical properties. The dimension of the area is 15.2 m x 60 m with a uniform inclination of 1°. The soil of the testplots was a sandy substrate with D_{50} of 0.16 mm (see Fig. 2), pH of 6.4, C_{org}-content of 2.9 % and $CaCO_3$-content of 0.2 %. The bulk density was 1.55 g cm^{-3} for the upper 20 cm and 1.69 g cm^{-3} below 20 cm. Fine sand, which is supposed to be the easiest erodible grain fraction; dominated with 52 % (particle size distribution is listed in Fig. 2).

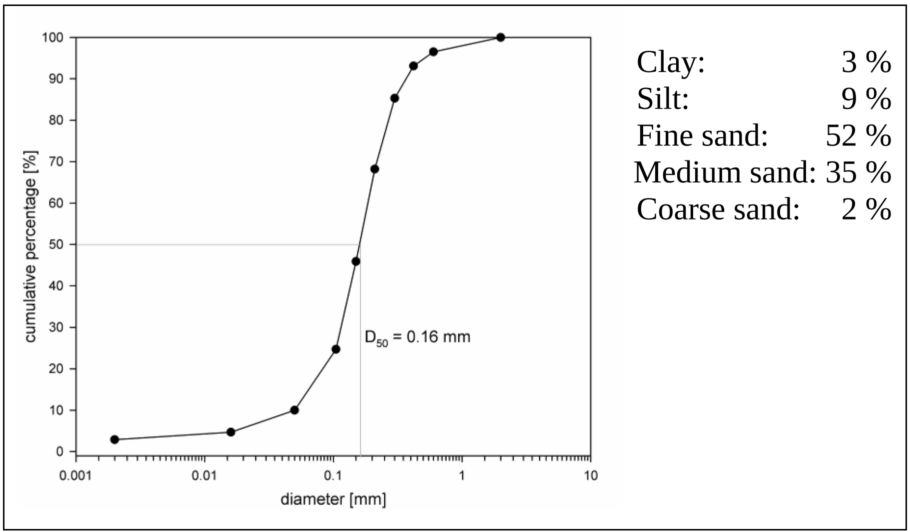

Fig. 2. Cumulative curve of particle size distribution.

The soil has been irrigated, ploughed and cultivated on a regular basis. Before conducting the experiments, we reaped crop remnants and levelled ridges and furrows to get a smooth and homogenous surface (Fig. 1b) and to reduce surface variability. The test plots could therefore be considered as uniform in soil surface conditions, particle- and pore size distribution, content of soil organic matter, stone content, bulk density and microrelief.

3. Results and discussion

Presented here (Fig. 3) are the four complete sequences (A to D) consisting of three succeeding simulations (1, 2 and 3), which were conducted on four respective plots (A to D).

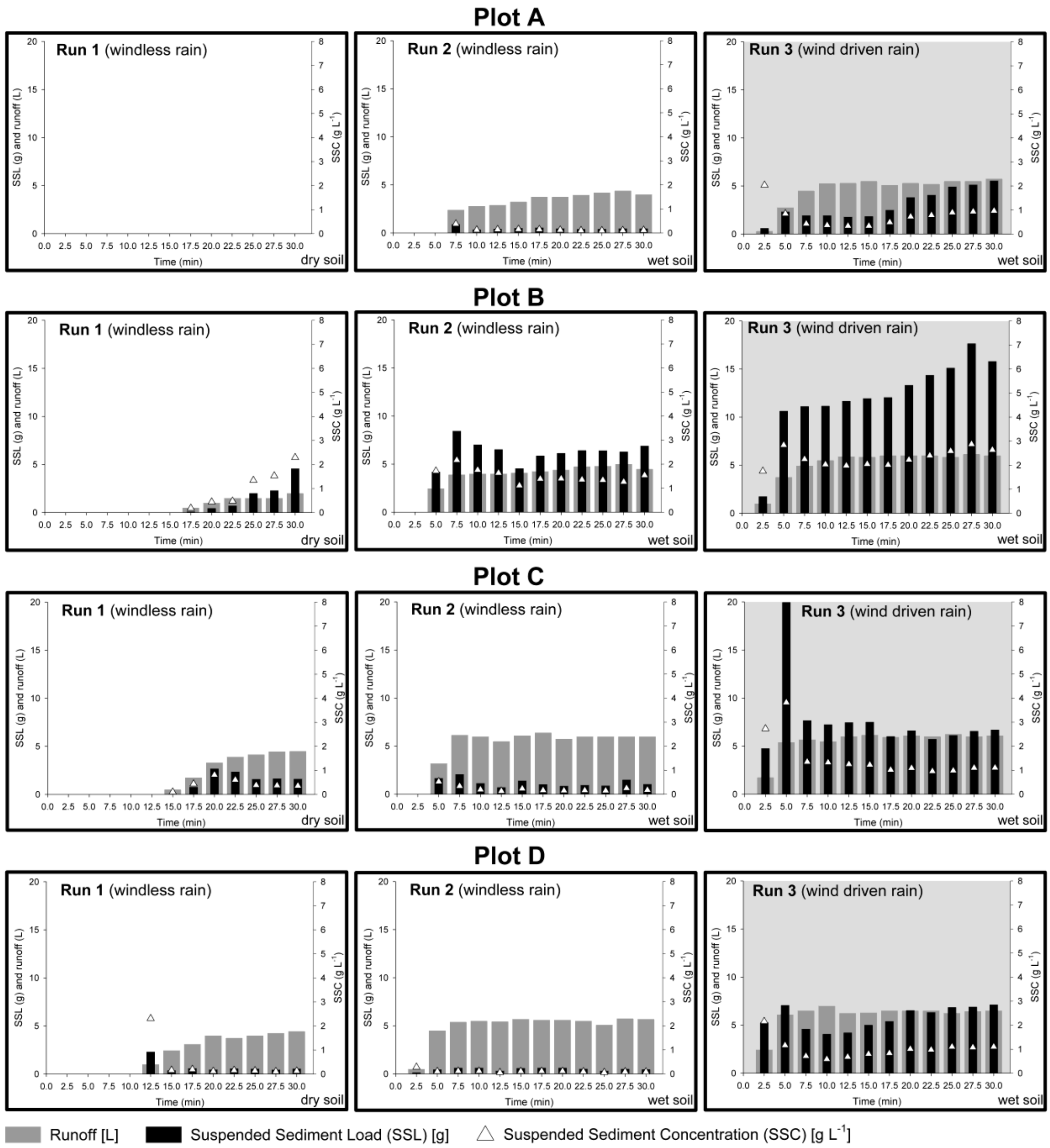

Fig. 3. Results of rainfall simulation experiments for windless and wind-driven rainfall events per 2.5 min interval for all experimental plots (A-D). Runoff is given in L, suspended sediment load in g (SSL) and suspended sediment concentration in g L^{-1} (SSC).

On all plots a regular runoff pattern developed during each sequential run (Fig. 3) showing an increase in overland flow over time. The high hydraulic conductivity and infiltration capacity of the sandy substrate as well as the low slope delayed the development of runoff. Runoff used to start at middle third of run 1 increasing (in one case even later in the beginning of run 2) and intensified until the end. A steady state runoff was reached during the first third in run

2 which slightly elevated during run 3. Altogether the runoff was lowest (0 - 26 %) during the first runs on all plots and can be considered moderate to high with runoff coefficients of 34 - 76 % during run 2 and run 3 (Table 2). Generally, higher runoff coefficients are found during the third runs indicating the influence of wind on amount, velocity and, thus, transport capacity of wind-driven overland-flow. The process of material transport strongly interacted with the generation of runoff, although it showed differences in quantity and also temporally variable patterns among the sequences. In three of four cases (A, C and D), erosion reached a first peak with the initially generated runoff and afterwards decreased, what could be explained by a first wash-off of the easily erodible sandy soil. The next and much higher peak was reached during the WDR simulation in run 3. In two cases (A and B) the eroded material increased gradually towards the end, in the other two cases (C and D) it stayed at a similar level after a peak at the beginning. Obviously, considerably more soil was eroded under the influence of wind: we assume that the wind accelerated shallow overland flow had a greater velocity, detachment and transport capacity and therefore erosivity during the WDR runs. Furthermore, the overland flow seemed to be shallower in the WDR runs and therefore more prone to splash processes (MOSS & GREEN 1983) and splash-drift-processes. An additional component is an increased erosivity of the water film due to induction of turbulences (ERPUL ET AL. 2011). In all cases, the highest amount of eroded material by far was collected during the WDR runs. Compared to the WLR runs, it increased by 113 % up to 1108 %. This adds up to the two- to twelvefold of eroded material by WDR compared to WLR simulation (Table 2).

Table 2. Results for each run of rainfall simulation experiments on all experimental plots (A-D) under windless and wind-driven rainfall conditions. Runoff is given in % of total simulated rainfall amount on plot (Runoff Coefficient: RC), suspended sediment load in g m^{-2} (SSL) and suspended sediment concentration in g L^{-1} (SSC). Additionally, increase from run 2 to run 3 is given in % and as a factor.

Plot	Run		RC (%)			SSL (g m^{-2})			SSC (g L^{-1})	
A	Run 1 (windless rain)		0			0			0	
	Run 2 (windless rain)	+ 71% ↓	34	↓ x1.7	+640% ↓	4.9	↓ x7.4	+368% ↓	0.1	↓ x4.7
	Run 3 (wind-driven rain)		58			36.3			0.6	
B	Run 1 (windless rain)		8			10.1			1.3	
	Run 2 (windless rain)	+48% ↓	44	↓ x1.4	+113% ↓	68.8	↓ x2.1	+56% ↓	1.6	↓ x1.6
	Run 3 (wind-driven rain)		65			146.6			2.3	
C	Run 1 (windless rain)		21			10.7			0.5	
	Run 2 (windless rain)	+15% ↓	60	↓ x1.1	+602% ↓	13.3	↓ x7.0	+562% ↓	0.2	↓ x6.6
	Run 3 (wind-driven rain)		69			93.1			1.4	
D	Run 1 (windless rain)		26			5.8			0.2	
	Run 2 (windless rain)	+32% ↓	57	↓ x1.3	+1108% ↓	5.8	↓ x12.1	+894% ↓	0.1	↓ x9.9
	Run 3 (wind-driven rain)		76			69.5			0.9	

Compared to the increase in eroded material, the increase in runoff is rather low with 15 % to 71 %. Hence, the highest sediment concentrations are also found during the WDR runs and increases in comparison to WLR runs from 56 % to 894 %. This clear trend of intensified soil erosion by WDR is in accordance with results from laboratory experiments for instance by CORNELIS ET AL. (2004 b) and ERPUL ET AL. (2005, 2011). The transported material collected during simultaneous wind and rainfall simulations consists of the components raindrop-impacted shallow overland flow and splash-drift. Both processes are closely related to each other and have not been experimentally separated yet. Depending on depth of water film, the impact energy of the falling raindrop is either amplified (thin film) or diminished (thick film). Under thin water film conditions, splash-drift processes might occur and even be intensified to an essential factor for detachment and transport under WDR. Splash-drifted particles also count for an important part of eroded material under wet-soil and wind-influenced conditions without generation of a water film (DE LIMA ET AL. 1992, VAN DIJK ET AL. 1998).

In this study however, the key factor to explain the higher amount of eroded material is the shallow overland flow which was impacted by wind-driven raindrops leading to higher hydraulic turbulences and a higher erosivity. By impacting the surface water film, the rain drops create turbulences that lead to detachment and entrainment of soil particles, a process that is even more accentuated under the influence of wind due to greater impact energy and drop number as well as a further development of lateral jets inside the runoff (ERPUL ET AL. 2011, KINNELL 2005). Furthermore, the wind might have directly accelerated the shallow overland flow, a finding that urgently needs to be addressed in further studies.

The results indicate that the established consecutive test sequence allows the required quantification of WDR influences on soil erosion and enables process observation. Parameters like soil surface conditions, particle- and pore size distribution, content of soil organic matter, stone content, bulk density and microrelief usually complicate the interpretation of runoff and erosion patterns, but can be regarded negligible during our study. Conditions can be regarded reproducible for all the simulations. The obvious variations of measured eroded material between test plots are due to the randomness of the processes themselves. Changes in microrelief, as a partly self-energising process, are an example of this natural randomness. The variability in amount of eroded material between identical test plots under equal rainfall conditions is well known and was observed in several studies (e.g., NEARING ET AL. 1999, WENDT ET AL. 1986).

5. Conclusions

WDR increases soil erosion on cohesionless sand substantially. While susceptibility to water erosion was low, even well drained cohesionless sand with a very low inclination was entrained significantly by WDR. The results suggest that neglecting the influence of wind on water erosion processes could lead to a severe underestimation of soil erosion rates. The experimental setup allows for detailed qualitative and quantitative observation of runoff and erosion processes due to WLR and WDR. Test device and test sequence meet the requirements of validity as well as reproducibility.

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References

CORNELIS, W.M., ERPUL, G. & GABRIELS, D. (2004 a): The I.C.E. wind tunnel for wind and water interaction research. – In: VISSER, S. & CORNELIS, W.M. (eds.): Wind and rain interactions in erosion. – Tropical Resource Management Papers **50**: 197-224.

CORNELIS, W.M., OLTENFREITER, G., GABRIELS, D. & HARTMANN, R. (2004 b): Splash-Saltation of Sand due to Wind-Driven Rain: Vertical Deposition Flux and Sediment Transport Rate. - Soil Sci. Soc. Am. J. **68**: 532-540.

DE LIMA, J.L.M.P. (2011): Wind-driven rainfall effects on overland flow and sediment transport. - In: VERMANG, J., GABRIELS, D., CORNELIS, W.M., DE BOEVER, M. (eds.): Land degradation processes and assessment- wind erosion, interrill erosion, gully erosion, land cover features: 9-18. UNESCO Chair of Eremology, Ghent, Belgien.

DE LIMA, J.L.M.P., SINGH, V.P. & DE LIMA, M.I.P. (2003): The influence of storm movement on water erosion: Storm direction and velocity effects. - Catena **52**: 39-56.

DE LIMA, J.L.M.P., TAVARES, P., SINGH, V.P. & DE LIMA, M.I.P. (2009): Investigating the importance of rainstorm direction on overland flow and soil loss in a laboratory circular soil-flume. - Geoderma **152**: 9–15.

DE LIMA, J.L.M.P., VAN DIJK, P.M. & SPAAN, W.P. (1992): Splash-saltatation transport under wind-driven rain. - Soil Technol. **5**: 151–166.

ERPUL, G. GABRIELS, D., NORTON, L.D., FLANAGAN, D., HUANG, C. & VISSER, S.M. (2011): Interactions between raindrop impact and shallow interrill flow under wind-driven rain (WDR). - In: VERMANG, J., GABRIELS, D., CORNELIS, W.M., DE BOEVER, M. (eds.): Land degradation processes and assessment- wind erosion, interrill erosion, gully erosion, land cover features: 9-18. UNESCO Chair of Eremology, Ghent, Belgien.

ERPUL, G., GABRIELS, D. & JANSSENS, D. (2000): Effect of wind on size and energy of small simulated raindrops: a windtunnel study. - Int. Agrophysics **14**: 1-7.

ERPUL, G., GABRIELS, D. & NORTON, L.D. (2005): Sand detachment by wind-driven raindrops. - Earth Surf. Proc. Land. **30**: 241-250.

ERPUL, G., NORTON, L.D. & GABRIELS, D. (2002): Raindrop-induced and wind-driven soil particle transport. - Catena **47**: 227–243.

FISTER, W. (2011): Ein mobiler Windkanal mit integrierter Beregnungsanlage zur experimentellen Erfassung der Bodenerosion durch Wind, Wasser und ihrer kombinierten Wirkung im Gelände. PhD thesis, Trier University, Germany.

FISTER, W. & SCHMIDT, R.-G. (2008): Concept of a single device for simultaneous simulation of wind and water erosion in the field. - In: GABRIELS, D., CORNELIS, W.M. (eds.): Proceedings of Conference on Desertification, 23.01.2008, Gent, Belgium: 106-113.

FISTER, W., ISERLOH, T., RIES, J.B. & SCHMIDT R.-G. (2011): Comparison of rainfall characteristics of a small portable rainfall simulator and a combined portable wind and rainfall simulator. - Z. Geomorphol. **55(3)**: 109-126.

FISTER, W., ISERLOH, T., RIES, J.B. & SCHMIDT R.-G. (2012): A portable combined wind and rainfall simulator for in situ soil erosion measurements. - Catena **91**: 72-84.

ISERLOH, T., FISTER, W., MARZEN, M., RIES, J.B. & SCHMIDT, R.-G. (2009): Wind and water erosion on abandoned land in High Andalusia - First results of a portable combined wind and rainfall simulator. - Geophysical Research Abstracts **11**: EGU2009-10511.

KINNELL, P.I.A. (2005): Raindrop-impact-induced erosion processes and prediction: a review. - Hydrol. Process. **19**: 2815–2844.

LYLES, L., DISRUD, L.A. & WOODRUFF, N.P. (1969): Effects of soil physical properties, rainfall characteristics, and wind velocity on clod disintegration by simulated rainfall. - Soil Sci. Soc. Am. Proc. **33(2)**: 302-306.

MOSS, A.J. & GREEN, P. (1983): Movement of solids in air and water by raindrop impact: Effects of drop-size and water-depth variations. - Aust. J. Soil Res. **21**: 257-269.

NEARING, M.A., GOVERS, G. & NORTON, L.D. (1999): Variability in Soil Erosion Data from Replicated Plots. - Soil Sci. Soc. Am. J. **63**: 1829-1835.

RAVI, S., BRESHEARS, D.D., HUXMAN, T.E. & D'ODORICO, P. (2010): Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. - Geomorphology **116**: 236-245.

RIES, J.B., FISTER, W., ISERLOH, T. & MARZEN, M. (2010): Wind driven rain as a new challenge for in situ rainfall simulation experiments. - Geophysical Research Abstracts **12**: EGU2010-2747.

UMBACK, C.R. & LEMBKE, W.D. (1966): Effect of wind on falling water drops. - Trans. ASAE **9**: 805-808.

VAN DIJK, P.M., STROOSNIJDER, L. & DE LIMA J.L.M.P. (1996): The influence of rainfall on transport of beach sand by wind. - Earth Surf. Proc. Land. **21**: 341-352.

VAN HEERDEN, W.M. (1964): Splash erosion as affected by the angle of incidence of raindrop impact. Unpublished PhD thesis. Purdue University, Lafayette, IN, USA.

VISSER, S.M., STERK, G. & RIBOLZI, O. (2004): Techniques for simultaneous quantification of wind and water erosion in semi-arid regions. –J. Arid. Environ. **59**: 699–717.

WENDT, R.C., ALBERTS, E.E. & HJELMFELT, J.R. (1986): Variability of runoff and soil loss from fallow experimental plots. - Soil Sci. Soc. Am. J. **50**: 730-736.

III

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Soil erosion in Mediterranean landscapes - Experimental investigation on crusted surfaces by means of the Portable Wind and Rainfall Simulator.

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Soil erosion in Mediterranean landscapes – Experimental investigation on crusted surfaces by means of the Portable Wind and Rainfall Simulator

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ABSTRACT

The influence of wind on raindrops and subsequent processes of soil detachment and transport on natural soil surfaces is an essential gap of knowledge. The urgently required data about reactions, interactions and actual impact on soil erosion rates are generally produced under laboratory conditions on highly disturbed substrates, which cannot reflect natural system responses. The Portable Wind and Rainfall Simulator was applied on autochthonous soils in semi-arid Spain to investigate and quantify the relative impact of wind-driven rain on total erosion.

On highly degraded crusted soils and freshly ploughed orchard soils in semi-arid Spain, total erosion measured during experiments (30 min; 96 mm h^{-1}) were 28.8–150.4 g m^{-2} and 29.5–30.7 g m^{-2}, respectively. Concerning the relative impact of wind-driven rain on total erosion, ambiguous results were obtained: the difference to erosion generated by windless rain ranged from +37.4 to −24.2%, to sediment concentration from +46.7 to −20.6% and to runoff coefficients from +18.8 to −7.4%.

The study indicates a potentially very strong impact of wind-driven rain and underlines the paramount importance of experimental data derived on autochthonous soil surfaces for process understanding, realistic assessment of soil erosion rates and application in soil erosion models.

1. Introduction

The influence of wind on water erosion is an essential gap of knowledge in soil erosion studies (Ravi et al., 2010; Visser et al., 2004), which is particularly true for the specific reactions of natural soil surfaces to the altered physical properties of wind-driven rain (WDR).

In the semi-arid landscapes of southern Spain, the often depleted and degraded soils are notably threatened by erosion due to high-erosive storm events of combined intensive rain and wind. Overexploitation, a substrate prone to erosion, the specific climatic conditions and not the last the European set-aside politic of arable land in recent years have been leading to the generation of large areas of abandoned land. For the typical vegetation on these areas it takes many years to develop a protective and stabilising coverage (Ries, 2005), and often these effects are severely disturbed by grazing and trampling (Monfreda et al., 2009). Due to Mediterranean farming systems, particularly concerning fruit tree orchards, arable land is often left uncovered and harrowed during the rainy periods and are susceptible to interrill erosive processes. On the bare soil surfaces, the wind-driven raindrops can unfold their full erosive power.

Interrill erosion acts as a combination of different processes: drop impact, shallow overland flow (SOF) and/or drop impacted shallow overland flow (IOF) (Kinnell, 2005). Laboratory studies showed, that wind does influence properties of raindrops, SOF and IOF that are essential for the impact on soil erosion: a modification of velocities and trajectories of falling raindrops (De Lima, 1989; Sharon, 1980) and the number of impacting drops per unit area were observed. The velocity of the drops was found to exceed the terminal fall velocity of windless, vertically falling rain (Pedersen and Hasholt, 1995). The higher kinetic energy of wind-accelerated drops provides a stronger impulse for the movement of soil particles, and the oblique impact angle extends the travelling distance of particles on a flat surface (Cornelis et al., 2004). As a result, a considerably higher kinetic energy could be measured in wind-driven rain under laboratory (Disrud and Krauss, 1971; Erpul

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et al., 2005; Umback and Lembke, 1966) as well as natural conditions (Helming, 2001). Furthermore, the erosivity of the (raindrop impacted) overland flow might be considerably increased by acceleration of flow and induction of turbulences via impacting wind-driven raindrops (Erpul et al., 2011; Samray et al., 2011). The erosion-relevant influences of wind on a falling raindrop and SOF accordingly are plural and haven't been comprehensively assessed yet, which is particularly true for the reactions of natural soil surfaces to wind-driven rain and the actual impact on soil erosion rates: In fact, the wind-driven rain-complex has been studied mainly as a problem of the eroding agents' physical properties only, whereas reactions and interactions of natural soil surfaces exposed to wind-driven rain have been neglected.

For investigation of WDR and its effects on soil erosion, the Portable Wind and Rainfall Simulator (PWRS) was developed at Trier University (Fister, 2011; Fister et al., 2011, 2012) and applied on different sites. Iserloh et al. (2013) measured on cohesionless sandy substrate an increased net-WDR-erosion (the difference to erosion due to windless rain experiments) ranging from +113 to +1108% due to WDR during all tests.

The here presented study with the same experimental device and setting shows the influence of WDR on autochthonous soils and investigates reactions of naturally developed soil surfaces to wind-influenced drops, SOF and IOF, which might count for a significant part of both, yet unexplained erosion-rates and variability of soil erosion on a given plot.

Wind erosion experiments are generally not conducted on substrates of that kind because they are not regarded susceptible to wind erosion, although these are the substrates that are significant for agricultural practices in dry regions (Albert et al., 2005; Fister and Ries, 2009). They can be found on marly locations, fluvial terraces and valley fillings, and also alluvial fans and pediments, and are generally nutrient-richer than and of a superior water balance in terms of food production to the sandy substrates on dunes and drifting sands, that often are the preferred areas of investigations (Albert et al., 2005; Fister and Ries, 2009).

We present the first results of experimental investigations with the PWRS on autochthonous soils with different surface structures in semi-arid Spain that may throw light upon the reactions and interactions of natural soil surfaces to WDR and quantify the actual impact on soil erosion rates.

The measurements aimed at 1. experimental quantification of soil erosion due to simulated high erosive rain events, 2. investigation of the relative impact of wind-driven rain on soil erosion and 3. identification of relevant soil surface parameters.

Two types of soil surface structures were tested: strongly crusted fallow land and recently ploughed orchard soil.

2. Material & methods

2.1. Study area

The experiments were accomplished in semi-arid Spain in the easterly foothills of the Betic cordillera (Fig. 1). The basin and range landscape is shaped by the post orogenic formation of the Guadalquivir basin. The Pliocene-Pleistocene pediment-landscape established on Pliocene sediments and consists mainly of marls with partly strong calcerous crusts (Marzolff et al., 2011).

The climatic conditions are semi-arid with high-erosive torrential rainfalls counting for most of the precipitation throughout the year. The average precipitation per year is 200–350 mm. It occurs dominantly in spring and autumn and is characterized by a high inter-annual variability (Schütt, 2001). The study sites are characterised by large areas of abandoned agricultural land in a region of low shrubland features. Even older fallow land is only patchily

Fig. 1. Study area.

covered by garrigue-vegetation such as *Thymus*, *Genista*, *Rosmarinus*, *Artemisia*, Esparto (*Lygeum spartum*) and Halfagras (*Stipa tenacissima*). The soils are mostly calcaric regosols (Seeger, 2007) and highly degraded: on the silty-loamy soil surfaces, infiltration capacity is severely reduced because of crusts and therefore exceedingly prone to interrill- and rill-erosion (Ries, 2003; Wirtz et al. 2012; Ries et al., in press). Additionally, further degradation by extensive pasturing takes place (Ries et al., in press). The tests were conducted on the sites Freila (FRE), Negratin (NEG) and Salada (SAL). The tested sites feature typical characteristics that are representative for large areas in southeastern Spain.

2.2. Experimental setup

We accomplished the measurements of the effect of WDR on soil erosion with the Portable Wind and Rainfall Simulator (PWRS) (Fig. 2). This device is suitable for wind simulations, rainfall simulations and simulation of rainfall events with the influence of wind. A collector was constructed that is able to catch runoff as well as detached surface material (Fister and Schmidt, 2008).

The analysis of wind and rainfall characteristics showed good results regarding reproducibility of air-stream and rainfall conditions (Fister et al., 2011, 2012). The device is able to simulate the impact of wind on falling raindrops (i.e. acceleration, partly enlargement, oblique impact angle of drops and an increase in number of drops per unit area) when the wind source is applied (Table 1).

2.2.1. Test sequence and procedure of sediment collection

For the assessment of the impact of wind-driven rain on erosion, a defined sequence of tests was developed (Iserloh et al., 2013). During each sequence, erosion experiments with wind, water and wind-driven rain are conducted consecutively. To enable a direct comparison between the amounts of eroded material, all tests within a sequence are carried out on the same plot.

The first test (0) is a wind test run of duration of 10 min that provides information about the susceptibility of the soil surface to wind erosion. This test is followed by a rainfall simulation on dry soil (1) that accounts for susceptibility of soil to an extreme rain event and is also conducted to moisten the soil surface for the next test run to equalise water content of soil surface for comparing wind-driven rain with windless rain. 30 min after this "moistening-run", a rainfall simulation on now moist soil (2) is conducted. The last test run is a simultaneous wind and rainfall simulation (3): additionally to the artificial rain, wind is applied that induces wind-

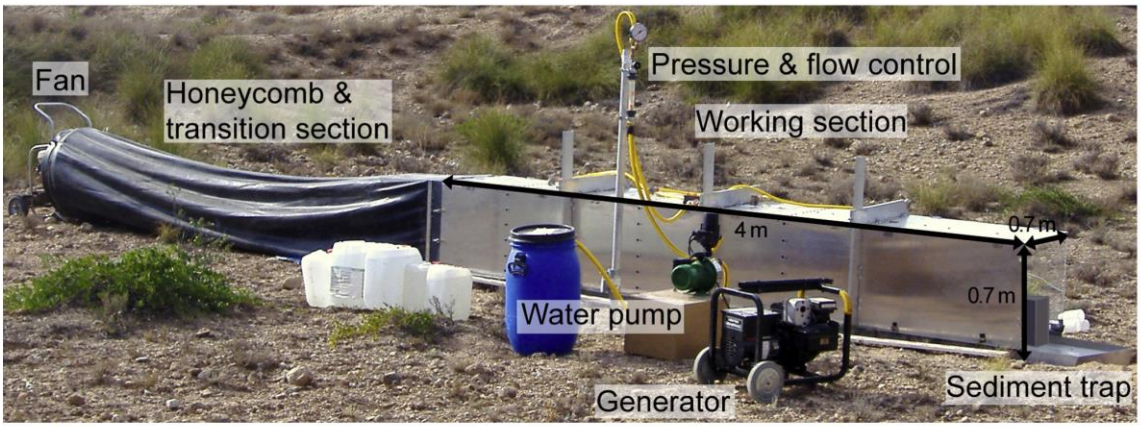

Fig. 2. Experimental setup: Portable Wind and Rainfall Simulator (PWRS). The PWRS consists of five parts: (1) The fan, (2) the 4 m long transition section, which is connected to the working section (3) by the honeycomb. The rainfall is simulated using a pump and a pressure and flow control system (4). 30 cm before the end of the tunnel a sediment trap (5) is positioned, which is able to catch runoff and detached sediment (gutter system) as well as splash and windborne material.

driven rain erosion on the plot. By comparing results of rainfall simulation (2) with that of wind-driven rainfall simulation (3), the impact of wind on water erosion can be assessed.

Each rainfall simulation is of 30 min duration, and a 30 min break in between allows for initial drainage of soil as well as cleaning and remounting of sediment catchers.

For this study, the complete test sequence was conducted 8 times on accordingly 8 plots (Plots FRE 1–5; NEG 1, 2; SAL). We collected total runoff and total amount of sediment detached from the 2.2 m^2 test area with 0.5 L bottles emptied into a bucket in 2.5 min intervals, which allows for a good time resolution and a detailed process study. After sedimentation, decanting, filtering (Munktell©, Prod.-Nr. 3.104.185, <2 μm mesh-width) and drying (105 °C), we weighed the amount of sediment for every 2.5 min interval and plotted it against runoff of the same interval. The runoff coefficient (RC) was calculated with 105 L average total water application for windless rain and 97 L average total water application for wind-driven rain. The difference in water amount is caused by the drift of finer drops beyond the test area due to the influence of wind. The wind-eroded material was collected by means of wedge-shaped samplers (Fister and Schmidt, 2008) and calculated to g m^{-2}. The wedgetraps are a combination of the ICE-sampler (International Centre for Eremology; Cornelis and Gabriels, 2003) and the Guelph-Trent -sampler (Nickling and McKenna-Neumann, 1997). The results of each test are displayed in detail in Fig. 3, Tables 3 and 4.

Before the final test setting (run 0, 1, 2, 3) was established, we had experimented with the sequence of windless rain- and WDR-runs. One of the test-sequences, FRE 0 (WDR-WDR-Rain-WDR), is displayed in Fig. 4. On the basis of this exemplary sequence that is not regarded in detail here, we show the impact of one wind-driven rain event on a dry surface as well as the advantages of the now established test-sequence for analysing the influence of WDR.

2.3. Test plots

The main characteristics of the tested plots are given in Table 2. We estimated the surface characteristics (vegetation, stones, crust) and measured aspect, inclination, soil H_2O and $C_{org.}$ The roughness (Cr) was measured after Saleh (1993). The test plot in the Guadalentin basin (Salada: SAL) was a young (~1 year old) fallow on calcareous, weakly sandy loam. The test plots in the Baza basin were extensively grazed old fallows (>25 years) with scarce and patchy garrigue vegetation on highly degraded calcaric regosols with historically repeatedly developed crusts of 5–10 mm strength (Freila: FRE) and a freshly ploughed orchard (Negratin: NEG) with downslope furrows. These surface-structures on silty-loamy soils are known as geomorphodynamic highly active and susceptible to erosion, particularly because of a reduced infiltration due to the development of crusts (Ries, 2003).

3. Results

We describe and analyse quantitative and qualitative results concerning the reaction of the tested soil surfaces to simulated erosive wind, rainfall without wind and rainfall with applied wind. In this way, we gain a better process understanding and derive the impact of wind-influenced rain on erosion from the comparison to erosion due to windless rain.

Table 1
Main wind and rainfall characteristics of the Portable Wind and Rainfall Simulator (source: Iserloh et al., 2013): Presented are mean wind velocity [v_w], mean Intensity [I], mean volumetric drop diameter [d_{50}], drop fall velocities for drops of the size d_{50} [v_r], mean kinetic energy expenditure [KE_R], and mean kinetic energy per unit area per unit depth of rainfall [KE] for windless and wind-driven rain simulations.

	v_w [m s^{-1}]	I [mm h^{-1}]	d_{50} [mm]	v_r [m s^{-1}]	KE_R [J m^{-2} h^{-1}]	KE [J m^{-2} mm^{-1}]
Windless rain	0	96	1.5–2.0	2.2–2.6	270.8	5.21
Wind-driven rain	7.5	88	1.75–2.5	3.4–4.2	1590.8	8.08

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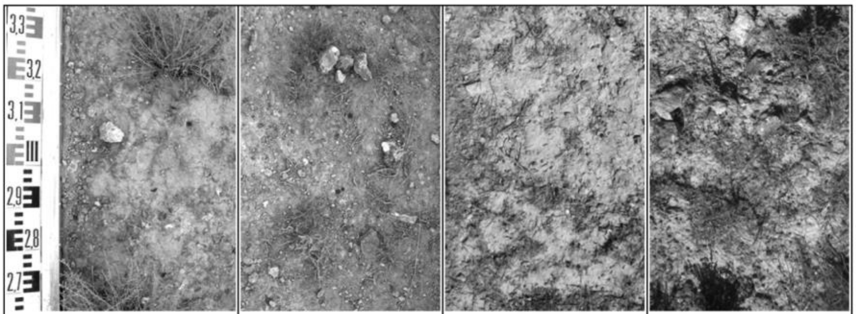
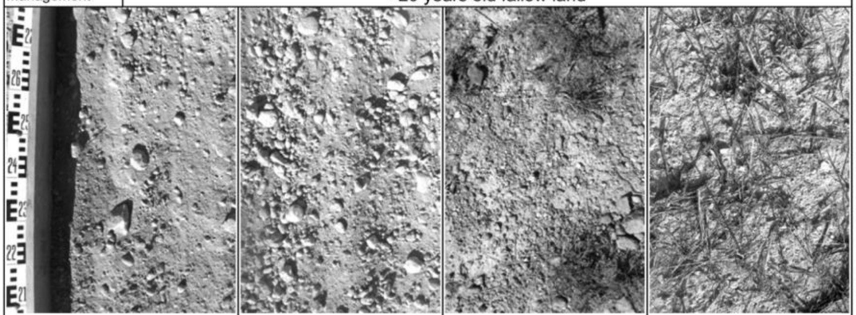
Table 2
Soil surfaces and physical properties of test plots.



	FRE 1	FRE 2	FRE 3	FRE 4
Vegetation (%)	20; Garrigue	10; Garrigue	15; Garrigue	20; Garrigue
Stones (%)	30.0	30.0	15.0	15.0
Crust (%)	50.0	60.0	70.0	65.0
Inclination (°)	5.0	5.0	5.0	5.0
Aspect	NE	N	NNE	NNE
Roughness (Cr)	5.9	4.7	5.5	5.5
Soil H2O (%)	5.8	0.9	0.5	0.5
Corg (%)	0.4	0.4	0.4	0.4
Substrate	Calcaric regosols from pliocene marl; silty loam			
Management	>20 years old fallow land			



	NEG 1	NEG 2	FRE 5	SAL
Vegetation (%)	0; Orchard	0; Orchard	15; Garrigue	30; Cereal
Stones (%)	60.0	60.0	65.0	10.0
Crust (%)	0	0	20.0	60.0
Inclination (°)	6.0	4.0	7.0	4.0
Aspect	W	W	NNE	SE
Roughness (Cr)	7.2	7.9	5.5	1.4
Soil H2O (%)	3.7	3.7	0.5	3.8
Corg (%)	1.2	1.2	0.4	0.7
Substrate	Calcaric regosols from pliocene marl; silty sand			Pleistocene valley filling
Management	Freshly ploughed olive orchard		>20 years old fallow land	1-2 years young fallow

Table 3
Wind eroded substrate during 10 min – experiments.

Plot	Surface	Crust	Stones	Roughness	Vegetation	Total (g)	g m^{-2}
FRE 1	Old fallow land	Strong	Embedded/overlying	4.7–5.9	Garrigue	0.35	0.16
FRE 2						1.44	0.64
FRE 3						1.38	0.62
FRE 4						0.89	0.40
FRE 5						1.42	0.63
SAL	Young fallow land	Medium	Sparse	1.4	Cereal remains	0.17	0.08
NEG 1	Freshly ploughed	None	Loose	7.2–7.9	–	1.68	0.75
NEG 2						1.29	0.58

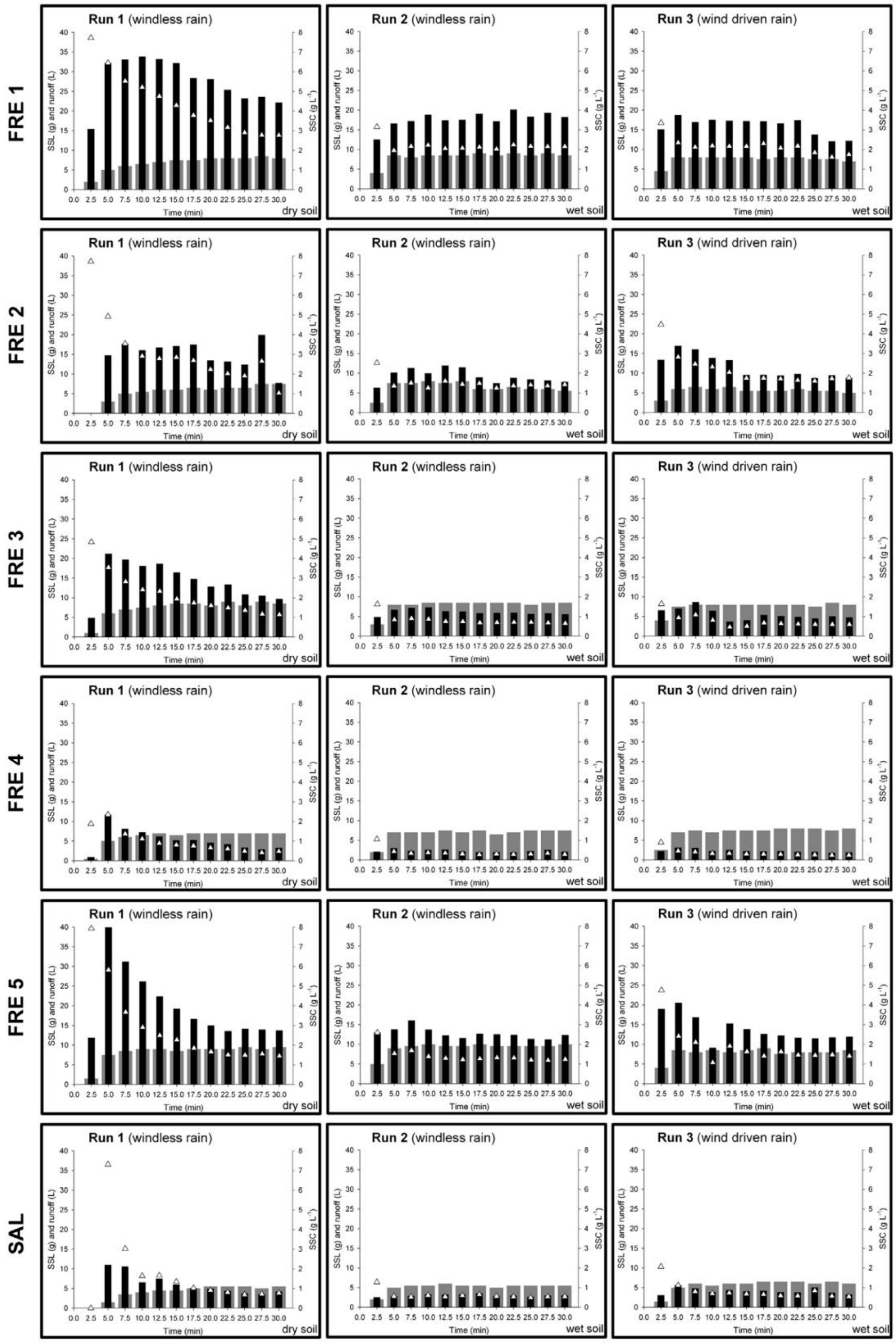


Fig. 3. Temporal development of runoff and erosion of all tests. (SSL: Suspended sediment load; SSC: Suspended sediment load concentration).

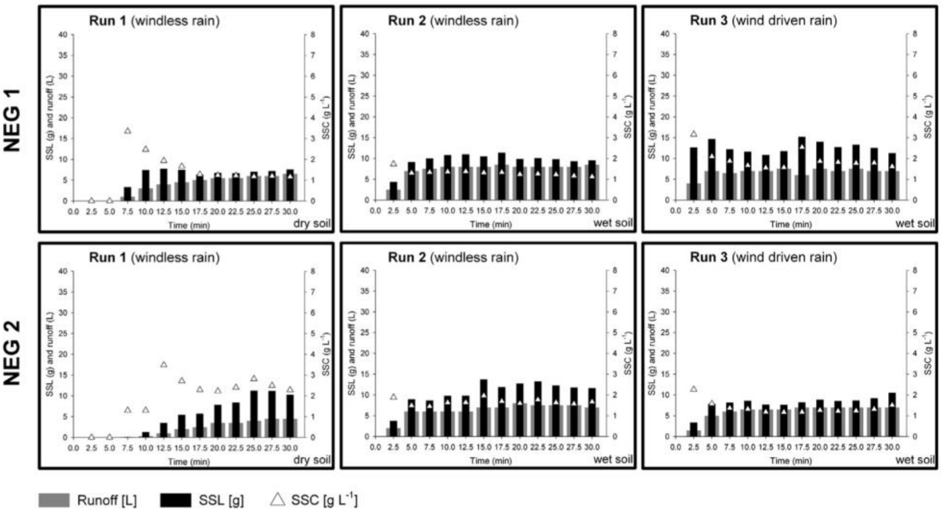


Fig. 3. (*continued*).

3.1. Erosion due to simulated wind (Run 0)

The wind eroded material was collected during the first run of each complete test sequence and the results are displayed in Table 3. The amount of collected sediment per m^2 ranges from 0.08 to 0.75 g and clarifies the low susceptibility of the tested soils to wind erosion.

Compared to the results of the water eroded substrate, the wind eroded substrate is about one to two dimensions lower (Table 4). The values support measurements of Fister and Ries (2009) at the Ebro basin with a slightly shorter version (3 m) of the same wind tunnel on crusted fallow land. Because of the small amounts of collected material, discrimination between the surface structures is not possible: crusted fallows of different age (FRE and SAL), goat-trampled surface (FRE 2) and tilled orchard surfaces (NEG) produced relatively similar values.

In the cases of FRE and SAL, probably the entire transported material was located loosely on the crust and blown away soon in the first 1–2 min: the wind did not appear to affect the crust itself, supporting findings of Zobeck (1991). In the case of NEG 1 and 2, the wind constantly transported fresh substrate particles, wind erosion rates of 4.5 and 3.45 g m^{-2} h^{-1} can be calculated from the eroded amount of 10 min. Compared to the erosion generated by rain and wind-driven rain, the wind erosion is low.

3.2. Erosion due to simulated highly erosive rain events (Run 1, 2)

Regarding total erosion on the degraded soils due to high-erosive rainfall-simulations (run 1), the results show a temporal development of runoff and erosion which coincides with the surface structure. The crusted soil surfaces produce a very fast reaction to the application of rain by immediate runoff generation and the highest total erosion rates and sediment concentrations during the first simulations. The peak in the first 10 min is followed by a continuous decline for the remaining 20 min. Much lower erosion rates are measured during the 2. run on wetted surfaces. The temporal development of erosion on crusted soil surfaces shows, that raindrop-disrupted aggregates and loose material on the very dry soil surface outweigh the actual detachment by surface overland flow and raindrop impacted overland flow. The first rainfall simulation always brings by far the highest erosion and sediment concentration compared to the following test runs, where more fresh erosion occurs. This fact gives insight into the strong effect of highly erosive rain events on bare crusted soil surfaces: already a few minutes of high rainfall intensity (as often observed during natural rain events) may count for a major part of the total eroded material. Recently ploughed orchard soils show a comparatively delayed and much less pronounced runoff generation in the beginning of the 1. run, and runoff and erosion increase throughout run 1 until the middle of the run 2. High infiltration rates and a higher soil roughness slow and lessen runoff generation, but once runoff has established, the surface material is easily entrained and steadily transported (Fig. 3). Erosion on loose, un-crusted soil surfaces rather tends to increase with time, so that short periods of highly erosive heavy rainfall might be buffered by the high infiltration capacity. However, a prolonged rain event with lasting runoff generation might enhance a severe soil loss.

While the two tests on freshly ploughed soil (NEG 1, 2) show similar results concerning total soil erosion and runoff generation, the results on degraded and crusted surfaces (FRE 1–5; SAL) differ considerably concerning both. These differences might be correlated with the variables soil texture, moisture, C_{org} and inclination (Table 2), but a clear pattern could not be found in the present dataset. Initial soil moisture is one example of factors regarded most important concerning the detachment of soil material by water (Duttmann, 2001; Poesen and Savat, 1981), but we observed the overall highest erosion rates on plots with the highest (FRE 1: 5.8%) as well as a very low (FRE 5: 0.5%) initial soil water contents. It can clearly be stated, that the actual detachment of soil material is a complex interaction of different parameters and effects concerning the impact of eroding agents as well as soil physical and chemical factors. As an essential factor-complex we, therefore, regard the surface cover structure, displayed in Table 2 as percentage vegetation, stone and crust of total surface.

While the NEG-plots share the relevant characteristics of surface-cover, the other plots differ in the percentage of vegetation-, stone- and crust-cover.

The well developed surface crusts had clear effects on soil erosion: by drastic reduction of infiltration rate they enhanced a high runoff generation (Ries and Hirt, 2008). Particularly these

Table 4
Results of all test sequences (RC: Runoff coefficient; EM: Eroded material; SSC: Suspended sediment load concentration).

Plot	Run		RC (%)			EM (g m^{-2})			SSC (g L^{-1})	
FRE 1	Run 1 (windless rain)		78.1			150.4			4.0	
	Run 2 (windless rain)	−1.1% ↓	93.8	↓ ×0.99	−9.6% ↓	96.6	↓ ×0.90	−1.1% ↓	2.2	↓ ×0.99
	Run 3 (wind-driven rain)		92.8			87.4			2.1	
FRE 2	Run 1 (windless rain)		62.9			75.7			2.5	
	Run 2 (windless rain)	−6.5% ↓	73.3	↓ ×0.93	+25.6% ↓	50.4	↓ ×1.26	+45.4% ↓	1.4	↓ ×1.45
	Run 3 (wind-driven rain)		68.6			63.3			2.1	
FRE 3	Run 1 (windless rain)		84.8			77.7			1.9	
	Run 2 (windless rain)	+4.2% ↓	90.5	↓ ×1.04	−9.7% ↓	33.4	↓ ×0.90	−6.2% ↓	0.8	↓ ×0.94
	Run 3 (wind-driven rain)		94.3			30.2			0.7	
FRE 4	Run 1 (windless rain)		70.0			28.8			0.9	
	Run 2 (windless rain)	+15.0% ↓	77.1	↓ ×1.15	+1.1% ↓	12.5	↓ ×1.01	−4.8% ↓	0.3	↓ ×0.95
	Run 3 (wind-driven rain)		88.7			12.6			0.3	
FRE 5	Run 1 (windless rain)		94.3			109.9			2.4	
	Run 2 (windless rain)	−7.4% ↓	105.2[a]	↓ ×0.93	+13.1% ↓	69.6	↓ ×1.13	+32.3% ↓	1.4	↓ ×1.32
	Run 3 (wind-driven rain)		97.4			78.7			1.8	
SAL	Run 1 (windless rain)		48.0			30.7			1.7	
	Run 2 (windless rain)	+18.8% ↓	59.0	↓ ×1.19	+37.4% ↓	16.4	↓ ×1.37	+14.2% ↓	0.6	↓ ×1.14
	Run 3 (wind-driven rain)		70.1			22.5			0.7	
NEG 1	Run 1 (windless rain)		44.8			30.7			1.4	
	Run 2 (windless rain)	−2.6% ↓	85.7	↓ ×0.97	+32.0% ↓	52.7	↓ ×1.32	+46.7% ↓	1.3	↓ ×1.47
	Run 3 (wind-driven rain)		83.5			69.5			1.9	
NEG 2	Run 1 (windless rain)		24.4			29.5			2.5	
	Run 2 (windless rain)	+3.4% ↓	73.8	↓ ×1.03	−24.2% ↓	58.4	↓ ×0.76	−20.6% ↓	1.7	↓ ×0.79
	Run 3 (wind-driven rain)		76.3			44.3			1.3	

[a] 105.2% is not a correct mathematical expression, but shows that in the case of FRE 5 run 2, slightly more runoff was collected (110.5 L) than applied on the plot (105 L). This might be explained by water storage on the plot from the antecedent run or by a handling problem with the flow control. However, other values are unaffected since this value (105.2%) is not used for further calculation.

crusts are prone to destabilisation by air disruption, absorption and dispersion and hence to high erosion rates (Roth, 1992), a fact that probably played an important role during all test sequences on crusted soils, and above all considerably affected the first run on dry soil (each run 1: 150.4, 75.7, 30.7, 77.7, 28.8, 109.9 g m^{-2}). Once this crust is destroyed, for instance by fresh ploughing on both NEG-plots, the infiltration rate increases and runoff generation is reduced on the one hand; on the other hand, the soil might be very easily erodible due to lowered shear resistance of the broken aggregates.

The influence of vegetation is rather variable and strongly depends on type and percentage of cover in so far, as the patchy distribution of perennial small shrubs of the garrigue group (e.g. *Thymus* spec., *Artemisia* spec.) enhances concentration of SOF and so lead to a higher detachment and entrainment of sediment. This type of vegetation cover is found to reduce erosion only beyond a 60%-coverage (Ries, 2010; Ries et al., 2000).

The influence of a stone cover on the FRE 5 plot might have lead to the comparatively greater amount of eroded material (109.9, 69.6 and 78.7 g m^{-2}): among the crusted soil surface-plots this plot has the highest percentage of stone cover (65%) and showed the second-highest total erosion and highest runoff. This supports the findings of Poesen et al. (1990, 1994) concerning embedded stones.

The roughness of the plots is rather low, which also might have led to the higher erosion rates due to the development of steady SOF (Auerswald, 1998).

3.3. Erosion due to wind-driven rain (WDR) (Run 3)

Regarding the influence of wind on total soil erosion by water, we find ambiguous results: Four Tests (FR 2, SAL, FRE 5 and NEG 1) show an increase in eroded material during run 3 with wind-driven rain (+13.13 - +37.38%) compared to run 2 without application of wind. Among these, runoff increases in one case (RC: SAL:+18.8%), but in three cases it even decreases (RC: FRE 2:-6.5; FRE 5: -7.4, NEG 1: -2.6%), so that a higher volume of SOF cannot be an effective factor to explain higher erosion during the wind-driven rain runs. This higher amount of eroded material is probably caused by the higher erosivity of the wind driven raindrops and the wind affected SOF and IOF.

The runoff, eroded material and net-soil erosion (+/− %) concerning the influence of wind are displayed in Table 4.

Test FRE 4 shows similar eroded material with only 1.1% more net-erosion but 15% more runoff. In this case, the higher IOF could count for the slightly higher net-erosion.

The IOF is supposed to be affected by wind in several ways: wind might accelerate the overland flow and thus increase its potential to entrain soil particles, it might reduce therefore also the depth of the waterfilm and so increase the erosivity of the impacting raindrops, and it might enhance the development of additional turbulences. However, in contrast to a rather clear increase in eroded material, that would be expected from the current scientific research concerning a raised erosivity of the WDR and wind-influenced SOF and IOF, in some cases we even found less eroded material with applied wind (−9.6, −9.67 and −24.15 g m^{-2} at FRE 1, FRE 3 and NEG 2, respectively).

The total net-erosion due to WDR, therefore, seems to depend not only on the wind altered attributes of raindrops and shallow overland flow, but is additionally considerably influenced by other parameters. We suppose these parameters to be strongly related to surface characteristics and reciprocal effects and reactions of the surface structure to the WDR, SOF and IOF. These soil surface parameters are difficult to assess during the full test sequence by traditional (disturbing) methods but general indications were derived by visual observation.

By visual observation we found much higher surface geomorphodynamic changes on the freshly ploughed soil surfaces than on the crusted soils. On the former, loose material and the ridges oriented in stream direction enhanced a high mobility of substrate particles and aggregates and consequent high puddle and pool-dynamics with fast filling and clearing, building of micro-fluvial relief features like terracettes and fans. The generation of wind accelerated single-particle movement as well as filling and clearing of pools, but lead only in one case (out of two; NEG1) to an increase in erosion.

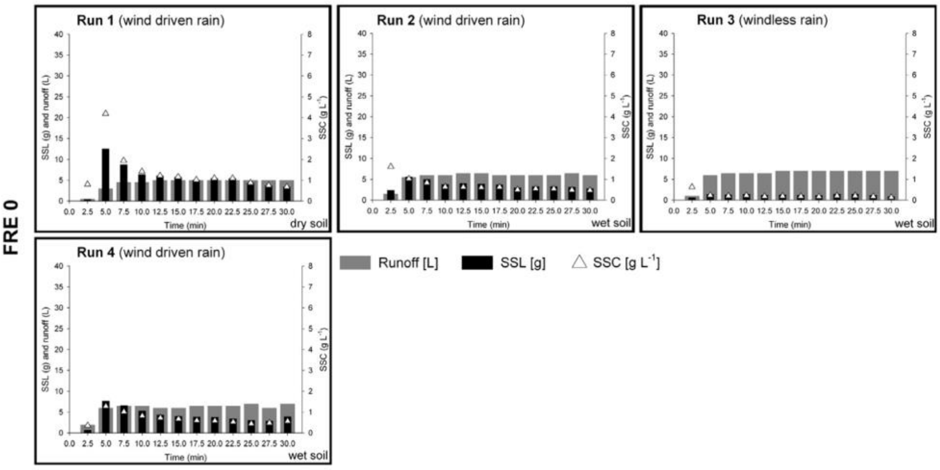


Fig. 4. Temporal development of runoff and erosion of test FRE 0 with WDR on dry ground (SSL: Suspended sediment load; SSC: Suspended sediment load concentration).

The strongly crusted surfaces weren't easily affected by SOF and drops, and showed only minor geomorphological changes in surface structure even after extended rainfall and with applied wind. Especially around plants and prominent stones, changes in surface structure where visible. These micro-geomorphodynamic differences could be an explanation for the differences in erosion patterns due to wind-driven rain (Table 4). During wind-driven rain tests on crusted surfaces the eroded material reaches a peak in the first third of the test and then decreases until the end: the peak of eroded material is actually reached during the first 5 min in four cases out of six (Fig. 3).

The effect of wind on simulated rainfall (runs 2 and 3) can be seen as well by using a different test sequence. A tentative test sequence (FRE 0) with following order was tested: 1. WDR simulation on dry ground; 2. WDR simulation on moist ground; 3. Windless rain simulation on moist ground and 4. WDR simulation on moist ground (Fig. 4). The soil surface is similar to FRE 1 with a higher percentage of stone cover (50%). The first run on dry ground shows, in contrast to the usually applied test sequence, the direct impact of wind-driven rain on dry soil.

The pattern of runoff generation and erosion shows the trend of the other test sequences on degraded and crusted soils (major part of erosion during the first run, much less erosion during the second), but differs at the third run: here, the third run is the only windless rain simulation, which generates much less erosion than all other runs. Furthermore, the subsequent fourth run, again WDR, generates much more eroded material (+232%) than the third (Table 5).

The total eroded material of the first WDR run is comparable low (30.7 g m^{-2}), as is the runoff generation with an RC of 56.5%. The sediment concentration (SSC) is one of the lowest of all here presented first runs (1.3 g L^{-1}). The RC increases during the third run but total eroded sediment stays on that low level. The comparable low erosion of FRE 0 can probably be explained by the high stone cover (50%) with a great part of loosely overlying stones, supporting the findings of De Figueiredo and Poesen (1998).

4. Discussion

The ambiguous results on crusted as well as on ploughed soil surfaces support the assumption that WDR indeed does increase soil loss compared to WLR, but that this effect also strongly depends on other factors concerning the soil surface's characteristics. Important factors might be micro-topography and factors that change during a test procedure like the development of a shallow waterfilm, development of puddles with filling and clearing events, and initiation of channelled water flow.

The test plot length of 3.20 m seems to be sufficient for an adequate process observation, particularly compared to the more frequently used micro-plots of <1 m. We suppose that with the here presented setting, the influence of wind on rainfall leads mostly to more erosion in the third wind driven rain run compared to the second windless run. Since soil erosion usually tends to decrease with time, even less eroded material during a WDR-run might still be more erosion than without applied wind. From the presented Test FRE 0 can be derived, that a simple WDR-simulation on dry ground is an option to generate WDR-erosion data, but lacks the opportunity to compare windless and wind-driven rain erosion. We focus on this comparison and an assessment of the influence of wind on rain erosion. Only in this way, a reliable estimation of the relative impact of wind on total rain erosion is possible. At this point, we can only accept a general "more" of eroded material in the WDR-run compared to the windless run to securely proof the intensifying influence of wind.

This might be particularly true for the here presented crusted soil surfaces of semi-arid, Spain, that show a clear tendency to produce less erosion with increasing time of rainfall application. As long as the crust is not destroyed by impacting raindrops or

Table 5
Results of FRE 0 (RC: Runoff coefficient; EM: Eroded material; SSC: Suspended sediment load concentration).

Plot	Run		RC (%)			EM (g m^{-2})			SSC (g L^{-1})	
FRE 0	Run 1 (wind-driven rain)		56.5			30.7			1.3	
	Run 2 (wind-driven rain)		53.8			20.0			0.9	
	Run 3 (windless rain)	+6.1%↓	71.9	↓ ×1.06	+232%↓	6.3	↓ ×3.32	+250%↓	0.2	↓ 3.5×
	Run 4 (wind-driven rain)		76.3			20.9			0.7	

(channelled) runoff, less and less material is available. Once the crust is destroyed or removed, fresh erosion can take place, either by wind or by water. In the case of water erosion, the silty loam substrate tends to create a fresh crust: processes of detachment and transport are determined by the available material and are in a geomorphological sense addressed as self-organised.

With the same test device and procedure, Iserloh et al., 2013 detected a WDR-effect of 113–1108% more net-soil erosion on cohesionless sand under semi-natural conditions. These extreme values could not be confirmed by our tests on autochthonous, crusted and cohesive substrates presented here. The measured intensifying WDR-effect is in the range of 13%–37%. The runoff increased from 3% to 19%, also much less intensive than in the above mentioned study with 15%–71%, and there was much less erosion and runoff generation taking place during the first run on dry soil.

This underlines the paramount importance of the soil surfaces' characteristics, micro-topography and substrate with its moisture for this kind of experimental setting and for all erosion studies. In general terms, *in-situ* investigations on autochthonous soils highlight to a much greater extent the natural variability of soil-surface related processes and therefore are essential for a comprehensive assessment of the effect of WDR on soil erosion.

5. Conclusion

With the test setting of the Portable Wind and Rainfall Simulator (PWRS), we could simulate wind erosion, extreme rain events and wind-driven rain events under controlled, reliable and reproducible conditions. This study fundamentally contributes to a realistic assessment of surplus-erosion due to the influence of wind. The latest results on cohesionless sand indicate an erosion up to 1000% higher than without wind influence (Iserloh et al., 2013) and have to be complemented by the here presented field study on autochthonous soils.

From this investigation, we conclude:

1. The susceptibility of the degraded soils of semi-arid Spain to runoff generation and erosion strongly depends on surface characteristics like crusts, stone cover, roughness and vegetation. On bare crusted soil surfaces, a few minutes of heavy rainfall intensity suffice for severe erosion (due to structural breakdown of dry soil aggregates by air slaking), while freshly ploughed soil surfaces are able to buffer short rainfall events by high infiltration rate. However, the incoherent substrate particles of the freshly ploughed soils showed a much higher mobility and rapid changes in micro-topography during rainfall events. Vulnerability to wind erosion on all investigated surfaces is low. The silty loam soils are slightly more prone to wind erosion, if the crust is destroyed.
2. The impact of wind-driven rain on soil erosion is potentially very powerful, yet an increased variability of soil erosion rates and runoff generation points to the necessity of further research. The influence of wind on erosion by rain is a most relevant topic that is far from well understood. The main empirical approach to deal with the WDR is a laboratory setup, where wind and rain are tested on highly disturbed substrate. This type of setup completely neglects the role of a naturally developed soil structure and soil surface structure and therefore brings forth results that focus factors concerning the eroding agents' physical parameters only. During this kind of studies, wind is usually found to have a profound influence on soil erosion by rain, a finding that we cannot completely support with the here presented tests on autochthonous soils. According to our results, the influence of wind-driven rains differs with not-yet completely understood and assessed properties of the soil surface.
3. Our results underline the importance of experimental studies on autochthonous soils and surfaces for identification and assessment of the influence of WDR for process understanding, realistic assessment of WDR-effect and soil erosion rates and reliable application in soil erosion modelling.

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References

Albert, K.-D., Müller, J., Ries, J.B., Marzolff, I., 2005. See und Sand – der Tschadsee in Nordost-Nigeria und der Sahel Burkina Fasos: 3.5 Aktuelle Landdegradation in der Sahelzone Burkina Fasos. In: Albert, K.-D., Löhr, D., Neumann, K. (Eds.), Mensch und Natur in Westafrika. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, pp. 289–330.

Auerswald, K., 1998. Bodenerosion durch Wasser. In: Richter, G. (Ed.), Bodenerosion: Analyse und Bilanz eines Umweltproblems. Wiss. Buchges., Darmstadt, pp. 33–42.

Cornelis, W.M., Gabriels, D., 2003. A simple low-cost sand catcher for wind-tunnel simulations. Earth Surf. Proc. Land. 28, 1033–1041.

Cornelis, W.M., Oltenfreiter, G., Gabriels, D., Hartmann, R., 2004. Splash-saltation of sand due to wind-driven rain: vertical deposition flux and sediment transport rate. Soil Sci. Soc. Am. J. 68, 32–40.

De Figueiredo, T., Poesen, J., 1998. Effects of surface rock fragment characteristics on interrill runoff and erosion of a silty loam soil. Soil Till. Res. 64, 81–95.

De Lima, J.L.M.P., 1989. Raindrop splash anisotropy: slope, wind and overland flow velocity effects. Soil Technol. 2, 71–78.

Disrud, L.A., Krauss, R.K., 1971. Examining the process of soil detachment from clods exposed to wind-driven simulated rainfall. Trans. ASAE 14, 90–92.

Duttmann, R., 2001. Bodenfeuchte als Steuergröße der Bodenerosion. Geographische Rundschau 53, 24–32.

Erpul, G., Gabriels, D., Norton, L.D., Flanagan, D., Huang, C., Visser, S.M., 2011. Interactions between raindrop impact and shallow interrill flow under wind-driven rain. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment- Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgium, pp. 9–18.

Erpul, G., Gabriels, D., Norton, L.D., 2005. Sand detachment by wind-driven raindrops. Earth Surf. Proc. Land 30, 241–250.

Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.-G., 2012. A portable combined wind and rainfall simulator for in situ soil erosion measurements. Catena 91, 72–84.

Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.-G., 2011. Comparison of rainfall characteristics of a small portable rainfall simulator and a combined wind and rainfall simulator. Z. Geomorphol. 55 (3), 109–126.

Fister, W., 2011. A Portable Wind Tunnel with Integrated Rainfall Simulator for the Experimental Assessment of Soil Erosion by Wind, Water and Their Combined Effect. PhD.-thesis at Trier University. Department of Geography and Geosciences, Trier.

Fister, W., Ries, J.B., 2009. Wind erosion in the central Ebro Basin under changing land use management. Field experiments with a portable wind tunnel. J. Arid Environ. 73, 996–1004.

Fister, W., Schmidt, R.-G., 2008. Concept of a single device for simultaneous simulation of wind and water erosion in the field. In: Gabriels, D., Cornelis, W. (Eds.), Proceedings of Conference on Desertification. Ghent, Belgium, pp. 106–113.

Helming, K., 2001. Wind speed effects on rain erosivity. In: Stott, D.E., Mohtar, R.H., Steinhardt, G.C. (Eds.), Sustaining the Global Farm, Selected Papers from the 10th International Soil Conservation Organization Meeting 1999, West Lafayette. Int. Soil Conservation Organization in Cooperation with the USDA and Purdue University, pp. 771–776.

Iserloh, T., Fister, W., Marzen, M., Seeger, M., Kuhn, N.J., Ries, J.B., 2013. The role of wind-driven rain for soil erosion – an experimental approach. Z. Geomorphol. Suppl. 57 (1), 193–201.

Kinnell, P., 2005. Raindrop-impact-induced erosion processes and prediction: a review. Hydrol. Process. 19, 2815–2844.

Marzolff, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. Earth Surf. Proc. Land 36, 1604–1623.

Monfreda, C., Ramankutty, N., Hertel, T.W., 2009. Global agricultural land use data for climate change analysis. In: Hertel, T.W., Rose, S., Tol, R.S.J. (Eds.), Economic Analysis of Land Use in Global Climate Change Policy. Routledge, pp. 33–48.
Nickling, W.G., McKenna-Neumann, C., 1997. Wind tunnel evaluation of a wedge-shaped aeolian sediment trap. Geomorphology 18, 333–345.
Pedersen, H.S., Hasholt, B., 1995. Influence of wind speed on rainsplash erosion. Catena 24, 39–54.
Poesen, J.W., Torri, D., Bunte, K., 1994. Effects of rock fragments on soil erosion by water at different spatial scales: a review. Catena 23, 141–166.
Poesen, J., Ingelmo-Sanchez, F., Mucher, H., 1990. The hydrological response of soil surfaces to rainfall as affected by cover and position of rock fragments in the top layer. Earth Surf. Proc. Land 15, 653–671.
Poesen, J., Savat, J., 1981. Detachment and transportation of loose sediments by raindrop splash: part II Detachability and transport ability measurements. Catena 8, 19–41.
Ravi, S., Breshears, D.D., Huxman, T.E., D'Odorico, P., 2010. Land degradation in drylands: interactions among hydrologic–aeolian erosion and vegetation dynamics. Geomorphology 116, 236–245.
Ries, J.B., 2003. Landnutzungswandel und Land degradation in Spanien – eine Einführung. In: Marzolff, I., Ries, J.B., De La Riva, J., Seeger, M. (Eds.), Landnutzungswandel und Landdegradation in Spanien. Universität Frankfurt a. M. and Universidad de Zaragoza, pp. 11–31.
Ries, J.B., 2005. Soil erosion on abandoned fields in Mediterranean mountains – monitoring of processes and development. J. Mediterr. Ecol. 6 (1), 43–52.
Ries, J.B., 2010. Methodologies for soil erosion and land degradation assessment in Mediterranean-type ecosystems. Land Degrad. Dev. 21, 171–187.
Ries J.B., Andres K., Wirtz S., Tumbrink J., Wilms T., Peter K.D., Burczyk M., Butzen V. and Seeger M., Sheep and goat erosion – experimental geomorphology as an approach for the quantification of underestimated processes, Z. Geomorphol. Suppl. (in press). http://dx.doi.org/10.1127/0372-8854/2013/S-00158.
Ries, J.B., Hirt, U., 2008. Permanence of soil surface crusts on abandoned farmland in the Central Ebro Basin/Spain. Catena 72, 282–296.
Ries, J.B., Mazolff, I., Seeger, M., 2000. Der Beweidungseinfluß auf Vegetationsbedeckung und Bodenerosion in der Flysch-Zone der spanischen Pyrenäen. In: Zollinger, G. (Ed.), Aktuelle Beiträge zur Angewandten Physischen Geographie der Tropen, Subtropen und der Regio Trirhena. Festschrift zum 60. Geburtstag von Prof. Dr. Rüdiger Mäckel, Freiburger Geographische Hefte, vol. 60, pp. 167–194.
Roth, C.H., 1992. Die Bedeutung der Oberflächenverschlämmung für die Auslösung von Abfluss und Abtrag. In: Bodenökologie und Bodengenese, vol. 6. Technische Universität Berlin.
Saleh, A., 1993. Soil roughness measurement-chain method. J. Soil Water Conserv. 48 (6), 527–529.
Samray, H., Erpul, G., Gabriels, D., 2011. Raindrop detachment and raindrop-induced flow transport (RD-RIFT) under different fall trajectories of wind-driven raindrops. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment – Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgium, pp. 19–24.
Sharon, D., 1980. Distribution of hydrologically effective rainfall incident on sloping ground. J. Hydrol. 46 (1–2), 165–188.
Schütt, B., 2001. Der Naturraum der Region Los Vélez und angrenzender Gebiete. In: Roth, D., Schütt, B., Baumhauer, R. (Eds.), Los Vélez – Ein Landeskundlicher Reiseführer für eine Region in Südost-Spanien, Trierer Geographische Studien, vol. 24, pp. 13–34. Trier.
Seeger, M., 2007. Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulations. Catena 71 (1), 56–67.
Umback, C., Lembke, W., 1966. Effects of wind on falling water drops. Trans. ASAE 9, 805–808.
Visser, S.M., Sterk, G., Ribolzi, O., 2004. Techniques for simultaneous quantification of wind and water erosion in semi-arid regions. J. Arid Environ. 59, 699–717.
Wirtz, S., Iserloh, T., Rock, G., Hansen, R., Marzen, M., Seeger, M., Betz, S., Remke, A., Wengel, R., Butzen, V., Ries, J.B., 2012. Soil erosion on abandoned land in Andalusia – a comparison of interrill- and rill erosion rates. ISRN Soil Sci., 16. http://dx.doi.org/10.5402/2012/730870. Article ID 730870.
Zobeck, T.M., 1991. Soil properties affecting wind erosion. J. Soil Water Conserv. 46 (2), 112–118.

IV

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Quantification of particle detachment by rain splash and wind-driven rain splash

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ABSTRACT

A surface-hitting raindrop transfers a part of its kinetic energy onto the surface and thereby destroys aggregates and moves soil particles. The magnitude of interrill processes is largely determined by the intensity and kinetic energy of rainfall.
Wind alters all erosion-relevant characteristics of a falling raindrop such as velocity, impact angle and kinetic energy. It also might capture and drag an airborne soil particle. To quantify the amount of raindrop erosion with and without the influence of wind, an experimental setting within the Portable Wind and Rainfall Simulator was developed and applied. The results on cohesionless sandy substrate suggest that wind considerably increases raindrop-erosion:

1. The mean amount of detached substrate is increased by the factor 50.
2. The covered distance is greater.
3. The process splash-creep is intensified.

The study highlights a potentially very strong impact of wind-driven rain on soil erosion. The evaluation of splash and splash-saltation is one important step towards the general understanding and realistic assessment of regional and global soil erosion rates and application in soil erosion models.

1. Introduction

Soil erosion by wind and water causes huge ecological and economic damages worldwide and the direct and indirect effects of soil erosion represent a major concern for environmental services and food security. A broad set of experiments has been applied to assess the impact of erosion by wind, rain and runoff (e.g. Butzen et al., 2014; Fister and Ries, 2009; Geißler et al., 2012; Iserloh et al., 2013b; Peter et al., 2014; Ries, 2010; Ries and Iserloh, 2013; Schindewolf and Schmidt, 2012; Wirtz et al., 2012), but very few on wind-driven rain (WDR).

The investigation of soil erosion traditionally considers the vertically falling rain as the driving component, and the subsequent processes are considered in the light of the physical parameters of a given vertically falling raindrop impacting a given soil surface. Only recently, experimental studies focus on the influence of wind-driven rain on soil detachment and transport (Cornelis et al., 2004; Iserloh et al., 2013a; Ries et al., 2014). The term "wind-driven rain" regards the raindrop as the main eroding agent, whose physical properties might be profoundly modified by the action of wind. Combined with the wind as an active transport agent for airborne substrate particles, this leads to a potential increase of soil erosion rates. A quantification of the influence of wind on rain erosion rates is difficult, and substantial data gaps exist concerning the potential effects of wind-driven rain (Ravi et al., 2010; Ries et al., 2013; Visser and Sterk, 2007; Visser et al., 2004). The lack of data leads to a wide variability of erosion model outputs and considerable uncertainty in the assessment of risks associated with land use and climate change (Nearing et al., 2004; Valentin, 1996).

This study focuses on the influence of wind on raindrop erosion (Fig. 1). Raindrop erosion is referred to as splash, wind-driven raindrop erosion as wind-driven splash or specified as splash-saltation (ejected particles) and splash-drift (particles transported by the air stream).

1.1. Raindrop erosion

Splash erosion is the initial detachment of soil particles by surface-hitting raindrops and a major factor controlling soil erosion. The impacting raindrop disrupts aggregates and ejects the downsized parts or single particles outwards from the point of drop impact (Auerswald, 1998; Le Bissonnais, 1996). The amount of disrupted soil material, the amount and size of transported particles and the distance

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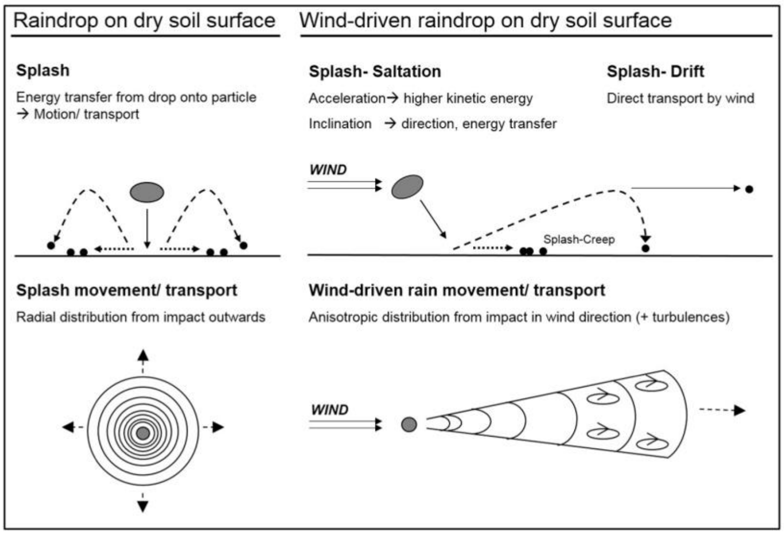

Fig. 1. Raindrop erosion: splash, splash-saltation, splash-drift and splash-creep.

covered by the ejected particles depend on the properties of the impacting raindrop and the soil surface properties.

The impact of raindrops on the soil surface and the subsequent transport of single soil particles or aggregates have long been recognised as essential factors of soil erosion (e.g. Ekern, 1953; Ellison, 1944, 1947; Kinnell, 2005). An impacting raindrop transmits a part of its energy onto the soil surface, hence leading to movement and/or disruption of particles and aggregates (Bisal, 1960; van Dijk et al., 2002). During the impact of raindrops on the surface, Ghadiri and Payne (1981) measured pressures of up to 10^5 Pa. The detached particles might be transported within splash-drops or via a shallow overland flow. The susceptibility to splash erosion depends on the factors' particle size distribution, aggregate stability, slope and the raindrops' kinetic energy, impact angle and size (Riezebos and Epema, 1985). The erosive effect of drops, often described with the kinetic energy (KE) [kJ m^{-2}], acts during the impact onto the soil surface and increases with increasing size (m) [kg] and impact velocity (v) [m s^{-1}]:

$$KE = \frac{1}{2}mv^2. \tag{1}$$

Infiltration capacity is usually not sufficient to absorb the drops immediately, so that the water radially expands, forming a corona

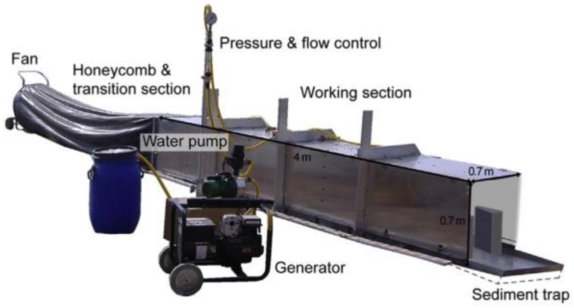

Fig. 2. Trier Portable Wind and Rainfall Simulator (PWRS). Figure modified from Iserloh et al. (2013a).

in the case of vertically falling and impacting drops. The expanding water might reach velocities of twice the drops' fall velocity and shear stresses of 10^2 Pa, exceeding the shear strength of the soil surface and leading to the disruption of aggregates and detachment of soil particles (Auerswald, 1998). Sharma et al. (1991) describe, that splash detachment and transport (D) [kg m^{-2}] occur when the forces (KE) of a raindrop impacting on the surface exceed a critical threshold of resistance (KE_0) [kJ m^{-2}]. An intrinsic empirical factor of soil detachability K_d [kg kJ^{-1}] is used to describe the soil resistance to particle detachment, resulting in the following equation:

$$D = K_d(KE - KE_o). \tag{2}$$

The transport distance of detached particles varies as a result of drop–surface interaction, such as the kinetic energy of an individual drop and the behaviour of the surface upon drop impact (e.g. Legout et al., 2005; Leguédois et al., 2005). For a range of materials, empirical relationships to estimate the sediment export from a given surface unit by splash have been determined. Generally, the total amount of erosion is considered relatively small due to short transport distances, but a significant effect on surface structure, summarised as sealing or crusting, occurs (Govers and Poesen, 1988; Morgan, 2005). Furbish et al. (2007) even state that splash is a relevant factor for the levelling of surfaces of micro- to macrotopographical ranges.

1.2. Wind-driven rain splash: splash-saltation and splash-drift

The wind-driven rain splash is a process combination of splash detachment and wind impact. The wind alters the physical properties of a surface-impacting raindrop: It accelerates the falling raindrops insofar as the fall velocity might exceed the terminal fall velocity of windless rain (Pedersen and Hasholt, 1995). The acceleration of drops, the generation of turbulences and the subsequent more frequent collisions lead to a complicated modification of drop size (either increase or decrease) and a modified drop form (Disrud et al., 1969; Erpul et al., 2000; Fister et al., 2012; Umback and Lembke, 1966). Wind also considerably influences the impact effect, which is found to be a function of drop size, impact energy and impact angle (Samray et al., 2011). Sharon (1980) found a connection between wind velocity and the angle of the falling drops and stated that wind velocities of 10 m s^{-1} already generate a deviation of 40 to 60° from a vertical fall.

Table 1
Main wind and rainfall characteristics (modified from: Iserloh et al., 2013a) with mean wind velocity [v_w], mean intensity [I], impact angle of drops hitting the surface [*impact angle*], mean volumetric drop diameter [d_{50}], drop fall velocities for drops of the size d_{50} [v_r], mean kinetic energy expenditure [KE_R], and mean kinetic energy per unit area per unit depth of rainfall [KE] for windless and wind-driven rain simulations.

	v_w [m s^{-1}]	I [mm h^{-1}]	Impact angle [°]	d_{50} [mm]	v_r [m s^{-1}]	KE_R [J m^{-2} h^{-1}]	KE [J m^{-2} mm^{-1}]
Windless rain	0	96	90	1.5–2.0	2.2–2.6	270.8	5.2
Wind-driven rain	7.5	88	~45	1.75–2.5	3.4–4.2	1590.8	8.1

This deviation from the vertical fall might lead to a modified transfer of kinetic energy and spatial distribution of drops, depending on wind velocity and wind direction (Visser et al., 2011). Soil movement of particles directly hit by wind-driven raindrops is defined as splash-saltation (de Lima et al., 1992; Moeyersons, 1983), and the subsequent raindrop-splash initiated lift of particles, followed by wind drag, is defined as splash-drift (Goossens et al., 2000; Rutin, 1983).

Wind-driven rain splash implies a higher variability concerning influencing factors and soil surface reactions than movement via solely wind or solely rain. Compared with solely raindrop-initiated splash, wind-driven rain splash can be assumed to have a more accentuated effect on particle detachment and transport. The higher kinetic energy of wind-accelerated drops provides a stronger impulse for the movement of soil particles, and the horizontal velocity vector caused by an altered impact angle extends the travelling distance of particles on a flat surface. Given the additional fall velocity of the wind-driven raindrop, as well as an altered impact angle and drop size (Table 1), much higher and directed shear stresses are to be considered for splash-saltation and splash-drift, subsequently leading to a higher amount of detached and transported soil material (Cornelis et al., 2004; Iserloh et al., 2013a; Leguédois et al., 2005; Ries et al., 2014; van Heerden, 1964).

The objectives of the study were:

1. Isolation of sub-processes splash and wind-driven rain splash from the diverse processes of detachment and transport.
2. Quantification of detached and transported material with and without applied wind on cohesionless sandy substrate.
3. Comparison of erosion potential of splash and wind-driven rain splash.

2. Method

To assess the impact of wind on raindrop erosion, a test setting with simulated rain, simulated wind and standardised substrate was used. The setting avoided complex natural conditions in most respects. Thus, it was possible to extract the factor "wind-driven rain" and study the impact on sediment detachment and transport.

The Trier Portable Wind and Rainfall Simulator (PWRS) (Fig. 2) was used to generate wind and rain in a uniform and reproducible way (Fister et al., 2012). All relevant parameters concerning the erosive forces of the applied wind and rain, as well as the wind-altered parameters of wind-driven rain, are known and supposed to be sufficient for the assessment of wind-driven rain erosion (Table 1). The wind influence leads to an increase of drop size, velocity and hence kinetic energy of the falling raindrops, as well as an oblique impact angle.

A special splash test device was installed inside the PWRS (Fig. 3). The device consisted of a substrate source with drainage holes (580 ∗ 130 ∗ 25 mm) and a gutter system for the collection of transported material (600 ∗ 360 ∗ 23 mm). Fifteen single gutters with an inside dimension of 20 mm collected the eroded material according to the transported distance. From each gutter a silicon tube transported sediment and water to PET-bottles. The gutter system was placed without a gap directly behind the substrate source. The complete device was integrated into the tunnel floor to prevent it from creating turbulences of the air stream. The substrate used was a standardised silty sand (82.1% fine sand; 11.8% silt; 6.1% middle sand; 0.1% coarse sand), mainly consisting of fine sand, which is the most readily erodible fraction.

Application of water on the point of the substrate source was ca. 130 mm h^{-1} during rain runs and ca. 100 mm h^{-1} during wind-

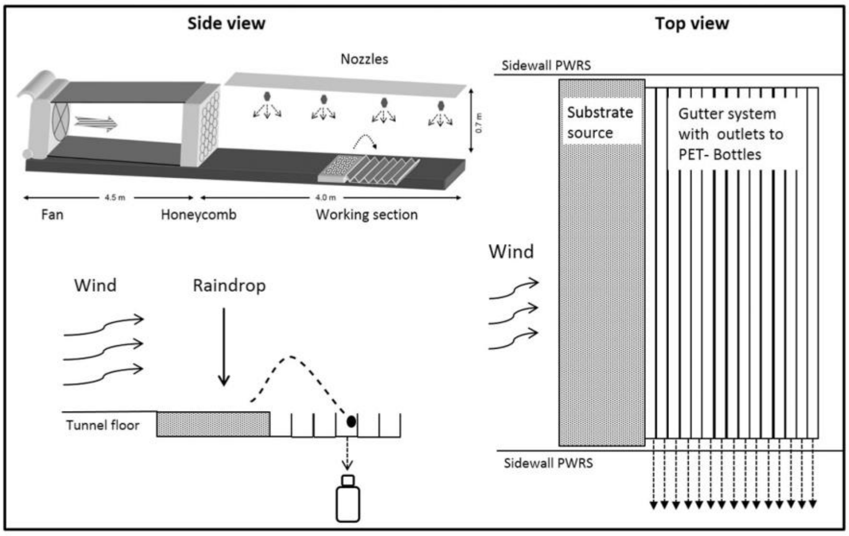

Fig. 3. Sketch of splashtest setup.

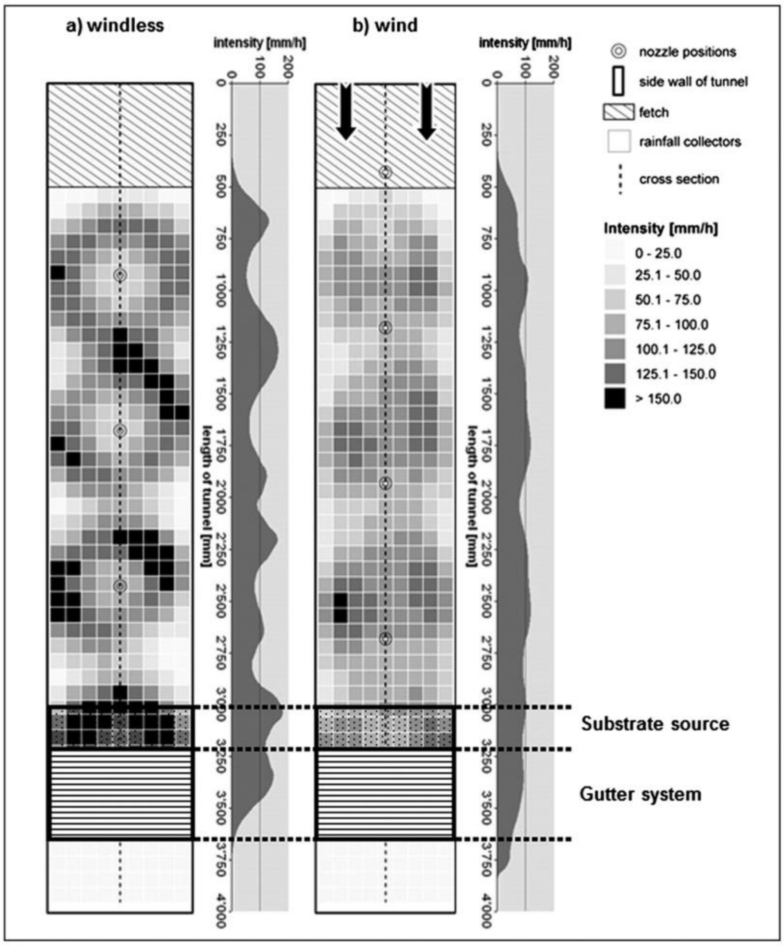

Fig. 4. Position substrate source and gutter system. Figure modified from Fister et al. (2011).

driven rain runs. The difference was caused by the varying water distribution on the plot during rain and wind-driven rain runs (a part of the raindrops is blown away from the air stream) and was kept as low as possible (Fig. 4). We accepted the difference of ~30 mm h^{-1} in this case, because the higher intensities were applied during the presumably less erosive rain runs, and the lower intensities were applied during the presumably more erosive wind-driven rain tests. The results therefore underestimate the influence of wind-driven rain splash due to the lower intensity, but the reasoning concerning the influence of wind on raindrop erosion is not distorted. The mean kinetic energy of applied rain was ca. 5 J m^{-2} h^{-1} without wind and ca. 8 J m^{-2} h^{-1} with wind. Reached wind velocity was 5.5–6.0 m s^{-1} at 0.3 m height. Compared to natural conditions, the generated rainfall represents a highly erosive heavy rain event, while the erosive power of the generated wind is rather low, but sufficient for wind erosion to take place (Hassenpflug, 1998).

Two test settings were applied: Tests 1–6 were rainfall simulations (1 was a single rainfall simulation on dry substrate, 2–6 on moist substrate) and tests 7–11 were wind-driven rain tests on moist substrate. A short test duration of 5 min and drainage holes prevented the development of surface water. After each test, the substrate source was filled up with fresh substrate. The substrate and setting were kept identical during all tests except for application of wind (tests 7–11). No inclination was applied and the roughness was induced by the substrate particles only.

The eroded material was oven-dried (105 °C/24 h) and weighed.

3. Results and discussion

Presented are the results of splash-tests and wind-driven rain splash. Due to the short measurement duration of 5 min each, the amount of eroded substrate ranges in low total quantities. Nevertheless, we found a clear general trend of transported amount and transport distance (Fig. 5).

The results show that the addition of wind to rainfall increases the amount of detached and transported material considerably. The amount of eroded material of all tests and all single values is about two orders of magnitude higher during WDR-tests (Table 2). Highest total splash-eroded material was 229.9 mg for windless rainfall and 10,490 mg for wind-driven rain. Only 2 out of 6 single windless tests, the transport went beyond 200 mm, whereas all WDR-tests showed sediment transport for distances up to the total measurement distance 350 mm and presumably beyond. The mean collected material during wind-driven rain tests was 50.9 times the mean amount of rain splash without

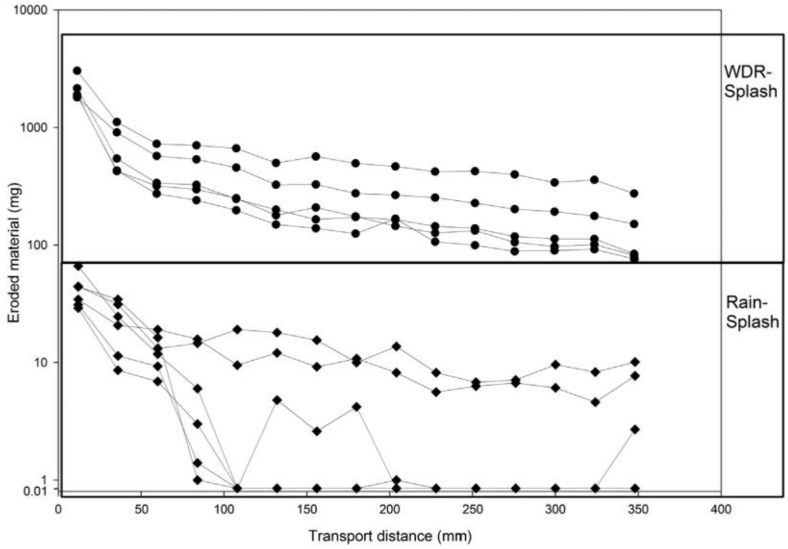

Fig. 5. Amount and transport distance of eroded material by rain and wind-driven rain (WDR).

wind. Even with less total applied water (130 mm h^{-1} during rain runs and ca. 100 mm h^{-1} during wind-driven rain runs because of the heterogeneous water distribution on the plot), the detachment and transport energy provided by wind-driven rain were much higher. The oblique impact angle generates a forward impetus on the substrate particle and leads to an extended distance of motion and transport. An additional component of particle transport during wind-driven rain events is the direct transport of airborne substrate particles via the wind stream, whereby the forward movement of the splashed particle can be supported and extended by the drag force of airflow. This process, the splash-drift, could not be quantified separately within this setting, but single splash-drifted particles could be observed (white paper sheet) up to 2000 mm from the substrate source. Another reason for the higher effect of WDR-splash on particle detachment is the larger size of the WDR-drops. Furbish et al., 2007 found that smaller drops (2 mm) tend to infiltrate on a porous stone surface rather than larger drops (4 mm), whose mass accelerates laterally with proportionally less infiltration.

A simple power function generally describes the transport of substrate particles (Fig. 6) for splash and WDR-splash best. The R^2 is high in both cases: 0.94 for splash and 0.98 for splash-saltation.

These particle distributions can also be presented as curves of probability of exceedance (Fig. 7) what is useful for modelling purposes. It shows for each test type (rainfall simulation and WDR-simulation) the probability of transport beyond a certain distance. In the case of rain-splash, the probability of transport beyond 50 mm is $p = 0.41$ (up to 50 mm it reads $p = 1 - p = 0.59$). In the case of WDR-splash is $p = 0.50$ ($p = 1 - p = 0.50$). For the transport beyond 200 mm p-values are 0.12 for rain-splash and 0.18 for WDR-splash. The comparison of these transport patterns shows a slightly higher probability of further transport for WDR-eroded particles. It has to be noted that for windless splash, distances >200 mm were exceeded during only 2 of 6 single tests, so that the calculation of the probability of exceedance could be derived from only 2 n (number of samples).

Another aspect of the splash processes is the splash-creep, the motion of particles on a waterlogged substrate surface via drop pressure. The material from gutter 1 reflects mainly this type of transport, because the first gutter connected without a break with the substrate source. Accordingly, the major part of the total material in this gutter can be assumed to be pushed by splash-creep. Table 2 shows this process to be much more effective during the WDR-tests (mean 2154.7 mg) than during rainfall tests (mean 41.6 mg). In terms of ratio, the splash-creep process is equally active during both types of compared simulations, rainfall and wind-driven rain. During rainfall simulation, mean 42.7% of the total eroded material was transported by splash-creep; during WDR-simulations, it was a mean of 37.2%, which is slightly less.

The results show a direct and powerful impact of wind-driven rain on particle detachment and transport by the splash processes. Wind-driven rain erosion extremely exceeds solitary rain erosion already at relatively low and thus less erosive wind speed. In addition, the transport can be assumed to reach much further beyond the test distance by the direct action of wind. Compared to wind erosion rates, Cornelis et al. (2004) found the impact of wind-driven rain on total soil loss budget to be considerable in the absence of particularly heavy winds.

The results correspond to Iserloh et al. (2013a), who found that on a similar cohesionless sandy substrate, total erosion during wind-driven rain events was up to 1100% higher or 12 times the amount collected during rain events. The increase in erosion found by Lyles (1977) from destruction of soil clods by WDR was up to 2.7 times the erosion from windless rain. An important factor could therefore be the amount of material that was detached and transported by wind-driven rain splash on the not-waterlogged soil surface during the first 10–15 min prior to

Table 2
Total eroded material and fraction splash-creep.

No.	Rain/WDR	Total (mg)	1 gutter/splash-creep (mg)	1. gutter/splash-creep (% of total)
1	Rain (dry)	107.5	44.1	41.0
2	Rain	108.9	66.2	60.8
3	Rain	48.6	29.1	59.9
4	Rain	176.8	34.4	19.5
5	Rain	55.8	31.0	55.6
6	Rain	229.9	44.5	19.4
		Mean: 121.3	Mean: 41.6	Mean % of total: 42.7
7	WDR	10490.0	3045.6	29.0
8	WDR	6664.4	1799.9	27.0
9	WDR	5020.3	2156.1	43.0
10	WDR	4534.9	1893.2	41.8
11	WDR	4151.7	1878.5	45.3
		Mean: 6172.3	Mean: 2154.7	Mean % of total: 37.2

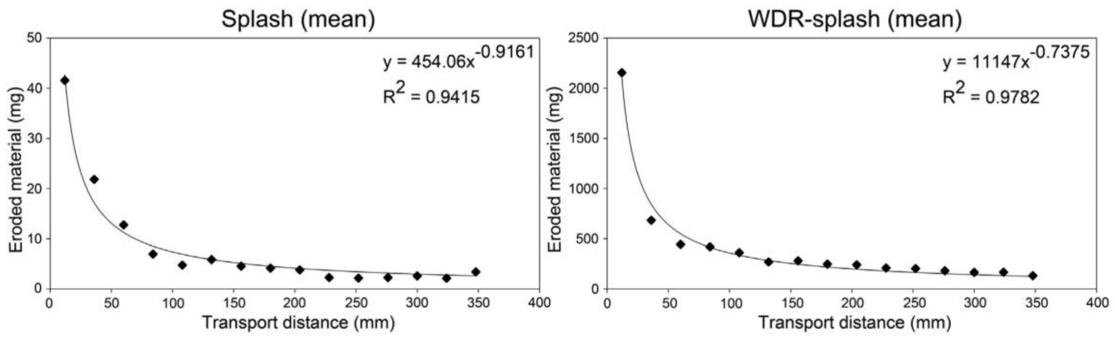

Fig. 6. Mathematical description of transport via splash and WDR-splash (note different scales on y-axis).

the generation of runoff, that could make up for a great part of the total eroded material. When applied on an autochthonous and undisturbed soil surface, the wind-driven rain splash is not so clearly marked because of the soil surface reaction (Ries et al., 2014). This reaction to the wind-driven and windless splash strongly relates to soil surface properties such as soil texture, aggregation and roughness, properties that should urgently be addressed in further studies. Under wind-driven rain conditions, soil properties controlling water-absorption, aggregate expansion and cohesion may be even more important than under windless conditions due to the additional effect of profile wind drag (Lyles, 1977).

4. Conclusion

The impact of wind on raindrop erosion was assessed by applying the Portable Wind and Rainfall Simulator. It was found that the initial detachment of soil particles and aggregates via the impacting raindrop is significantly influenced by wind. The detachment and transport by wind-driven rain splash differ in the following aspects from rain splash erosion:

1. The mean amount of detached substrate is increased by the factor 50.
2. The covered distance is greater.
3. The process splash-creep is intensified.

The results show that the amount of raindrop-detached soil material might be severely underestimated, if the impact of wind is not taken into account. Wind-driven splash plays a significant role for total soil erosion: in contrast to rain splash without wind influence, wind-driven rain splash is capable to detach and transport a considerable amount of substrate. The detached material is not only directly transported by the wind-driven rain splash processes, but is also a readily available material for further erosion by rain and wind. Therefore, the impact of wind-driven rain on the initial soil erosion process might affect all following erosion processes to a not yet assessed extent. Wind-driven rain splash can be assumed to be an important key factor for understanding, analysis and projection of quantity and quality of soil erosion.

The test setup reflects very simplified conditions on cohesionless sand without inclination and surface water. It might be considered as the first minutes of a (wind-driven) rain event prior to the generation of surface water (puddles, runoff). To a closer approach of natural wind-driven rain erosion processes, more tests are therefore necessary. The extended test setup should provide information about applications on different soils, varying surface structures and slopes.

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References

Auerswald, K., 1998. Bodenerosion durch Wasser. In: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems. Wiss. Buchges, Darmstadt, pp. 33–42.
Bisal, F., 1960. The effect of raindrop size and impact velocity on sand-splash. Can. J. Soil Sci. 40, 242–245.
Butzen, V., Seeger, M., Wirtz, S., Hümann, M., Müller, C., Casper, M.C., Ries, J.B., 2014. Quantification of Hortonian overland flow generation and soil erosion in a Central European low mountain range using rainfall experiments. Catena 113, 202–212.
Cornelis, W.M., Oltenfreiter, G., Gabriels, D., Hartmann, R., 2004. Splash-saltation of sand due to wind-driven rain: vertical deposition flux and sediment transport rate. Soil Sci. Soc. Am. J. 68, 32–40.

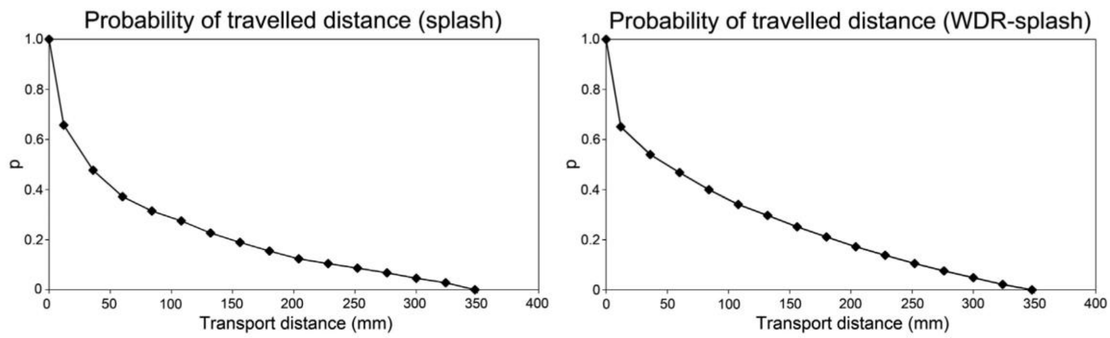

Fig. 7. Probability (p) of exceedance for splash and WDR-splash.

De Lima, J.L.M.P., van Dijk, P.M., Spaan, W.P., 1992. Splash-saltation transport under wind-driven rain. Soil Technol. 5, 151–166.
Disrud, L.A., Lyles, L., Skidmore, E., 1969. How wind affects the size and shape of raindrops. Agric. Eng. 50, 617.
Ekern, P., 1953. Problems of raindrop impact erosion. Agric. Eng. 34, 23–25.
Ellison, W.D., 1944. Studies of raindrop erosion by single raindrops of varying kinetic energy. Agric. Eng. 25, 131–136.
Ellison, W.D., 1947. Soil erosion studies—part II: soil detachment hazard by raindrop splash. Agric. Eng. 28, 197–201.
Erpul, G., Gabriels, D., Janssens, D., 2000. Effect of wind on size and energy of small simulated raindrops: a wind tunnel study. Int. Agrophys. 14, 1–7.
Fister, W., Ries, J.B., 2009. Wind erosion in the central Ebro Basin under changing land use management. Field experiments with a portable wind tunnel. J. Arid Environ. 73, 996–1004.
Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.G., 2011. Comparison of rainfall characteristics of a small portable rainfall simulator and a portable wind and rainfall simulator. Z. Geomorphol. 55, 109–126.
Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.-G., 2012. A portable wind and rainfall simulator for in situ soil erosion measurements. Catena 91, 72–84.
Furbish, D.J., Hamner, K.K., Schmeeckle, M., Borosund, M.N., Mudd, S.M., 2007. Rain splash of dry sand revealed by high-speed imaging and sticky paper splash targets. J. Geophys. Res. 112 (F01001).
Geißler, C., Kühn, P., Böhnke, M., Bruelheide, H., Shi, X., Scholten, T., 2012. Splash erosion potential under tree canopies in subtropical SE China. Catena 91, 85–93.
Ghadiri, H., Payne, D., 1981. Raindrop impact stress. J. Soil Sci. 32, 41–49.
Goossens, D., Poesen, J., Gross, J., Spaan, W., 2000. Splash drift on light sandy soils: a field experiment. Agronomie 20, 271–281.
Govers, G., Poesen, J., 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. Geomorphology 1, 343–354.
Hassenpflug, W., 1998. Bodenerosion durch Wind. In: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems, Wiss. Darmstadt, Buchges., pp. 69–82.
Iserloh, T., Fister, W., Marzen, M., Seeger, M., Kuhn, N.J., Ries, J.B., 2013a. The role of wind-driven rain for soil erosion — an experimental approach. Z. Geomorphol. Suppl. 57 (1), 193–201.
Iserloh, T., Ries, J.B., Arnáez, J., Boix-Fayos, C., Butzen, V., Cerdà, A., Echeverría, M.T., Fernández-Gálvez, J., Fister, W., Geißler, C., Gómez, J.A., Gómez-Macpherson, H., Kuhn, N.J., Lázaro, R., León, F.J., Martínez-Mena, M., Martínez-Murillo, J.F., Marzen, M., Mingorance, M.D., Ortigosa, L., Peters, P., Regüés, D., Ruiz-Sinoga, J.D., Scholten, T., Seeger, M., Solé-Benet, A., Wengel, R., Wirtz, S., 2013b. European small portable rainfall simulators: a comparison of rainfall characteristics. Catena 110, 100–112.
Kinnell, P., 2005. Raindrop-impact-induced erosion processes and prediction: a review. Hydrol. Process. 19, 2815–2844.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. J. Soil Sci. 47, 425–437.
Legout, C., Leguédois, S., Le Bissonnais, Y., Malam Issa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124, 279–292.
Leguédois, S., Planchon, O., Legout, C., Bissonnais, Y.L., 2005. Splash projection distance for aggregated soils: theory and experiment. Soil Sci. Soc. Am. J. 69, 30–37.
Lyles, L., 1977. Soil detachment and aggregate disintegration by wind-driven rain. SCSA Spec. Publ. 21, 152–159.
Moeyersons, R., 1983. Measurements of splash-saltation fluxes under oblique rain. Catena Suppl. 4, 19–31.
Morgan, R.P.C., 2005. Soil Erosion and Conservation. 3rd ed. Wiley-Blackwell, Maiden, Oxford, Carlton.
Nearing, M.A., Pruski, F.F., O'Neal, M.R., 2004. Expected climate change impacts on soil erosion rates: a review. J. Soil Water Conserv. 59, 43–50.
Pedersen, H.S., Hasholt, B., 1995. Influence of wind speed on rainsplash erosion. Catena 24, 39–54.
Peter, K.D., d' Oleire-Oltmanns, S., Ries, J.B., Marzolff, I., Ait Hssaine, A., 2014. Soil erosion in gully catchments affected by land-levelling measures in the Souss Basin, Morocco, analysed by rainfall simulation and UAV remote sensing data. Catena 113, 24–40.
Ravi, S., Breshears, D.D., Huxman, T.E., D'Odorico, P., 2010. Land degradation in drylands: interactions among hydrologic–aeolian erosion and vegetation dynamics. Geomorphology 116, 236–245.
Ries, J.B., 2010. Methodologies for soil erosion and land degradation assessment in Mediterranean-type ecosystems. Land Degrad. Dev. 21, 171–187.
Ries, J.B., Iserloh, T. (Eds.), 2013. Rainfall simulation experiments with smalls scale simulators. Z. Geomorphol. Suppl. 57 (1).
Ries, J.B., Iserloh, T., Seeger, M., Gabriels, D., 2013. Rainfall simulations — constraints, needs and challenges for a future use in soil erosion research. Z. Geomorphol. Suppl. 57 (1), 1–10.
Ries, J.B., Marzen, M., Iserloh, T., Fister, W., 2014. Soil erosion in Mediterranean landscapes — experimental investigation on crusted surfaces by means of the Portable Wind and Rainfall Simulator. J. Arid Environ. 100–101, 42–51.
Riezebos, H.T., Epema, G.F., 1985. Drop shape and erosivity part II: splash detachment, transport and erosivity indices. Earth Surf. Process. Landf. 10, 69–74.
Rutin, J., 1983. Erosional Processes on a Coastal Sand Dune, De Blink Dunes, Noordwijkerout, The Netherlands. 35. Publication of the Physical and Soils Laboratory, University of Amsterdam (144 pp.).
Samray, H., Erpul, G., Gabriels, D., 2011. Raindrop detachment and raindrop-induced flow transport (RD-RIFT) under different fall trajectories of wind-driven raindrops. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment — Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgium, pp. 19–24.
Schindewolf, M., Schmidt, J., 2012. Parameterization of the EROSION 2D/3D soil erosion model using a small-scale rainfall simulator and upstream runoff simulation. Catena 91, 47–55.
Sharma, P.P., Gupta, S.C., Rawls, W.J., 1991. Soil detachment by single raindrops of varying kinetic energy. J. Soil Sci. Soc. Am 55, 301–307.
Sharon, D., 1980. The distribution of hydrologically effective rainfall incident on sloping ground. J. Hydrol. 46, 165–188.
Umback, C., Lembke, W., 1966. Effects of wind on falling water drops. Trans. ASAE 9, 805–808.
Valentin, C., 1996. Soil erosion under global change. In: Walker, B., Steffen, W. (Eds.), Global Change and Terrestrial Ecosystems, International Geosphere–Biosphere Programme Book Series, pp. 317–340.
Van Dijk, A.I.J.M., Bruijnzeel, L.A., Rosewell, C.J., 2002. Rainfall intensity–kinetic energy relationships: a critical literature appraisal. J. Hydrol. 261, 1–23.
Van Heerden, W.M., 1964. Splash Erosion as Affected by the Angle of Incidence of raindrop Impact. Purdue University, Lafayette, USA.
Visser, S.M., Sterk, G., 2007. Nutrient dynamics—wind and water erosion at the village scale in the Sahel. Land Degrad. Dev. 18, 578–588.
Visser, S.M., Sterk, G., Ribolzi, O., 2004. Techniques for simultaneous quantification of wind and water erosion in semi-arid regions. J. Arid Environ. 59, 699–717.
Visser, S.M., Erpul, G., Gabriels, D., Flanagan, D., Huang, C., Norton, L.D., Stroosnijder, L., 2011. Evaluation of interrill erosion under wind-driven rain events in northern Burkina Faso. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment — Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 25–31.
Wirtz, S., Seeger, M., Ries, J.B., 2012. Field experiments for understanding and quantification of rill erosion processes. Catena 91, 21–34.

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The effect of rain, wind-driven rain and wind on particle transport under controlled laboratory conditions

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ABSTRACT

Transport of soil particles prior to the occurrence of overland flow is one of the big question marks in soil erosion studies. The exact measurement of short-distance transported soil particles is a challenge to soil erosion science due to the particular requirements of the experimental design and test procedure. To quantify amount and distance of each type of transport, we developed an experimental laboratory setup including a multiple-gutter system and the Trier Portable Wind and Rainfall Simulator (PWRS). Measured were amount and travel distance of soil particles detached and transported by raindrops (splash-creep and splash), wind-driven rain (splash-creep, splash-saltation and splash-drift) and wind (reptation and saltation). The test setup included three different agents of erosion (rain solely, wind-driven rain and wind solely), two substrates (sandy and loamy), three surface structures (smooth/ grain roughness, rills lengthwise and rills transversal) and three slope angles (0°/horizontal, 7° downslope and 7° upslope). The results give detailed transport patterns of the three erosion agents under the varying substrates and surface conditions up to a distance of 1.6 m. Influence of the surface factors varies, whereas the factor "agent of erosion" seems to be the most crucial one. Under the applied rain intensity and wind velocity, wind-driven rain splash generates the highest erosion and a further travel distance of the particles due to the combined action of wind and rain. The impact of all three agents of erosion implicates considerable redistribution processes and is a crucial factor for investigation of source- and sink dynamics, field scale sediment budgets and connectivity.

1. Introduction

Soil erosion is today being recognized as a severe threat to social-ecological security and stability on a regional and global scale. The direct and indirect effects of soil erosion are a major concern for environmental services, particularly in terms of their consequences for food security. To understand erosion processes, scientific research by means of erosion measurement techniques is needed (Stroosnijder, 2005).

Specific processes of soil erosion have been extensively discussed in theory, but reliable measurements remain scarce. One big gap of knowledge concerns on-site redistribution processes of soil material over short distances in the range of mm to m. Initial processes are rain splash and wind-driven rain (WDR) splash as well as reptation and saltation by wind. These processes dominate erosion and redistribution prior to the generation of surface water and are essential factors for a reliable assessment of

- Quantity and quality of on-site sediment redistribution processes
- Source and sink dynamics concerning sediment erosion and flow path development
- Adequate sediment budgets on catchment scale

The assessment of the extent of these short-distance transported particles involves several highly speculative components: the eroded material of unknown quantity stays on-site for an unknown time and moves in an unknown way. These sediments do not reach a monitoring station and remain entirely hidden, what is the more unfortunate, since the spatial dynamics of runoff and erosion are crucial for the assessment of connectivity issues (Helming et al., 2005). Model simulations (Schmidt et al., in press) show the powerful impact of wind on water erosion on catchment scale concerning the spatial distribution of soil loss and accumulation as well as the total sediment output. An exact measurement of short-distance transported soil particles is a challenge to experimental soil erosion science due to the particular requirements

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of experimental design and test procedure. One of the challenges relates to the tempo-spatial scale of the regarded processes that happen within seconds to minutes and cover distances of millimeters to meters. The measurement equipment and procedure was carefully designed to capture the initial soil erosion processes counting for short distance erosion without the presence of surface water (Fig. 1). The comparison of rain and wind-driven rain was the main aspect. Raindrop erosion is referred to as splash, wind-driven raindrop erosion as wind-driven rain splash or specified as splash-saltation (ejected particles) and splash-drift (particles transported by the air stream). We included measurements of wind erosion, which is a different type of erosion but still partly measurable within the presented setup (reptation and saltation).

Splash erosion is the initial detachment of soil particles by surface-hitting raindrops and a major factor controlling soil erosion. The impacting raindrop disrupts aggregates and ejects the downsized parts or single particles outwards from the point of drop impact (Auerswald, 1998; De Lima, 1989; Le Bissonnais, 1996; Van Dijk et al., 2002a, 2002b). Transport amount and distance of detached particles vary as a result of drop-surface interaction, such as the kinetic energy of an individual drop and the behaviour of the surface upon drop impact (De Lima, 1990; Kinnell, 2005; Legout et al., 2005; Leguédois et al., 2005; Riezebos and Epema, 1985). The major effects of raindrop splash are sealing and crusting and compaction (Govers and Poesen, 1988; Morgan, 2005). Dunne et al. (2010) investigate the splash-effect on hillslopes and Furbish et al. (2007) deem it as possibly relevant for levelling of surfaces of micro- to macrotopographical ranges, but splash is not generally assumed a considerable erosion process. That changes if wind action supports the raindrop in combined *wind-driven rain erosion*. The term "wind-driven rain" regards the raindrop as the main eroding agent, whose physical properties and erosivity can be profoundly modified by the action of wind (Marzen et al., 2015). Wind increases the drop-fall and impact velocity, leads to partly larger drops, a smaller impact angle (~45° on level ground) and thus to a potentially higher erosive potential (Disrud et al., 1969; Erpul et al., 2000; Fister et al., 2012; Sharon, 1980; Umback and Lembke, 1966; Van Heerden, 1964). Measurements on natural soil surfaces as well as cohesionless sandy substrate showed a high heterogeneity of the erosive impact of wind-driven rain on total erosion rates but generally supported this theoretically implied, partly drastic increase of soil erosion (Iserloh et al., 2013a; Marzen et al., 2015; Ries et al., 2014). Compared to raindrop and wind-driven rain erosion, wind erosion is supposed to act mainly at larger scales. This is caused by the fact that the wind's erosive force strongly increases with the length of passed surface. Crucial factors hereby are wind speed, turbulences, and the fetch effect (Chepil and Milne, 1939), consisting of avalanching (Chepil, 1957), aerodynamic feedback and soil resistance effects (Gillette et al., 1996). We included the wind into our setup to gather information about short-distance transport by reptation and saltation, being aware that the conditions for measurement of wind erosion are very limited.

While a number of experimental studies have been conducted on water erosion including shallow overland flow (e.g. Butzen et al., 2015; Iserloh et al., 2013b, 2013c, 2012; Keesstra et al., 2016; Montenegro et al., 2013; Peter et al., 2014; Prosdocimi et al., 2016; Ries et al., 2013, 2009; Rodrigo Comino et al., 2016; Vermang et al., 2015; Wirtz et al., 2012) and wind (e.g. Fister and Ries, 2009; Funk and Engel, 2015; Goossens, 2000; McKenna Neuman et al., 2005; Youssef et al., 2012; Zhang et al., 2014; Zobeck et al., 2013), few focused on wind-driven rain (Cornelis et al., 2004; De Lima et al., 1992; Iserloh et al., 2013a; Ries et al., 2014). Experimental quantifications on autochthonous soils (Ries et al., 2014) and disturbed substrates (Iserloh et al., 2013a) reveal a powerful impact of wind-driven rain on erosion rates that is highly dependent on soil surface characteristics. A first laboratory comparison between transport rates of cohesionless sand by rain and wind-driven rain (Marzen et al., 2015) emphasized the impact of wind on rain erosion and showed the necessity for further analysis concerning impact of soil surface properties. Following the hereby identified research needs, the objectives for the study were:

(i) Development and application of a reliable and reproducible experimental procedure to measure splash, wind-driven rain splash and saltation.

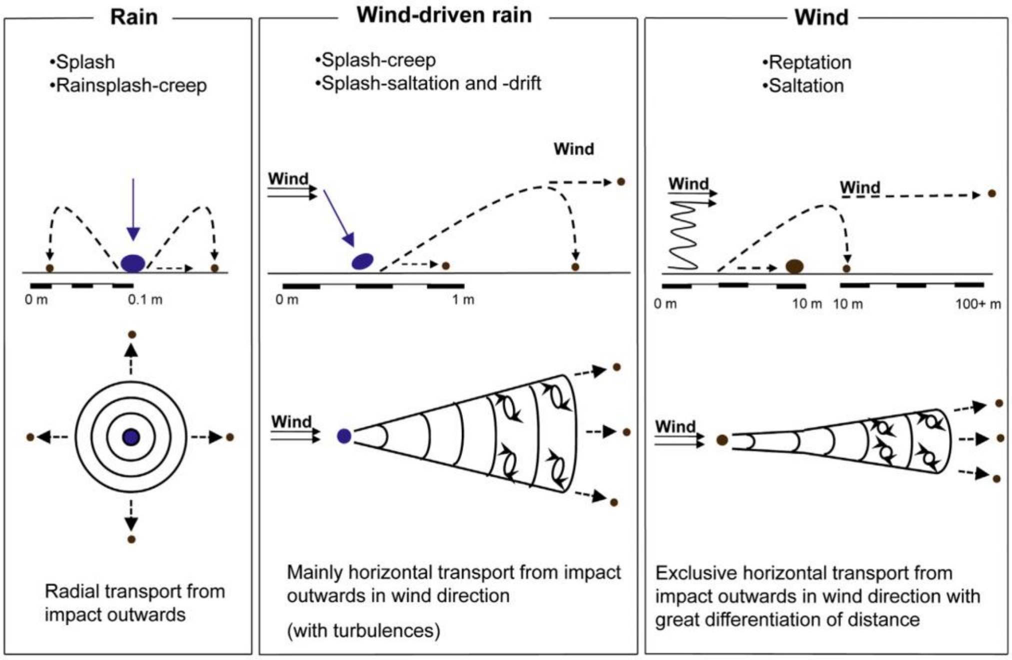

Fig. 1. Sketches of initial soil erosion processes by rain, wind-driven rain and wind.

(ii) Quantification of amount and transport distance of short-distance erosion by rain, wind-driven rain and wind under various surface conditions and substrates.
(iii) Assessment and comparison of the erosion potential of wind-driven rain, rain and wind and their impact on short-distance erosion.

2. Materials and methods

2.1. Test equipment and procedure

We used the Trier Portable Wind and Rainfall Simulator (PWRS) (Fig. 2) to generate wind, rain and wind-driven rain in a uniform and reproducible way (Fister et al., 2012). The relevant factors determining the erosive forces of the applied wind, rain and wind-driven rain are adequate for the assessment of wind erosion, rain erosion and wind-driven rain erosion processes. Application of simultaneous wind and rain leads to an increase of drop size, velocity and hence kinetic energy of the falling raindrops, as well as an oblique impact angle (Iserloh et al., 2013a).

The PWRS was installed on a metal flume at the Department of Civil Engineering of the University of Coimbra (De Lima et al., 2011) for the application of different inclinations. A multiple-gutter system was installed inside the PWRS (Fig. 3). Since the experimental device was mounted inside an experimental hall, we could ensure controlled conditions concerning environmental influences that affect erosive processes (e.g. uniform impact of solar radiation, humidity) and measurement results (e.g. no disturbance by external air movement or sediment deposition).

Basing on the gutter system described by Marzen et al. (2015), a more easily applicable device made of stainless steel was constructed (Fig. 3). To be suitable for the test procedure with many repetitions, we designed it more stable as well as easier to clear and faster drainable. It consisted of 15 single gutters that collected the eroded material according to the transported distance. The first 10 gutters had a ridge-to-ridge length of 20.0 mm, the following five gutters of 40.0 mm. From each gutter a silicon tube transported sediment and water into PET-bottles. After each test, the gutters were cleared precisely by hand with a wash bottle to collect the entire eroded material accumulated in each gutter. The gutter system was placed without a gap directly behind the substrate source in order to measure splash-creep. Behind the multiple gutter system, six additional trays (580 mm length, 145 mm width and 25 mm height) were installed without a gap in order to collect transported material up to 1.3 m. One more tray was placed at a distance of 1.5 m. For wind erosion tests, the last tray was exchanged with two wedgetraps in order to collect airborne material. As a substrate source, we installed a tray with drainage holes (580 * 130 * 25 mm) in front of the metal gutter system. The complete sediment source and gutter system was integrated into the tunnel floor (laid out with Styrofoam) to prevent it from creating an obstacle in the air stream. For drainage and creating near surface turbulences, the tunnel floor prior to the inserted sediment tray was filled with fine gravel (Fig. 3).

Fig. 2. Portable wind and rainfall simulator mounted on laboratory flume.

Application of water onto the substrate source area was ca. 130 mm h^{-1} during rain runs and ca. 100 mm h^{-1} during wind-driven rain runs, since a part of the raindrops is blown away due to the application of wind. We accepted this difference, since the reasoning concerning the influence of wind on raindrop erosion is not distorted apart from an underestimation of the influence of wind-driven rain splash due to the lower intensity. The mean kinetic energy of applied rain was ca. 5 J m^{-2} h^{-1} without wind and ca. 8 J m^{-2} h^{-1} with wind (Fister et al., 2011). Reached wind velocity was ca. 7 m s^{-1} at 0.3 m height. Compared to natural conditions, the generated rainfall represents a highly erosive heavy rain event, while the wind is of a lower intensity but adequate for wind erosion to take place (Hassenpflug, 1998).

We measured the amount and travel distance of soil particles detached and transported by raindrops (splash-creep and splash), wind-driven rain (splash-creep, splash-saltation and splash-drift), and wind (reptation and saltation). We measured each erosion agent on two substrates (sandy and loamy), three surface structures (grain roughness, rills lengthwise and rills transversal to the airstream), and three slope angles(0°, 7° downslope and 7° upslope). It has to be noted that the whole PWRS structure including nozzles, fan and substrate source was adapted to the different inclinations, so that airstream and rain droplets always hit the substrate surface at a similar angle (Fig. 4).

We conducted 3–5 single tests per test group for an adequate calculation of mean values (Table 1). Each test includes measurements of 15 (+6) single samples corresponding to the 15 single gutters of the splash trap plus the 6 additional collection trays. Each presented mean value therefore includes 3–5 measured values.

Test duration was limited to 5 min to ensure constant conditions concerning the substrate and to prevent the generation of surface water. Prior to each test, the used substrate was removed, refilled with fresh substrate, and the surface was levelled with a window-wiper. We used a "loamy substrate" (clay–silt–sand mixture; d_{50}: 0.09 mm/ very fine sand) and a "sandy substrate" (sand mixture; d_{50}: 0.35 mm/ medium sand) of cohesionless, single grained structure. For the creation of roughness elements in loamy substrate (rills) we used a hand rake (Fig. 5).

To prevent the substrate from blowing away with the first wind gust the moment the fan starts, the surface was slightly moistened by means of a spray bottle. To ensure uniform test conditions, the sediment source was shielded against wind and rain prior to test start and with completed test duration.

2.2. Sample processing and statistical analyses

Due to the short test duration and the small dimensions of each gutter collector, the amount of collected material per sample was partly very small, so that particular care was taken with processing. We cleared each gutter by means of a spray bottle in a PET-container, let the material sink overnight (12–15 h), drew off most of the water and transferred the eroded material using a spray bottle into light aluminium containers. The material was oven-dried (105 °C/ 24 h). By using very light containers (~2.5 g) for weighing on the precision scales, the measuring error was kept as low as possible and the weight determined at a precision of 0.001 g (mg). From this weight, the weight of an average involved amount of tab water (suspended and dissolved content) was subtracted (0.007 g). The weight was then used to calculate mean values of the unit g m^{-2}. For wind tests (only one test each) and for

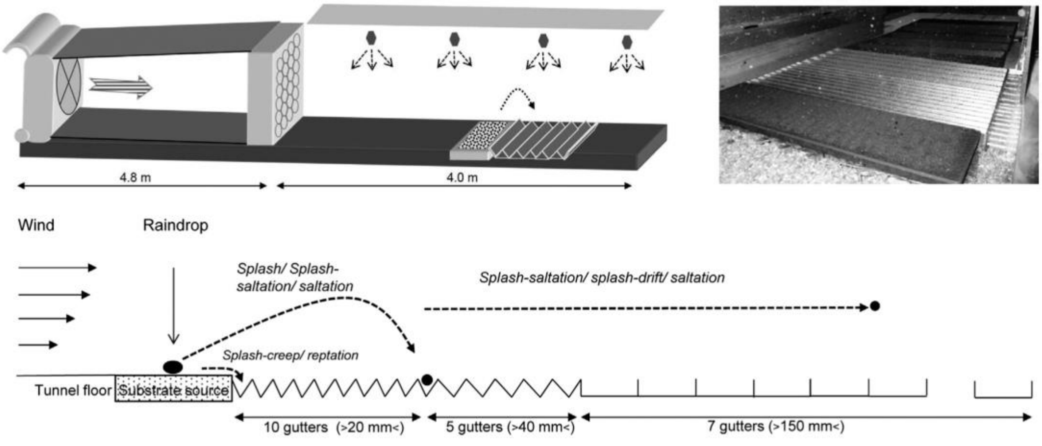

Fig. 3. Sketch of splashtest device and its installation inside the simulator.

distances >0.4 m (additional trays, applied once per test group), the measured values were used. Exemplary standard deviations are given in Table 6.

The test preparations, test procedure, material collection and material processing as well as the researchers who performed the single steps were kept identical during all tests.

3. Results and discussion

The test results are arranged according to the varying erosion agents and soil surface factors. To present the impact of one factor, only tests with the same conditions concerning the remaining factors were chosen (given in figure caption). The figures show the mean amount of eroded material in g m^{-2}, referring to the amount of eroded material collected inside each gutter. Units in tables are adapted to the purpose and given either given in g (measured eroded amount) or g m^{-2} (referring to the sediment source area). To compare the three erosion patterns by WDR, rain and wind, the results are presented at logarithmic scale (y-axis). To focus on the first 0.4 m with the highest resolution, the transport distance (x-axis) is not true to scale but categorised. For comparison reasons, one true-to-scale graphic is given at the end of the section (Fig. 12b).

3.1. Factor "agent of erosion"

Fig. 6 shows the results of the tested "agents of erosion" rain, wind-driven rain and wind. For rain and WDR, the points indicate the means of 3–5 measured values. Erosion by wind-driven rain, rain and wind are located on entirely different scales concerning 1. amount of transported material and 2. transport distance. WDR erodes much higher amounts of soil material than rain and wind and at further distances than rain. Rain generally erodes smaller amounts of substrate and the transport ranges in very short distances. Wind erodes total amounts similar to those of rain splash, whereas less is eroded at distances up to 0.1 m and more beyond. The transport distance of WDR is comparable to that of wind erosion, although the amount strongly reduces towards the end of the measuring distance (152.5 cm), whereas the amount of wind eroded material increases. Rain eroded material strongly decreases from gutter to gutter and no erosion is measurable after 15 cm. It has to be noted, that an inherent difference between splash-patterns of raindrop (radially from impact outwards) and WDR (in wind direction) causes a systematic measuring error: total transported material is measured in one direction only, so raindrop splash is measured only partly. We therefore assume the rain splash to be underrated according to the different splash-patterns due to differing slopes (isotropic transport on horizontal area, anisotropic transport on slope), which should be regarded in further analysis. For the here presented conclusions we consider it a minor error due to the great differences of total eroded material and the very clear results. Table 2 gives an exemplary comparison between the erosion amounts and proportions of the single erosion agents. The mean erosion by WDR is 27.5 times that of windless rain on loamy material, on sandy substrate it is even 100 times. These values even exceed the values found by Marzen et al. (2015).

In the case of wind erosion, the measured amount of wind eroded material (2.8 g m^{-2}) is similar to that of rain splash (3.5 g m^{-2}).So, the amount of rain eroded material is 1.2 times that of wind, the amount of WDR erosion is 33.8 times that of wind erosion. It has to be noticed, that all values are derived from an event that lasted only 5 min. These results show that all erosion agents, including wind erosion, must be recognized as relevant factors controlling processes that are crucial for the assessment of sediment budgets and connectivity such as on-site redistribution processes and total material fluxes.

3.2. Factor "substrate"

We applied a sandy and a loamy substrate. The amount of eroded material by WDR and single rain on loamy and sandy substrate is

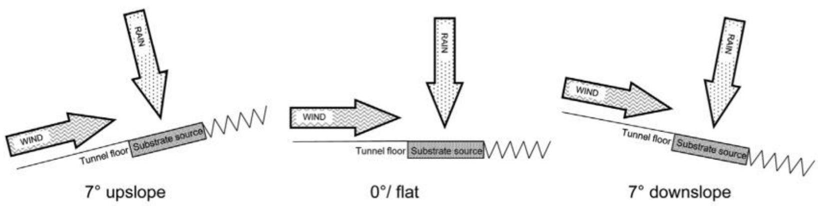

Fig. 4. Sketch of nozzle and fan (rain and air fluxes) configuration for the used inclinations.

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Table 1
Summary of conducted tests.

Rain		Soil surface roughness: Smooth		Rills lengthwise		Rills transversal	
		Sand	Loam	Sand	Loam	Sand	Loam
Slope	0°	5	5	/	3	/	3
	7° down	5	5	/	3	/	3
	7° up	3	3	/	/	/	/

Wind		Soil surface
		Smooth; Loam
Slope	0°	1
	7° down	/
	7° up	1

Wind-driven rain		Soil surface roughness: Smooth		Rills lengthwise		Rills transversal	
		Sand	Loam	Sand	Loam	Sand	Loam
Slope	0°	5	5	/	3	/	3
	7° down	5	5	/	3	/	3
	7° up	3	3	/	/	/	/

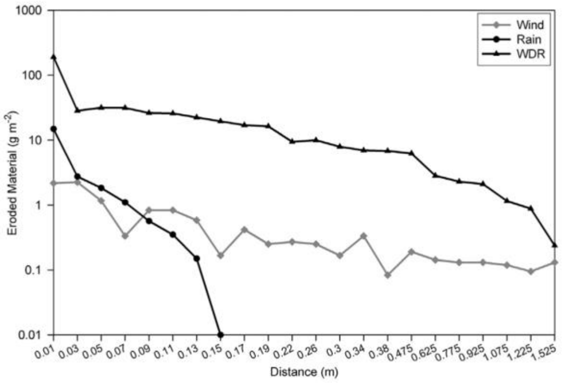

Fig. 6. Factor "agent of erosion" (rain, wind-driven rain, wind). Substrate: loamy; surface: smooth; slope: 0°.

displayed in Fig. 7. The surface is smooth (grain roughness) and the inclination 7° downslope. WDR erodes higher amounts of the sandy material than of the finer loamy substrate, while rain erodes higher amounts of the loamy material and only marginal amounts of sand (Table 3). The difference in the prevailing particle size between the two erosion agents is caused by the higher impact and transport energy of the wind-influenced rain drops. Windless rain is only able to transport very few sand particles, whereas larger and heavier particles can be transported by wind-driven raindrops. The tests show that WDR even transports higher amounts of sand particles than of the smaller ("loamy") particles. This is probably caused by the difference in weight of single particles that are needed to reach "transport capacity" of a single droplet: while the number of transported silt particles is higher, the weight is still lower than of the few sand particles transported by one droplet.

For both, WDR and rain erosion, the process splash-creep, represented by the first gutter, is an important factor. For windless rain, the transport distance <2 cm often contains the highest proportion of total eroded material. Depending on other factors, most notably the surface structure, it makes up for 37–98% of the total eroded material during rain tests and 36–80% during WDR tests (Tables 3 and 5). For wind erosion this makes up only 6–12% of the total collected material.

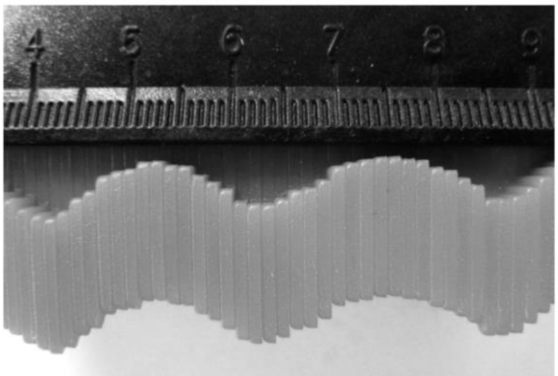

Fig. 5. Representation of surface roughness elements "rills" by means of a shape template (cm).

3.3. Factor "slope"

We measured erosion on three inclinations: 7° upward slope, 0° slope/ horizontal and 7° downward slope. The extent of impact of the factor slope seems to depend on the erosion agent (Fig. 8). For rain splash the factor slope is crucial in so far, as the gravitational force is one of the most important factors explaining travel distance: more kinetic energy is transferred downslope (Poesen, 1985). Transport distance and amount are by far the highest for a loamy substrate and, in accordance with Wright (Wright, 1986) on a downward sloping surface (Table 4). On a horizontal and on an upwards sloping surface, we measured rain-splashed substrate of 3.47 g and 3.03 g, respectively on loamy and 1.56 g and 1.15 g, respectively, for sandy substrate, with lowest values found upslope. In the case of wind-driven rain drops, splashed particles are supposed to be transported by the wind parallel to the surface irrespective of slope gradient (Jungerius and Dekker, 1990; Rutin, 1983). We can partly support this findings, since on horizontal and on an upwards sloping surface, we measured identical amounts of WDR-splashed substrate for loamy (95.47 g and 91.29 g, respectively) and for sandy substrate (155.59 g and 158.28 g, respectively). However, the WDR-transport showed to be highly dependent on slope in so far, as the material transported downslope exceeds the other slopes by more than 1/3rd.

For both, rain and WDR, a downward slope supports the erosive action of the medium. The factor slope seems to have its major impact on the travel distance of the detached particles, although the end of the transport distance for WDR is not reached within this setup. The maximum transport distance of rain reaches up to 0.15 m on a level surface and maximum 0.4 m on a downslope surface.

When wind is the sole factor mobilising the substrate particle, we find a greater difference between a horizontal area and an upwards slope (Fig. 9). While on a horizontal surface (0° slope), a high proportion of total eroded material is found as reptation-material in the first gutter and as saltated material up to a distance of 0.15 m, total erosion on an upsloping surface is much less (Table 4). Beyond this distance, transport on a horizontal surface continues to be higher than on the 7° upslope, until the same amounts of eroded material are collected in the wedgetraps at a distance of 1.5 m downwind.

Table 2
Comparison of mean erosion by rain, WDR and wind (0° slope, smooth surface).

	Rain (g m^{-2})	WDR (g m^{-2})	% rain of WDR	WDR/Rain factor
Loamy	3.5	95.5	2749.7	27.5
Sandy	1.6	155.6	9958.9	99.6
Total	5.0	251.1	4986.9	49.9

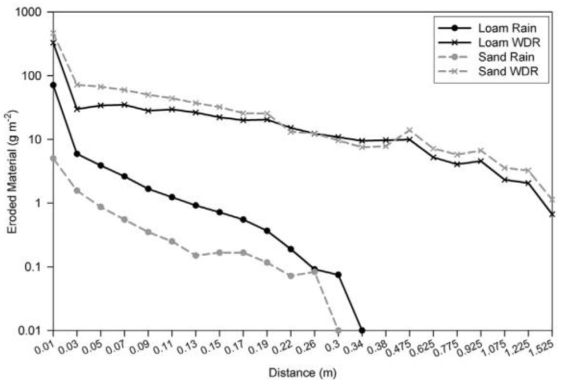

Fig. 7. Factor "substrate" (loamy, sandy). Surface: smooth; slope: 7° downslope.

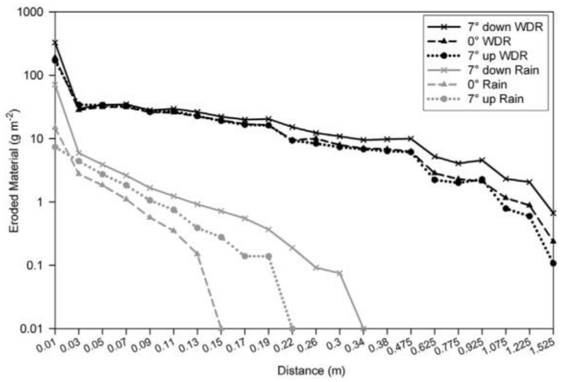

Fig. 8. Factor "slope" (0°, 7° upward slope, 7° downward slope). Substrate: loamy; surface: smooth.

Altogether, total erosion on a horizontal surface is about 3 times that on an upwards slope (Table 4).

Furthermore, the transport in this range is subject to higher fluctuations compared to rain and WDR-erosion, what is probably caused by a higher susceptibility to the turbulences in the wind stream. Since reptation was completely measured and is assumed to make up for as high a proportion as 40% of total transported material (Zobeck et al., 2003) and it was found that on loamy substrate, 50% of the total transport occurred <17 mm (Stout and Zobeck, 1996), the measurements can be regarded a good approach. However, the setup was not able to allow for some considerable factors for the entrainment of sand particles by wind such as bombardment, so that total wind erosion is certainly underestimated.

3.4. Factor "roughness"

We applied three micro-scale-roughnesses on loamy substrate: "smooth" (grain roughness), rills transversal and lengthwise to the airstream. Comparison of the results shows slightly variable mean values for rain splash and clearer differences for WDR-splash. Differences in total erosion are strongly related to the first gutter (process splash-creep) (Table 5). On the same surface conditions (loam, 7° downward slope) and by WDR (Fig. 10a), lengthwise rills generate the highest erosion (21.39 g), of which 3/4th are splash creep. On transversal rills and smooth surfaces, less total erosion is measured, but the percentage of splash creep is also much less (about 2/5th of total erosion), what means that more material is transported further than the first rill. Beyond gutter one (>20 mm), lengthwise rills generate the lowest erosion amounts per gutter (Fig. 10) and transversal rills the highest, what could be caused by a better exposition of single particles to drops and particularly airstream on top of the ridges.

In the case of rain tests, these proportions of the first gutter/splash creep are nearly 100% on both rill types and 4/5th on a smooth surface. Beyond gutter one (>0.02 m), a smooth surface generates the highest, lengthwise rills again the lowest erosion amounts per gutter (Fig. 10b).

It seems that differences in erosion rates on the varying roughnesses (for rain as well as wind-driven rain) are explained mostly by the connection of the sediment source to the first gutter. While smooth and rills transversal to the airstream generate similar erosion, the open structure of a lengthwise rill might act as a channel for splash-creep, maybe combined with a minor impact of channeled rain splash and WDR splash. The differences of erosion rates beyond the 1st gutter might be associated with complex wind patterns between the rills. Blocken et al. (2006) simulated the wind field for larger roughness elements and found rain shaded areas in between the ridges (lee and bottom) due to a wind of a comparable velocity.

3.5. Display of data

We used a categorised distance (x-axis) to focus on the first 0.4 m, where variations in transported amounts are most pronounced and of highest interest. To compare both types of representation, the distances are here displayed on a categorised scale (Fig. 11a) and on a true-to-scale x-axis (Fig. 11b). From this, we can also derive exemplary regression lines.

The trend lines indicate that short distance-transport by rain ($R^2 = 0.91$) and WDR ($R^2 = 0.90$) up to 1.60 m seems to be reasonably precisely mathematically described by exponential functions. This fact is most useful for further analysis and modelling.

3.6. Quality, reliability and plausibility of the collected data

For an estimation of the quality and reliability of the measurements, we used the standard deviation values (Table 6) and a boxplot-visualisation (Fig. 12) of exemplary test groups.

The standard deviation (SD) for all measured values is remarkably low for WDR tests. In the case of rain tests, the SD is also low to a distance of ca. 70 mm (gutter 4), and higher beyond that distance due to a smaller total amount of eroded material and less measuring values per test group. Since this fact is owed to the nature of the process, we do not deem it a sign for a poor performance of the

Table 3
Erosion concerning surface factor substrate and proportion creep (1st Gutter %).

Medium	Slope	Substrate	Total mean (g)	1st Gutter (g)	1st Gutter (%)
WDR	7° downslope	Loamy	10.65	3.93	36.90
		Sandy	15.20	5.57	36.65
Rain		Loamy	1.08	0.85	79.70
		Sandy	0.12	0.06	50.00

Table 4
Erosion concerning surface factor slope.

	Rain (g m^{-2})			WDR (g m^{-2})			Wind (g m^{-2})
	Loamy	Sandy	Total mean	Loamy	Sandy	Total mean	Total
7° downwards	14.27	1.53	15.80	141.27	201.52	342.79	/
0°	3.47	1.56	5.03	95.47	155.59	251.07	2.82
7° upwards	3.03	1.15	4.19	91.29	158.28	249.57	0.99

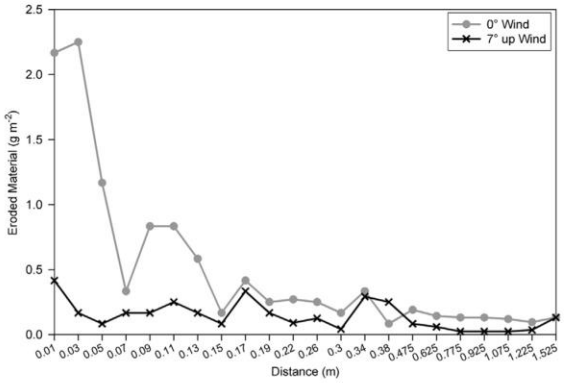

Fig. 9. Wind erosion transport (loamy substrate, 2 slopes).

test setup, but it reflects the blurred probability of distribution of raindrop splash.

Regarding the plausibility of the data, the fundamental concepts of particle transport under the tested media and surface conditions are supported in a uniform way by all repetitions. Minor irregularities concerning the uniformity of the transport curve are found to not unduly affect the results. This leads us to the conclusion that the data are sound in terms of accuracy and plausibility. Still, the results have to be processed with care, since the results are not yet converted to actual detachment rates by means of mathematical operations which consider the specific geometry of the experimental setup (Van Dijk et al., 2002a, 2002b).

We therefore propose the data for assessment of source and sink dynamics concerning sediment erosion and flow path development as well as sediment budgets on catchment scale.

4. Conclusion

Objective i) Development and application of a reliable and reproducible experimental procedure to measure splash, wind-driven rain splash and saltation

The short-distance transport by rain, wind-driven rain and wind was measured with a very high accuracy up to a distance of 1.6 m. The experimental setup including the splashtest device proved to be adequate to measure the aspired processes concerning quantity and quality of on-site sediment redistribution processes. The presented data are of a high quality and reliability and suitable for further analysis and modelling.

Objective ii) Quantification of amount and transport distance of short-distance erosion by rain, wind-driven rain and wind under various surface conditions and substrates

For all conducted test arrangements, the factor "agent of erosion" is the key factor explaining amount and transport distance of erosion patterns. The impact of the surface factors varies with the agent of erosion and measurement distance. For all conducted test arrangements, wind-driven rain is the most powerful erosion agent with mean total erosion ranging from 91.29 to 283.69 g m^{-2} or, given as transport rate, 0.30 to 0.95 g m^{-2} s^{-1}, respectively. The maximum transport distance reaches well beyond our measurement distance of 1.60 m. Raindrop erosion is generally less powerful with mean erosion ranging from 1.15 to 59.26 g m^{-2} (0.004–0.20 g m^{-2} s^{-1}, respectively) with highest amounts at the closest distance (splash-creep). The maximum transport distance reaches up to 0.15 m on a level surface and 0.40 m on a downslope surface. Mean wind erosion values range from 0.99 to 2.82 g m^{-2} (0.003–0.01 g m^{-2} s^{-1}, respectively), thus located among lower rain splash erosion values. The processes reptation and short saltation seem to be particularly sensitive to slope, whereas further transport is not affected. For the agent wind, too, the very-short transport process reptation seems to move considerable amounts of soil surface material apart from the distances beyond the test area.

Raindrop erosion depends strongly on finer grain sizes, whereas wind-driven rain erodes both, finer and coarser grain sizes. A downward slope supports the action of erosion by rain and WDR concerning both, amount and travel distance, a horizontal area and an upward slope lead to similar erosion. The effect of surface structures (rills) changes with travelling distance: the major influence seems to be related to the accessibility between sediment source and collector gutter one (splash-creep), but for WDR, transversal rills are an additional enhancing factor. The exact ranking of the surface factors needs to be further investigated.

Table 5
Erosion concerning surface factor roughness.

	Rain		WDR	
	Total mean (g)	1st gutter (%)	Total mean (g)	1st gutter (%)
Smooth	1.08	79.16	10.65	36.94
Transversal	1.46	89.83	13.43	38.53
Lengthwise	4.47	98.41	21.39	76.18

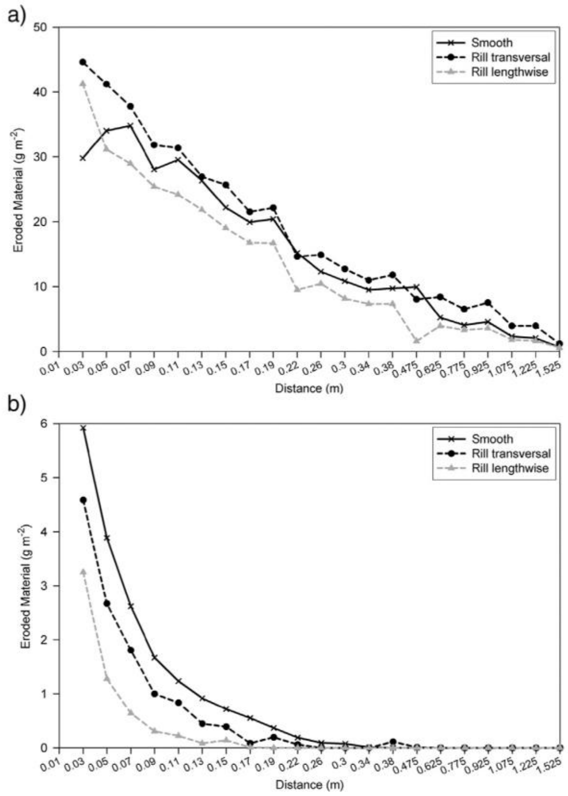

Fig. 10. Factor roughness (smooth, rills transversal, rills lengthwise). Agent: WDR (a), Rain (b); substrate: loamy; slope: 7°downward. (Value 0.01 m excluded for clearer display of following values).

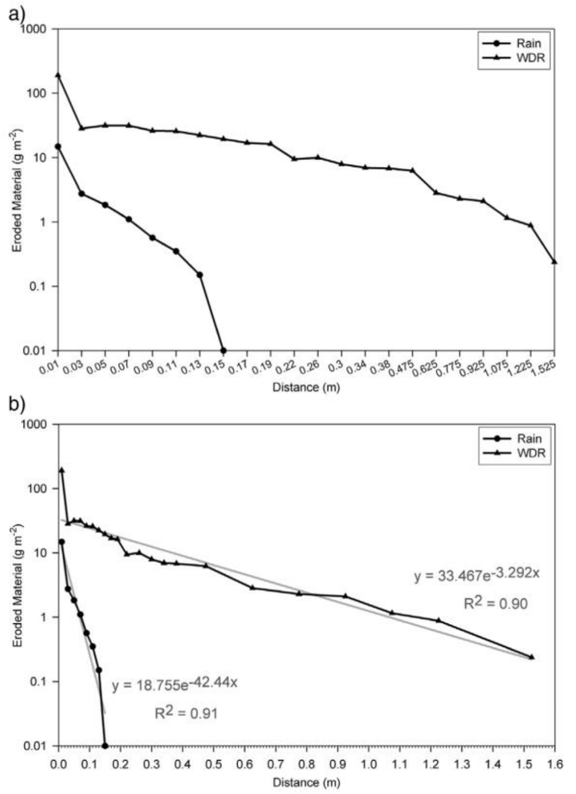

Fig. 11. Comparison of categorised (a) and true-to-scale distance on x-axis (b) with exponential functions explaining exemplary rain and WDR-transport.

Objective iii) Assessment and comparison of the erosion potential of wind-driven rain, rain and wind and their impact on short-distance erosion

All erosion agents must be recognized as relevant factors for the assessment of sediment budgets and connectivity such as on-site redistribution processes and total material fluxes.

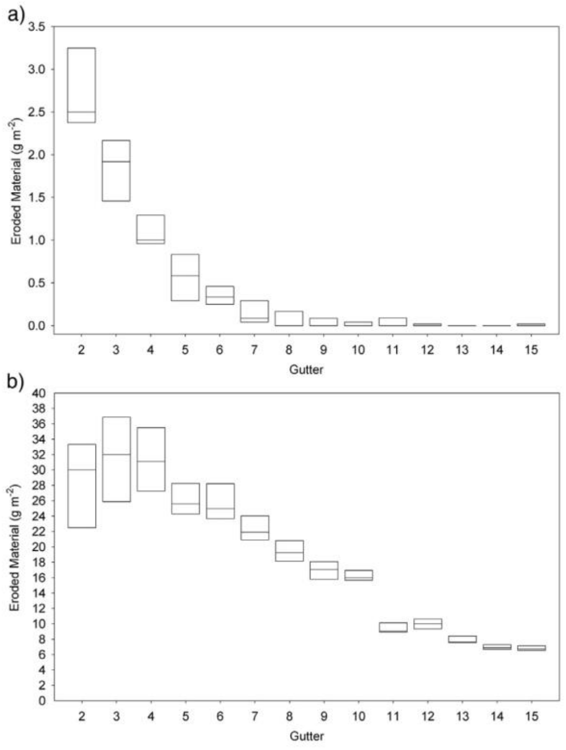

Fig. 12. Boxplots of two exemplary tests (Rain (a) and WDR (b); substrate: loamy; slope: 0°; without 1. Gutter for better display).

Particularly the processes of a medium storm event related to wind-driven rain can lead to considerable soil erosion in the short-distance range. *WDR* is able to detach, transport and redistribute considerable amounts of soil material even without the generation of shallow runoff. Neglecting the powerful impact of WDR on short-distance transport might cause a severe underestimation of total erosion. *Rain splash* erosion works mainly at very short distances at the mm-range with highest erosion by the sub-process splash-creep. It is able to detach and

Table 6
Basic statistics of exemplary erosion measurements.

	Rain eroded material				Wind-driven rain eroded material			
	Loam/ 0°		Sand/ 7° downslope		Loam/ 0°		Sand/ 7° downslope	
Gutter	Mean (g)	SD	Mean (g)	SD	Mean (g)	SD	Mean (g)	SD
1	0.1782	0.0520	0.0604	0.0194	22.890	0.3016	55.686	0.4983
2	0.0330	0.0066	0.0188	0.0077	0.3400	0.0713	0.8612	0.2078
3	0.0220	0.0044	0.0104	0.0043	0.3780	0.0703	0.8032	0.0656
4	0.0132	0.0024	0.0066	0.0029	0.3758	0.0566	0.7142	0.2442
5	0.0068	0.0038	0.0042	0.0041	0.3136	0.0326	0.6002	0.0287
6	0.0042	0.0018	0.0030	0.0027	0.3090	0.0315	0.5286	0.0346
7	0.0018	0.0019	0.0018	0.0013	0.2684	0.0217	0.4458	0.0581
8	0.0008	0.0013	0.0020	0.0010	0.2332	0.0195	0.3854	0.0386
9	0.0004	0.0009	0.0020	0.0020	0.2036	0.0147	0.3084	0.0195
10	0.0002	0.0005	0.0014	0.0013	0.1950	0.0089	0.3046	0.0234
11	0.0008	0.0013	0.0016	0.0022	0.2094	0.0146	0.2914	0.0389
12	0.0002	0.0005	0.0020	0.0019	0.2394	0.0158	0.2988	0.0374
13	0,0000	0.0000	0.0006	0.0009	0.1900	0.0131	0.2314	0.0676
14	0.0000	0.0000	0.0004	0.0009	0.1670	0.0099	0.1806	0.0290
15	0.0002	0.0005	0.0004	0.0009	0.1634	0.0077	0.1884	0.0137

redistribute considerable amounts of soil surface material of the smaller grain sizes. We classify this process therefore effective for detachment and redistribution processes as well as provision of readily available soil material for following erosion events. Despite considerable limitations to generate and measure *wind erosion* within this particularly specialised setting, wind was found to have an impact on short-distance erosion. Therefore, it can be classified an important factor that should be taken into account for assessment of short-distance transport.

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References

Auerswald, K., 1998. Bodenerosion durch Wasser. In: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems. Wiss. Buchges, Darmstadt, pp. 33–42.
Blocken, B., Poesen, J., Carmeliet, J., 2006. Impact of wind on the spatial distribution of rain over micro-scale topography: numerical modelling and experimental verification. Hydrol. Process. 20, 345–368.
Butzen, V., Seeger, M., Marruedo, A., de Jonge, L., Wengel, R., Ries, J.B., Casper, M.C., 2015. Water repellency under coniferous and deciduous forest — experimental assessment and impact on overland flow. Catena 133, 255–265.
Chepil, W.S., 1957. Width of field strips to control wind erosion. Kansas Agric. Exp. Stn. Bull. 92.
Chepil, W.S., Milne, R.A., 1939. Comparative study of soil drifting in the field and in a wind tunnel. Sci. Agric. 19, 249–257.
Cornelis, W.M., Oltenfreiter, G., Gabriels, D., Hartmann, R., 2004. Splash-saltation of sand due to wind-driven rain: vertical deposition flux and sediment transport rate. Soil Sci. Soc. Am. J. 68, 32–40.
De Lima, J.L.M.P., 1989. Raindrop splash anisotropy: slope, wind and overland flow velocity effects. Soil Technol. 2, 71–78.
De Lima, J.L.M.P., 1990. The effect of oblique rain on inclined surfaces: a nomograph for the rain-gauge correction factor. J. Hydrol. 115, 407–412.
De Lima, J.L.M.P., Singh, V.P., Isidoro, J.M.G.P., de Lima, M.I.P., 2011. Incorporating the effect of moving storms into hillslope hydrology: results from a multiple-slope soil flume. World Environmental and Water Resources Congress 2011. American Society of Civil Engineers, pp. 1398–1407.
De Lima, J.L.M.P., van Dijk, P.M., Spaan, W.P., 1992. Splash-saltation transport under wind-driven rain. Soil Technol. 5, 151–166.
Disrud, L.A., Lyles, L., Skidmore, E., 1969. How wind affects the size and shape of raindrops. Agric. Eng. 50, 617.
Dunne, T., Malmon, D.V., Mudd, S.M., 2010. A rain splash transport equation assimilating field and laboratory measurements. J. Geophys. Res. Earth Surf. 115, F01001.
Erpul, G., Gabriels, D., Janssens, D., 2000. Effect of wind on size and energy of small simulated raindrops: a wind tunnel study. Int. Agrophys. 14, 1–7.
Fister, W., Ries, J.B., 2009. Wind erosion in the central Ebro Basin under changing land use management. Field experiments with a portable wind tunnel. J. Arid Environ. 73, 996–1004.
Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.G., 2011. Comparison of rainfall characteristics of a small portable rainfall simulator and a portable wind and rainfall simulator. Z. Geomorphol. 55, 109–126.
Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.-G., 2012. A portable wind and rainfall simulator for in situ soil erosion measurements. Catena 91, 72–84.
Funk, R., Engel, W., 2015. Investigations with a field wind tunnel to estimate the wind erosion risk of row crops. Soil Tillage Res. 145, 224–232.
Furbish, D.J., Hamner, K.K., Schmeeckle, M., Borosund, M.N., Mudd, S.M., 2007. Rain splash of dry sand revealed by high-speed imaging and sticky paper splash targets. J. Geophys. Res. 112, F01001.
Gillette, D.A., Herbert, G., Stockton, P.H., Owen, P.R., 1996. Causes of the fetch effect in wind erosion. Earth Surf. Process. Landf. 21, 641–659.
Goossens, D., 2000. Dry aeolian dust accumulation in rocky deserts: -a medium-term field experiment based on short-term wind tunnel simulations. Earth Surf. Process. Landf. 25, 41–57.
Govers, G., Poesen, J., 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. Geomorphology 1, 343–354.
Hassenpflug, W., 1998. Bodenerosion durch Wind. In: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems. Wiss. Buchges, Darmstadt, pp. 69–82.
Helming, K., Auzet, A.-V., Favis-Mortlock, D., 2005. Soil erosion patterns: evolution, spatio-temporal dynamics and connectivity. Earth Surf. Process. Landf. 30, 131–132.
Iserloh, T., Ries, J.B., Arnáez, J., Boix-Fayos, C., Butzen, V., Cerdà, A., Echeverría, M.T., Fernández-Gálvez, J., Fister, W., Geißler, C., Gómez, J.A., Gómez-Macpherson, H., Kuhn, N.J., Lázaro, R., León, F.J., Martínez-Mena, M., Martínez-Murillo, J.F., Marzen, M., Mingorance, M.D., Ortigosa, L., Peters, P., Regüés, D., Ruiz-Sinoga, J.D., Scholten, T., Seeger, M., Solé-Benet, A., Wengel, R., Wirtz, S., 2013b. European small portable rainfall simulators: a comparison of rainfall characteristics. Catena 110, 100–112.
Iserloh, T., Ries, J.B., Cerdà, A., Echeverría, M.T., Fister, W., Geißler, C., Kuhn, N.J., León, F.J., Peters, P., Schindewolf, M., Schmidt, J., Scholten, T., Seeger, M., 2013c. Comparative measurements with seven rainfall simulators on uniform bare fallow land. Z. Geomorphol. Suppl. 57 (1), 11–26.
Iserloh, T., Fister, W., Marzen, M., Seeger, M., Kuhn, N.J., Ries, J.B., 2013a. The role of wind-driven rain for soil erosion — an experimental approach. Z. Geomorphol. Suppl. 57 (1), 193–201.
Iserloh, T., Fister, W., Seeger, M., Willger, H., Ries, J.B., 2012. A small portable rainfall simulator for reproducible experiments on soil erosion. Soil Tillage Res. 124, 131–137.
Jungerius, P.D., Dekker, L.W., 1990. Water erosion in the dunes. Catena Suppl. 18, 185–193.
Keesstra, S., Pereira, P., Novara, A., Brevik, E.C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., Cerdà, A., 2016. Effects of soil management techniques on soil water erosion in apricot orchards. Sci. Total Environ. 551–552, 357–366.
Kinnell, P., 2005. Raindrop-impact-induced erosion processes and prediction: a review. Hydrol. Process. 19, 2815–2844.
Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur. J. Soil Sci. 47, 425–437.
Legout, C., Leguédois, S., Le Bissonnais, Y., Malam Issa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124, 279–292.
Leguédois, S., Planchon, O., Legout, C., Bissonnais, Y.L., 2005. Splash projection distance for aggregated soils: theory and experiment. Soil Sci. Soc. Am. J. 69, 30–37.
Marzen, M., Iserloh, T., Casper, M.C., Ries, J.B., 2015. Quantification of particle detachment by rain splash and wind-driven rain splash. Catena 127, 135–141.
McKenna Neuman, C., Maxwell, C., Rutledge, C., 2005. Spatial and temporal analysis of crust deterioration under particle impact. J. Arid Environ. 60, 321–342.
Montenegro, A.A.A., Abrantes, J.R.C.B., de Lima, J.L.M.P., Singh, V.P., Santos, T.E.M., 2013. Impact of mulching on soil and water dynamics under intermittent simulated rainfall. Catena 109, 139–149.
Morgan, R.P.C., 2005. Soil Erosion and Conservation. third ed. Wiley-Blackwell, Maiden, Oxford, Carlton.
Peter, K.D., d'Oleire-Oltmanns, S., Ries, J.B., Marzolff, I., Ait Hssaine, A., 2014. Soil erosion in gully catchments affected by land-levelling measures in the Souss Basin, Morocco, analysed by rainfall simulation and UAV remote sensing data. Catena 113, 24–40.
Poesen, J., 1985. An improved splash transport model. Z. Geomorphol. 29, 193–211.
Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., Cerdà, A., 2016. The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. Sci. Total Environ. 547, 323–330.
Ries, J.B., Iserloh, T., Seeger, M., Gabriels, D., 2013. Rainfall simulations — constraints, needs and challenges for a future use in soil erosion research. Z. Geomorphol. Suppl. 57 (1), 1–10.
Ries, J.B., Marzen, M., Iserloh, T., Fister, W., 2014. Soil erosion in Mediterranean landscapes — experimental investigation on crusted surfaces by means of the portable wind and rainfall simulator. J. Arid Environ. 100-101, 42–51.
Ries, J.B., Seeger, M., Iserloh, T., Wistorf, S., Fister, W., 2009. Calibration of simulated rainfall characteristics for the study of soil erosion on agricultural land. Soil Tillage Res. 106, 109–116.
Riezebos, H.T., Epema, G.F., 1985. Drop shape and erosivity part II: Splash detachment, transport and erosivity indices. Earth Surf. Process. Landf. 10, 69–74.
Rodrigo Comino, J., Iserloh, T., Morvan, X., Malam Issa, O., Naisse, C., Keesstra, S.D., Cerdà, A., Prosdocimi, M., Arnáez, J., Lasanta, T., Ramos, M.C., Marqués, M.J., Ruiz Colmenero, M., Bienes, R., Ruiz Sinoga, J.D., Seeger, M., Ries, J.B., 2016. Soil erosion processes in European vineyards: a qualitative comparison of rainfall simulation measurements in Germany, Spain and France. Hydrology 3, 6.
Rutin, J., 1983. Erosional processes on a coastal sand dune, De Blink dunes, Noordwijkerout, The Netherlands. Publication of the Physical and Soils Laboratory 35. University of Amsterdam (144 pp.).
Schmidt, J., Werner, M.v., Schindewolf, M., 2016. Wind effects on soil erosion by water — a sensitivity analysis using model simulations on catchment scale. Catena http://dx.doi.org/10.1016/j.catena.2016.03.035 (in press).
Sharon, D., 1980. The distribution of hydrologically effective rainfall incident on sloping ground. J. Hydrol. 46, 165–188.
Stout, J.E., Zobeck, T.M., 1996. The Wolfforth field experiment: a wind erosion study. Soil Sci. 161, 616–632.
Stroosnijder, L., 2005. Measurement of erosion: is it possible? Catena 64, 162–173.
Umback, C., Lembke, W., 1966. Effects of wind on falling water drops. Trans. ASAE 9, 805–808.
Van Dijk, A.I.J.M., Bruijnzeel, L.A., Rosewell, C.J., 2002a. Rainfall intensity–kinetic energy relationships: a critical literature appraisal. J. Hydrol. 261, 1–23.
Van Dijk, A.I.J.M., Meesters, A.G.C.A., Bruijnzeel, L.A., 2002b. Exponential distribution theory and the interpretation of splash detachment and transport experiments. Soil Sci. Soc. Am. J. 66, 1466–1474.
Van Heerden, W.M., 1964. Splash Erosion as Affected by the Angle of Incidence of Raindrop Impact. Purdue University, Lafayette, USA.
Vermang, J., Norton, L.D., Huang, C., Cornelis, W.M., da Silva, A.M., Gabriels, D., 2015. Characterization of soil surface roughness effects on runoff and soil erosion rates under simulated rainfall. Soil Sci. Soc. Am. J. 79, 903–916.
Wirtz, S., Iserloh, T., Rock, G., Hansen, R., Marzen, M., Seeger, M., Betz, S., Remke, A., Wengel, R., Butzen, V., Ries, J.B., 2012. Soil erosion on abandoned land in Andalusia: a comparison of interrill- and rill erosion rates. ISRN Soil Sci. 2012, 730870 (16 pages).
Wright, A.C., 1986. A physically-based model of the dispersion of splash droplets ejected from a water drop impact. Earth Surf. Process. Landf. 11, 351–367.
Youssef, F., Visser, S.M., Karssenberg, D., Erpul, G., Cornelis, W.M., Gabriels, D., Poortinga, A., 2012. The effect of vegetation patterns on wind-blown mass transport at the regional scale: a wind tunnel experiment. Geomorphology 159–160, 178–188.
Zhang, K., Qu, J., Han, Q., Xie, S., Kai, K., Niu, Q., An, Z., 2014. Wind tunnel simulation of wind-blown sand along China's Qinghai–Tibet railway. Land Degrad. Dev. 25, 244–250.
Zobeck, T.M., Baddock, M., Scott Van Pelt, R., Tatarko, J., Acosta-Martinez, V., 2013. Soil property effects on wind erosion of organic soils. Aeolian Res. 10, 43–51.
Zobeck, T.M., Sterk, G., Funk, R., Rajot, J.L., Stout, J.E., Van Pelt, R.S., 2003. Measurement and data analysis methods for field-scale wind erosion studies and model validation. Earth Surf. Process. Landf. 28, 1163–1188.

VI

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Impact of severe rain storms on soil erosion: Experimental evaluation of wind-driven rain and its implications for natural hazard management

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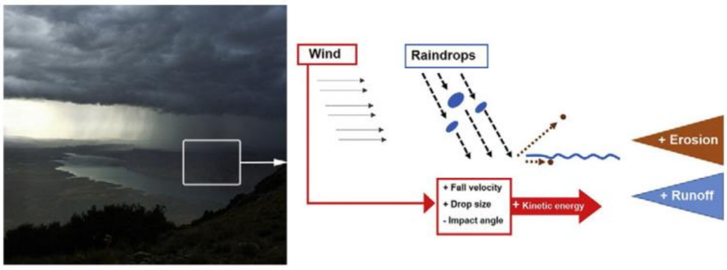
HIGHLIGHTS

- Strong impact of wind-driven rain on soil erosion and runoff generation
- Susceptibility of different environments to climate change associated storm impact
- Improvement of environmental risk assessment by empirical evaluation

GRAPHICAL ABSTRACT



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Climate change

ABSTRACT

Prediction and risk assessment of hydrological extremes are great challenges. Following climate predictions, frequent and violent rainstorms will become a new hazard to several regions in the medium term. Particularly agricultural soils will be severely threatened due to the combined action of heavy rainfall and accompanying winds on bare soil surfaces. Based on the general underestimation of the effect of wind on water erosion, conventional soil erosion measurements and modeling approaches lack related information to adequately calculate its impact. The presented experimental-empirical approach shows the strong impact of wind on the erosive potential of rain. The tested soils had properties that characterize three environments 1. Silty loam of semi-arid Mediterranean dryfarming and fallow, 2. clayey loam of humid agricultural sites and 3. cohesionless sandy substrates as found at coasts, dune fields and drift-sand areas. Total erosion was found to increase by a factor of 1.3 to 7.1, depending on site characteristics. A complementary laboratory procedure was applied to quantify explicitly the effect of wind on raindrop erosion as well as the influence of substrate, surface structure and slope on particle displacement. These tests confirmed the impact of wind-driven rain on total erosion rates to be of great importance when compared to all other tested factors. To successfully adapt soil erosion models to near-future challenges of climate change induced rain storms, wind-driven rain should be included into the hazard management agenda.

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1. Introduction

Soil erosion is now being recognized as a severe threat to socio-ecological security and stability. The manifold issues concerning soil health involve aspects as fundamental as food security, resilience to climate change and geosocial stability. Providing decision-makers and soil managers with information about the processes of soil erosion based on a reliable assessment of vulnerability and risk levels is a necessary step for the control of soil erosion.

Prediction and risk assessment of hydrological extremes are great challenges, particularly if associated with climate change.

Projections point to an increased danger of extreme events including severe storms with heavy precipitation (Kovats et al., 2014). Storm frequency can be triggered by changes of atmospheric circulation, and trend of an increased frequency of winter storms has already been observed in coastal oceans (Bromirski et al., 2003). Both frequency and violence of heavy rain events will increase with a very high confidence (Madsen et al., 2014; Rajczak et al., 2013; Routschek et al., 2015; Westra et al., 2012). The concept of rainstorms very often includes the factor wind, since severe rainfall under windless weather conditions is rare. However, soil science and erosion modelling ignore or underestimate the influence of wind on the processes involved on water erosion (Gabriels et al., 2011). This might be caused by the fact that exclusive test procedures testing wind erosion (e.g. Al-Awadhi and Willetts, 1999; Funk et al., 2008; Gao et al. 2016) or rain erosion (e.g. Iserloh et al., 2013b; Kaiser et al., 2015; Rodrigo Comino et al., 2015; 2016) have long been state of the art. One important reason to overcome this restriction is a rising awareness of the impact of global climatic change on soil health and fertility. An intensification of soil erosion would be a hazard to many regions of the world with fatal ecological and socio-economic implications. Particularly agricultural soils are severely threatened due to the combined action of strong winds and heavy rainfall on bare surfaces. Therefore, scientists need to focus on the wind-driven rain factor, because of its potential to strongly increase erosion of already severely damaged soils with poor health and productivity.

The Mediterranean is considered a hot spot of climate change impact and even more prone to the expected effects of global change (Giorgi, 2006). In addition to changes in the seasonal distribution of extreme precipitation events, also their intensity could increase (e.g. de Lima et al., 2015, 2013; Santo et al., 2014), possibly depending on precipitation type (e.g. Berg and Haerter, 2013). Our study sites at Spain are representative for large parts of the Mediterranean (Ries et al., 2014b) and for northern Spain (Casalí et al., 2008) and particularly threatened by degradation processes by wind and water erosion. The sites at southern Spain include different surface characteristics such as strong crusts, patchy vegetation and recently ploughed soil surface. In some aspects, the sites at northern Spain resemble many European agricultural environments i.e. concerning management (non-irrigated, ploughed, bare during particularly rainy periods, disadvantageous tillage practices) and soil character (silty-sandy loam). The third site represents coastal areas with dunes and beaches all over Europe as well as the drifting sand areas of Belgium and the Netherlands, both generally conservation area due to the crucial ecological function and vulnerability.

To investigate the impact of heavy rainfall on soil erosion and runoff generation is only half the truth, since it neglects the influence of wind on the falling and impacting raindrops. When raindrops enter a local wind field, they will be driven by the wind vectors and redistributed in a specific pattern, causing a very large rainfall gradient (Blocken et al., 2006). Wind is long known to alter regional rainfall distribution (Poreh and Mechrez, 1984) and cell movement under wind has an important impact on the hydraulics of overland flow and, consequently, on associated transport processes (de Lima et al., 2003; Nunes et al., 2006). Wind influences a falling and impacting raindrop in so far, as its potential erosivity is strongly enhanced. The drops fall and hit the ground with an oblique trajectory and increased velocity, thus leading to a higher kinetic energy, providing a stronger impulse for the movement of soil particles and extending the travelling distance (Cornelis et al., 2004; de Lima, 1989; Disrud and Krauss, 1971; Erpul et al., 2005; Helming, 2001; Kinnell, 2005; Pedersen and Hasholt, 1995; Sharon, 1980; Umback and Lembke, 1966). The impact angle is difficult to measure and its effect variable, but it is assumed that less energy is transferred than by vertical rains, while downwind displacement of particles is stimulated (Goossens et al., 2000). Furthermore, a higher number of impacting drops per unit area was observed, and the erosivity of the (raindrop impacted) overland flow might be considerably increased by acceleration of flow and induction of turbulences via impacting wind-driven raindrops (Erpul et al., 2011; Kinnell, 1990; Samray et al., 2011). The impact of wind-driven rain erosion can be particularly strong, if motion by aeolian processes is inhibited by a high water content (van Dijk et al., 1996). All approaches applied in soil erosion models still imply considerable uncertainty of model outputs (Bryan, 2000; Smith et al., 2010; Wainwright et al., 2015). Few empirical studies on WDR highlight the processes acting during a WDR event (de Lima et al., 1992; Erpul et al., 2002; Iserloh et al., 2013a; Ries et al., 2014b) and Marzen et al. (2015, 2016) measure amount and distance of transported soil particles via raindrops and wind-driven raindrops.

This article concentrates on the impact of wind-driven rain (WDR) on soil erosion and its potential to become a frequent natural hazard to agricultural soils. Experiments on autochthonous substrates were conducted as well as laboratory tests on standardized substrates. In-situ investigations on autochthonous soils reflect the natural variability of soil-surface related processes to a great extent, but produce results with a limited interpretability due to a multitude of possible factors, parameters, effects and interactions. To investigate the role of single factors very exclusively, laboratory tests with a highly specialized setup were applied. They can elucidate processes and interactions that lead to a given output, but clearly lack the connection to natural conditions. By combining both methods in a complementary way, we assume to produce reliable and reproducible data that can highlight the relative effect and impact of wind-driven rain on soil erosion and runoff generation.

With the presented work, we intend to achieve following objectives:

1. Determining the relative impact of wind-driven rain on soil erosion.
2. Assess the potential of wind-driven rain erosion as a natural hazard.

2. Material & methods

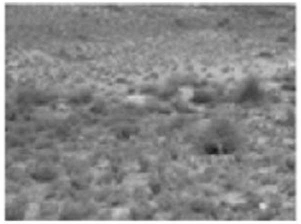
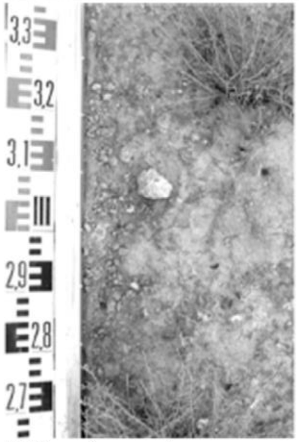
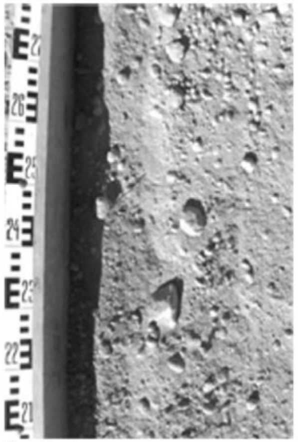
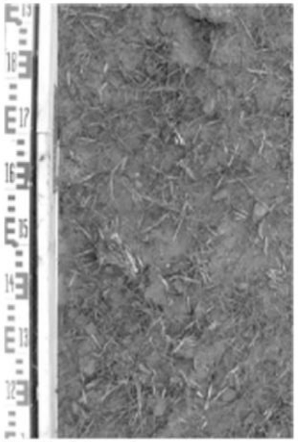
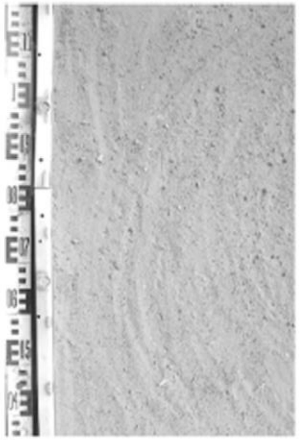
For data acquisition, an experimental-empirical approach was applied. The evaluation procedure includes a statistical analysis of the measured data. We found the combination of in-situ tests and laboratory test a worthwhile procedure to approach natural conditions as close as possible. In the following, the study areas and the methods applied are described.

2.1. Study areas of field tests

Two study areas feature a considerable percentage of European soil surface with agricultural management including the Mediterranean. A third features characteristics of a beach, dune field or drift-sand area. Characteristics are described in Table 1.

The first area is located in Andalusia at the easterly foothills of the Betic cordillera. As part of the post orogenic formation of the Guadalquivir basin, the Pliocene-Pleistocene pediment-landscape has been developing from Pliocene sediments and consists of marls with calcareous crusts (Marzolff et al., 2011). Climatic conditions are semi-arid including high-erosive torrential rainfalls (mainly during spring and autumn) accounting for the greatest part of annual precipitation (200–350 mm) (e.g. Corella et al., 2016; Diodato and Bellocchi, 2014). This combined with overexploitation of soils, a substrate prone to erosion and specific management practices including abandoned land politics have already been creating a landscape that features large areas of abandoned, bare and severely degraded soils with a patchy vegetation. The soils are mostly silty-loamy calcaric regosols (Seeger, 2007) and Leptosols

Table 1
Soil surfaces and physical properties of testplots.

	Mediterranean		Humid/agriculture	Beach/dunes
	Fallow	Orchard		
Survey				
Exemplary plot photo				
Vegetation (%)	10–30; garrigue, cereal	0; orchard	10–50; winter grains	0
Stones (%)	10–65	60	10–15	0
Crust (%)	20–70	0	0	0
Inclination (°)	4.0–7.0	4.0–6.0	4.7–10.7	1.0
Roughness (Cr)	1.4–5.9	7.2–7.9	1.2	0
Corg (%)	0.4–0.7	1.2	1.6	2.9
Substrate	Calcaric regosols from Pliocene marl; silty loam/Pleistocene valley filling	Calcaric regosols from Pliocene marl; silty sand	Haploxerepts; clayey-silty loam	Fine sand
Management	>20 years old fallow/1.2 years young fallow	Freshly ploughed olive orchard	Conventional tillage practices	none

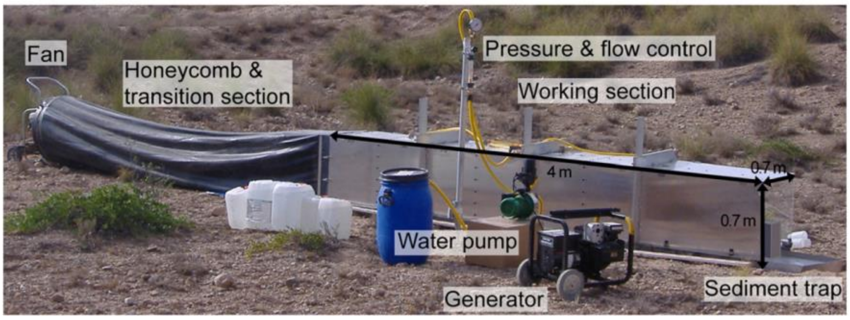


Fig. 1. Experimental setup: Portable Wind and Rainfall Simulator (PWRS). The PWRS consists of five parts: (1) The fan, (2) the 4 metre long transition section, which is connected to the working section (3) by the honeycomb. The rainfall is simulated using a pump and a pressure and flow control system (4). About 25 cm before the end of the tunnel a sediment trap (5) is positioned, which is able to catch runoff and detached sediment (gutter system) as well as splash and windborne material.

(Wirtz et al., 2012) and highly degraded. They are sealed by strong (>10 mm) crusts of a strongly reduced infiltration capacity and therefore exceedingly prone to interrill- and rill-erosion (Ries, 2010; Ries and Hirt, 2008; Wirtz et al., 2012). The development of a protective vegetation coverage takes years (Ries, 2010) and might be entirely prevented by grazing and trampling (Ries, 2010; Ries et al., 2014a). Experiments were conducted by the beginning of autumn prior to the seasonal rainfall. We investigated strongly crusted young (1 year) and old (>15 years) fallow land with extensive trampling and grazing pressure related to transhumance, patchily covered by semi-natural Garrigue-vegetation (*Thymus*, *Genista*, *Rosmarinus*, *Artemisia*, *Lygeum spartum*, *Stipa tenacissima*) or single grains. We also tested a recently ploughed olive orchard with a high stone content.

The second area is located in the humid sub-Mediterranean north of Spain in Navarre with an annual precipitation of 72–835 mm. The soil is developed on clay marls, Pamplona grey marls and sandstones. The sites are on gentle to steep slopes, non-irrigated and under regular agricultural management with winter grains. Soil erosion problems are common (Casalí et al., 1999; Poesen et al., 2003) including high output of sediments and pollutants (Casalí et al., 2008). "Humid agriculture" plots were gently sloped fields with a sparse vegetation of young winter grain and slight furrows. The soils were silty-loamy Haploxerepts (Casalí et al., 2008) and had a (very) high initial water content (test time February). The third site features surface characteristics of a dune field or a beach environment. The tests were conducted on semi-natural substrate at a roofed test field (Iserloh et al., 2013a). The paramount feature of this substrate was the homogeneous cohesionless sand substrate without soil development. It consisted mainly of fine (52%) and medium sand (35%) with a minor proportion of coarse sand, clay and silt (2%, 3% and 9%, respectively).

The three presented groups are recognised as geomorphodynamically highly active and susceptible to erosion (Casalí et al., 2008; Ries, 2003).

2.2. Experimental setup

We used the Portable Wind and Rainfall Simulator (PWRS) (Fig. 1). This device is appropriate for studying erosion by wind, rain and wind-driven rain on natural soil surfaces as well as in laboratory with good results regarding reproducibility of air-stream and rainfall as well as properties of the simulated rainfall (Fister et al., 2011, 2012; Fister and Schmidt, 2008). Compared with windless rainfall, wind-driven rain features an increased drop size, velocity and hence kinetic energy of the falling raindrops, as well as an oblique impact angle (Iserloh et al., 2013a). The kinetic energy is increased by the factor 1.5. Reached wind velocity was ca. 7 m s^{-1} at 0.3 m height. Compared to natural conditions, the generated rainfall represents a highly erosive heavy rain event, while the wind is of a lower intensity but adequate for wind erosion to take place (Hassenpflug, 1998). Table 2 shows the parameters of the test device.

The experimental setup's physical limitations are addressed in (Fister et al., 2012; Iserloh et al., 2013a; Marzen et al., 2016). The presented study does not deliver real amounts of erosion in a completely natural situation but fills the gap between "observation" and "conceptual model" and provides valuable data that are basis for any further investigation and progress in process understanding.

For the here presented study, the PWRS was installed on 1. in-situ soil surfaces and 2. an adjustable metal flume for laboratory tests.

2.3. Procedure under field conditions

In-situ tests are used to measure total amount of runoff and eroded substrate by the soil erosion processes of windless rain (raindrop splash, splash-creep), wind-driven rain (splash-saltation, splash-drift, splash-creep) and wind (reptation, saltation) and the subsequent transport of substrate by the runoff (sheetflow, initial rill development). Respective tests for comparison of windless rain and wind-driven rain were conducted on the same experimental plot and soil loss and runoff coefficients compared. Test plots were chosen as being representative surfaces for three environments with typical substrates and soil surfaces as well as requirements of the test equipment, in particular a uniform inclination over the whole length of 10 m. Surface characteristics vegetation, stones and crust cover were estimated. Inclination and soil C_{org} were measured and roughness (Cr) was approached after Saleh (1993). Test duration was 30 min for rain and wind-driven rain test and 10 min for wind tests. Total runoff and total amount of sediment detached from the 2.2 m^2 test area were collected, filtered (Munktell©,

Table 2
Main wind and rainfall characteristics of the Portable Wind and Rainfall Simulator (source: Iserloh et al., 2013a): Presented are mean wind velocity [v_w], mean Intensity [I], mean volumetric drop diameter [d_{50}], drop fall velocities for drops of the size d_{50}, mean kinetic energy expenditure [KE_R], and mean kinetic energy per unit area per unit depth of rainfall [KE] for windless and wind-driven rain simulations.

	v_w [m s^{-1}]	I [mm h^{-1}]	d_{50} [mm]	v_r [m s^{-1}]	KE_R [J m^{-2} h^{-1}]	KE [J m^{-2} mm^{-1}]
Windless rain	0	96	1.5–2.0	2.2–2.6	270.8	5.21
Wind-driven rain	7.5	88	1.75–2.5	3.4–4.2	1590.8	8.08

Prod.-Nr. 3.104.185, <2 μm mesh-width), dried (105 °C) and weighed. Wind eroded material was collected by means of wedge traps and weighed.

2.4. Procedure under laboratory conditions

Few experimental studies were carried out minutely investigating splash patterns by windless raindrops (Furbish et al., 2007; Dunne et al., 2010), but none for wind-driven raindrops. The splash test equipment and procedure under laboratory conditions was designed to accurately measure amount and distance of substrate particles transported by rain (raindrop splash, splash-creep), wind-driven rain (splash-saltation, splash-drift, splash-creep) and wind (reptation, saltation) up to a distance of 1.5 m (Marzen et al., 2016). The PWRS was installed on a metal flume (de Lima et al., 2011) for the application of different inclinations and a multiple-gutter system was installed inside the PWRS. Rain and wind-driven rain were tested on two substrates (sandy and loamy), three surface structures (level, rills lengthwise and rills transversal to the airstream), and three slope angles (0°, 7° downslope and 7° upslope). Three to five single tests were performed per test group. Each test includes measurements of 15 (+6) single samples corresponding to 15 single gutters of the splash trap plus six additional collection trays applied once per set. Test duration was limited to five minutes to ensure constant substrate conditions and to inhibit the generation of surface water. The material was collected, dried and weighed.

The used substrates were "loam" (clay-silt-sand mixture; d_{50}: 0.09 mm/very fine sand) and "sand" (sand mixture; d_{50}: 0.35 mm/medium sand).

All measured values were calculated to g m^{-2} referring to the output area. We strongly focus on the comparison of "windless rain" and "wind-driven rain" test, while tests "wind" are added rather as a marker for the relative impact of wind within this special setups.

2.5. Statistical analysis

For statistical investigation, both data sets were tested for normal distribution after Kolmogorov-Smirnov. Simple tests related to comparison of the mean were conducted (*t*-test, paired *t*-test). Both data sets were in a first step processed as one group and in a second step arranged according to their specific groups.

3. Results

Wind-driven rain was found to be the paramount factor controlling runoff generation and water erosion.

3.1. Erosion and runoff on autochthonous soil surfaces

54 single tests (18 tests for each erosion agent windless rain, WDR and wind) were conducted on accordingly 18 plots and three sites. The soil surface characteristics differed a lot between single plots as well as between sites. Obviously, these differences of soil surface lead to differing values of erosion and runoff in itself, thusly disguising the impact of each erosion agent. But even if we statistically process all these differing surface structures (plots and sites) together, we do find slightly higher erosion during wind-driven rain runs compared to erosion by windless rain (Fig. 2). The mean amount of eroded material is 41, 31 and 24 g m^{-2} for WDR, rain and wind, respectively, while mean runoff coefficient is 72% for rain and 80 % for WDR (Table 3). Highest (87 g m^{-2}) and lowest (6 g m^{-2}) WDR-erosion were both measured on crusted soil surfaces, as was highest rain erosion (97 g m^{-2}). Lowest rain erosion value was measured on cohesionless sand (2 g m^{-2}), which was most susceptible to wind erosion (154 g m^{-2}). Minimal and maximal values are in a narrower range and standard deviations are lower for WDR compared to rain and wind.

For investigation of the WDR-effect, the tests "rain" and "WDR" are conducted on the same plot in a sequence to compensate for the strong differences and influences of the soil surface on erosion and runoff/infiltration. Following this logic, the respective rain and WDR tests are compared to investigate the differences in runoff and erosion total values. The results show that WDR produced higher erosion than the compared rain experiment in 13 out of 18 cases. In four cases, rain erosion is measured higher, in two cases the results are equal (Fig. 3). The difference in erosion is most notably on sandy substrate.

The same is true for runoff generation: in 13 out of 18 cases, more runoff is measured during WDR runs compared with the respective windless rain test. Particularly on the sandy substrate, the difference

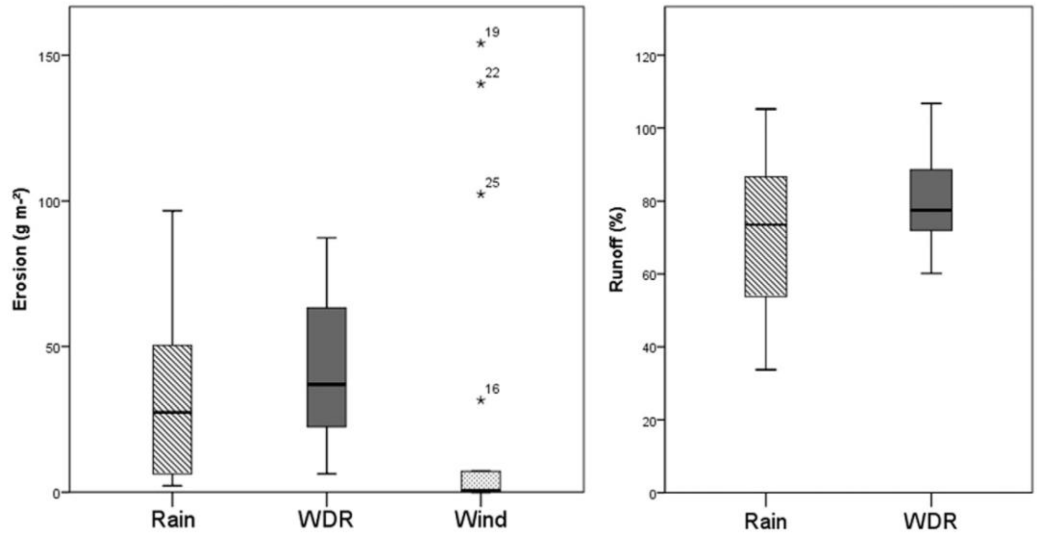


Fig. 2. Boxplots of mean erosion and runoff coefficients from all tests in one set. Even without grouping (e.g. respective test plots, soil surface conditions) wind-driven rain erosion is higher than that by windless rain.

Table 3
Results of all tests on autochthonous soil surfaces.

		N	Min	Max	Mean	SD
Soil erosion (g m^{-2})	Wind-driven rain	18	6.32	87.36	41.13	23.56
	Rain	18	2.23	96.64	31.29	26.2
	Wind	18	0	154.12	24.51	50.94
SSC (g L^{-1})	Wind-driven rain	18	0.2	2.33	1.19	0.66
	Rain	18	0.1	2.16	0.85	0.61
Runoff (%)	Wind-driven rain	18	60.16	100	79.9	12.07
	Rain	18	33.71	100	71.43	19.71

Abbreviations: SSC: suspended sediment concentration; N: number of tests; SD: standard deviation.

in runoff generation is strongly enhanced (Fig. 4). This is all the more interesting, since the overall water application is slightly less during WDR runs due to a wind-induced drift of drops beyond the test area. Further statistical analysis proves the strong impact of WDR on erosion and runoff. Distribution of erosion and runoff was found normal after Kolmogorov-Smirnov. A simple paired samples t-test was conducted (Table 4) with the corresponding windless rain and wind-driven rain tests on the same plot. It shows differences with a high significance for erosion ($p = 0.01$) and runoff coefficient ($p = 0.003$) and thus suspended sediment concentration ($p = 0.002$). These results support the findings that WDR produces a significantly higher erosion than windless rain as well as a significantly higher runoff.

Fig. 4 shows that erosion by windless rain strongly depends on surface parameters, while it is found on a similar level when wind-driven rain is applied. In the case of runoff, we find a similar trend for both windless and wind-driven rain. Mediterranean and humid agricultural plots generate values in the same range, while the sandy substrate produces less runoff and shows a much stronger impact of WDR.

The wind-driven rain coefficient

From the results on different surface characteristics, grouped as sites, we derive a "wind-driven rain coefficient" that shows the effect of wind on rain erosion amount (Table 5) associated with one of the tested environments. The coefficient is 1.3 for both environments, semi-arid Mediterranean and humid agricultural field. That means that in combination with wind, 30 % more water erosion is generated than estimated with excluded wind effect. On cohesionless sand, the coefficient is 7.1, showing a scale of erosion that is well beyond "traditional" estimation (i.e. excluding wind effect).

These coefficients are obviously mean values from many tests with differing conditions and results. They give a good overview because the single factors for each test couple (rain/WDR) are mostly found in this range with few individual outliers. We found a mean WDR-generated runoff increase of 4% on humid agricultural sites, 11% on crusted Mediterranean substrates and 50% more runoff on cohesionless sand (Table 6).

The wind-driven rain coefficient for runoff generation is on the one hand smaller than the one derived for erosion; on the other hand it is in a narrower range for the three tested environments, which means that a stable increase of runoff could be assumed for very different types of surfaces. It has to be noted that the increase in runoff generation is caused by a rather low wind velocity and it can be assumed that it might be increased with increasing wind velocity.

3.2. Particle transport under controlled laboratory conditions

For a closer examination of the WDR-effect, we measured exclusively the material transported by raindrop splash including splash-creep, splash saltation and splash-drift.

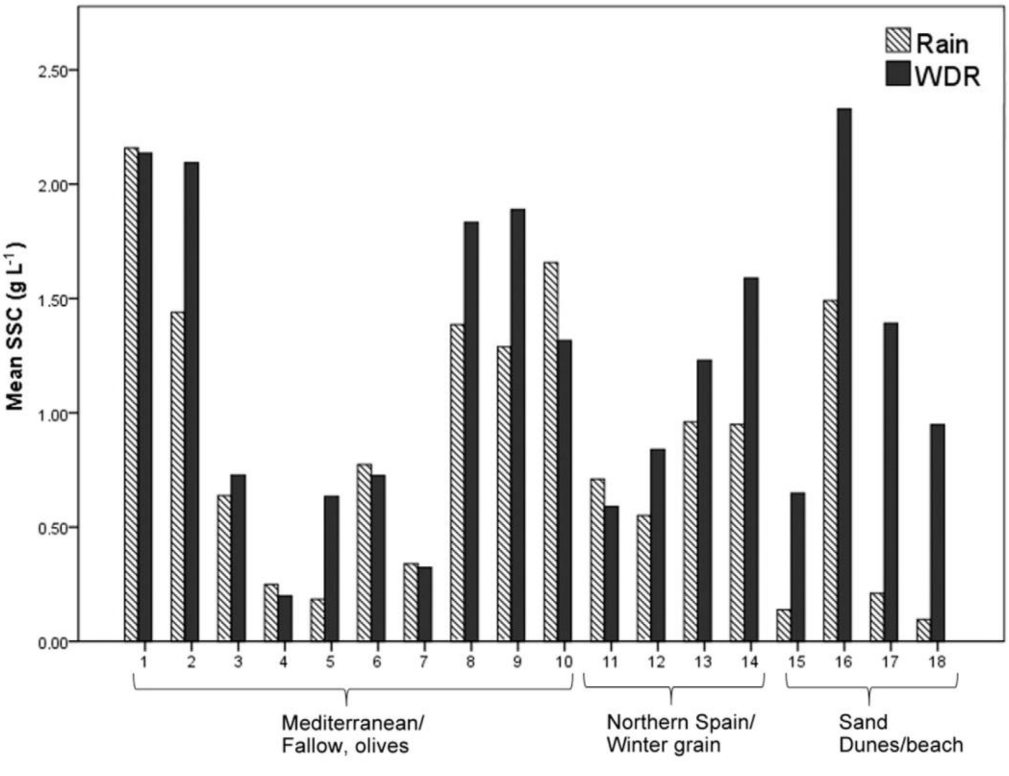


Fig. 3. Comparison of mean suspended sediment concentration (SSC) of different plots and sites.

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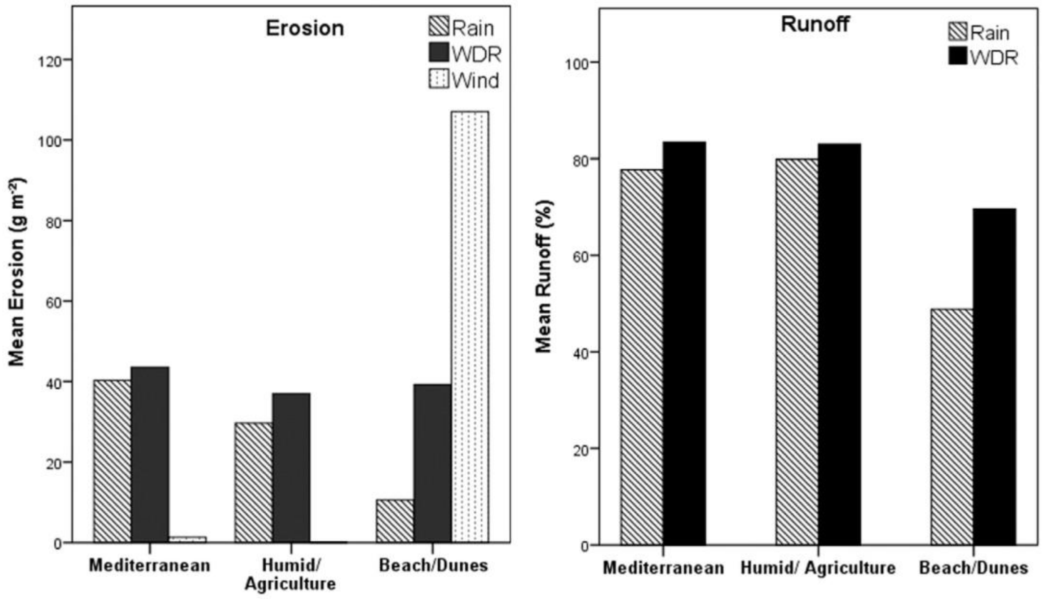

Fig. 4. Mean soil erosion and runoff initiated by different erosion agents associated to the tested environments. Wind-driven rain (WDR) is a stronger erosion agent and runoff generator than windless rain on all tested soil surfaces, particularly on cohesionless homogeneous sand (beach/dunes).

Results from all tests statistically analyzed together in a first step are presented in Table 7. The results show that WDR generates particle transport by wind-driven rain splash that is up to two scales greater than windless rain. Both amount and distance are profoundly intensified by the impact of wind on rain splash transport, even in the case of other factors influencing total erosion. Mean amount of eroded particles was 12.22 g m^{-2} for rain and 154.02 g m^{-2} for wind-driven rain. Wind erosion was only measured twice with values of 1 and 2.8 g m^{-2}.

The mean transported distance was 0.2 m for rain splash. Wind-driven rain transport by splash-creep, splash-saltation and splash-drift was in all cases found to reach the maximum measurement distance (1.52 m), as was found for wind tests, thus producing the mean distance of 1.52 m with a zero SD.

These mean values indicate the strong effect of WDR on both, amount and transport distance of substrate particles, but due to the multitude of involved factors, the data must be grouped according to the respective parameters to filter the impact of one single factor. That is important, because if all tests are analyzed together, the impact of one factor is to an unknown extent hidden among the other factors. The impact of one particular factor is revealed if all other factors are kept constant. For example, to exactly and exclusively focus on the factor "agent of erosion", only tests on the same substrate, the same slope and with the same roughness are used for a comparison. To focus on the impact of the factor "erosion agent" on erosion on different substrates, measurements of the three erosion agents on the two substrates are used that are derived from tests with the same slope and the same roughness. After organizing the data according to the other tested factors for windless and wind-driven rain splash, the difference of total erosion between both is striking (Table 8). A plus of 127 and 200 g m^{-2} for loam and sand, respectively, is measured for a downward slope (7°) without roughness elements (plane). That means a factor 10 on loam and a factor 132 on sand substrate. Highest differences in erosion values are found for tests on sand for the different

Table 4
Paired sample test of in-situ tests. WDR generates significantly higher erosion (0.01), runoff (0.003) and suspended sediment concentration (0.002).

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	Erosion (g m-2)	18	,840	,000
Pair 2	Runoff (%)	18	,905	,000
Pair 3	SSC (%)	18	,800	,000

Paired Samples Test

		Paired Differences: RAIN WIND- DRIVEN RAIN					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference: Lower	Upper			
Pair 1	Erosion (g m-2)	-9,840	14,327	3,377	-16,965	-2,715	-2,914	17	,010
Pair 2	Runoff (%)	-8,433	10,182	2,400	-13,497	-3,370	-3,514	17	,003
Pair 3	SSC (%)	-,343	,405	,095	-,545	-,142	-3,599	17	,002

Table 5
Wind-driven rain (WDR) coefficient for erosion of tested environments.

Site	Erosion (g m^{-2})		WDR-factor (test)	WDR-factor (environment)
	Rain	WDR		
Semi-arid Mediterranean agricultural and fallow sites	96.6	87.4	0.9	1.3
	50.4	63.3	1.3	
	16.4	22.5	1.4	
	6.2	6.3	1.0	
	6.3	20.9	3.3	
	33.4	30.2	0.9	
	12.5	12.6	1.0	
	69.6	78.7	1.1	
	52.7	69.5	1.3	
	58.4	44.3	0.8	
Humid agricultural sites	34.4	28.1	0.8	1.3
	20.9	29.1	1.4	
	39.6	47.3	1.2	
	23.6	43.1	1.8	
Cohesionless sand beach, dunes	2.2	16.5	7.4	7.1
	31.3	66.6	2.1	
	6.0	42.3	7.0	
	2.6	31.6	12.0	

slopes (factors 100–138). Results from in-situ tests and laboratory tests show highest erosion and highest impact of WDR for a sandy surface with a moderate downslope.

These values confirm WDR as the main factor controlling erosion. The impact of the other tested factors on amount of erosion seems comparably less important and depends on the erosion agent (Table 9).

The substrate does influence transport very strongly in the case of windless rain splash in so far, as nearly no erosion takes place on sand (Figure 5a). The relative difference between wind-driven rain splash erosion on sand and on loam is comparably small, but there is a greater amount of sand erosion. Slope has even less influence on wind-driven rain splash, while erosion by windless rain splash is affected to a great extent. The surface roughness equally plays a role for windless rain splash (Figure 5b), but for the total amount of eroded substrate by wind-driven rain splash, the rills and their orientation seems to have a minor influence.

Table 9 shows the impact of the respective tested factors on the agent of erosion in one possible combination and supports the assumption that raindrop erosion is very much influenced by the substrate (factor 9.15), followed by slope (4.71) and roughness (4.15). For WDR, the influence is much smaller and differences are ranked roughness (2.01), slope (1.55) and substrate (1.43).

Table 6
Wind-driven rain (WDR) coefficient for runoff of tested environments.

Site	Runoff (%)		WDR-factor (test)	WDR-factor (environment)
	Rain	WDR		
Semi-arid Mediterranean agricultural and fallow sites	93.81	96.77	1.03	1.11
	73.33	71.51	0.98	
	53.81	73.12	1.36	
	52.00	75.00	1.44	
	72.00	77.00	1.07	
	90.50	94.33	1.04	
	77.10	88.66	1.15	
	100.00	97.42	0.97	
	85.70	83.51	0.97	
	73.80	76.29	1.03	
Humid agricultural sites	100.00	100.00	1.00	1.04
	79.71	78.06	0.98	
	86.67	86.53	1.00	
	52.10	60.71	1.17	
Cohesionless sand beach, dunes	33.71	60.16	1.78	1.50
	43.95	67.69	1.54	
	60.10	71.94	1.20	
	57.43	78.82	1.37	

4. Discussion

The factor "erosion agent" proved the most powerful factor by far.
We assume the substrate and surface characteristics a major factor controlling soil loss.

4.1. Objective 1: determining the relative impact of wind-driven rain on soil erosion

Wind-driven rain is an important erosion agent and has a great potential to increase soil erosion rates. The impact of WDR on soil erosion was not measured during every single test, but on all types of autochthonous substrate. This variability of results reflects the inherent complexity of the soil-surface-system interacting with the erosion agent. Rainfall simulations are generally known for their highly variable output (Iserloh et al., 2013b; Ries et al., 2013; Seeger, 2007). It is all the more remarkable, that the statistical analysis showed such a strong significance of the impact of wind-driven rain. One reason for the higher erosion rates is the influence of wind on rain splash transport. Rain splash is generally considered a minor contributor to total erosion (Beguería et al., 2015; Govers and Poesen, 1988; Nouwakpo et al., 2016; Wirtz et al., 2012). Under specific conditions of a desert environment, Hoffman et al. (2013) found it a considerable factor of soil replacement and some researchers assume it important for geomorphologic development (Dunne et al., 2016). It acts during the first minutes of a rainfall event prior to the generation of shallow surface flow and is mostly seen as sediment supply for succeeding erosion processes (e.g. Angulo-Martínez et al., 2012; Beguería et al., 2015; Geißler et al., 2012; Poesen, 1985). Wind affects the splash-transport to such a great extent, that it can in itself be considered as an erosive process beyond its role in sediment supply. Not only the distance, but particularly the amount of potentially eroded material is surprising. For a catchment scale, Schmidt et al. (2017) show the impact of wind on water erosion concerning the spatial distribution of soil loss and accumulation as well as the total sediment output. Foulds and Warburton (2007) and Warburton (2003) found an increased erosion on peatlands due to the additional action of wind.

The results from laboratory tests show that the impact of each tested factor on erosion depends on the respective combination of test factors and on the agent of erosion. For windless rain splash erosion, the ranking is: substrate, roughness and slope. For wind-driven rain splash the ranking is: roughness, slope, substrate for the here presented combination.

Compared with the impact of factors related to the soil surface, the impact of wind on rain splash erosion is paramount. Coefficients of substrate, slope and roughness are found in the range of four to five. In one single case up to nine, while the coefficients related to the impact of WDR are mostly 10–130. It can be stated, that rainsplash erosion is strongest by far if it is accompanied by wind on a sandy substrate on downward slope, apparently further strengthened by rills lengthwise to the airstream. Marzen et al. (2015) found for a sandy substrate without inclination and roughness elements a mean factor of 25, which is much less than found here (factor 100) and probably caused by the much shorter measurement distance of 0.4 m (compared to 1.6 m).

Wind driven rain did not only increase soil erosion, but also runoff generation. The amount of surplus runoff during in-situ tests can be an additional factor explaining the higher erosion. While the plus erosion by WDR compared to windless rain is 31.5%, the plus in runoff is 11.8%. Reasons for this increase might be an acceleration of the shallow runoff including a rapid slaking and crusting.

Although it is an open question to what extent a shallow sheet flow enhances or prevents soil erosion (e.g. Erpul et al., 2004), we generally assume the surplus generation of runoff a considerable erosive force which might be even increased with increasing wind velocity. The degree of impact on soil erosion is determined by the soil surface

Table 7
Descriptive statistics erosion agents for laboratory results.

Descriptive statistics	N	Minimum	Maximum	Mean	Std. deviation
Rain					
Distance_m	38	.07	.38	.1958	.10676
Erosion g m^{-2}	38	.64	71.02	12.2176	17.24916
Valid N (listwise)	38				
Wind-driven rain					
Distance_m	38	1.52	1.52	1.5200	.00000
Erosion g m^{-2}	38	83.04	309.35	154.0184	53.83458
Valid N (listwise)	38				
Wind					
Distance_m	2	1.52	1.52	1.5200	.00000
Erosion g m^{-2}	2	.99	2.82	1.9050	1.29401
Valid N (listwise)	2				

Table 9
Impact of tested factors on the single agents of erosion for a range of test conditions in laboratory.

Substrate (7° down, plane)	Loam	Sand	Difference	Factor
Rain	14.27	1.56	12.71	9.15
WDR	141.27	201.52	60.25	1.43

Roughness (loam, 7° down)	Plane	Rills lengthwise	Rill transversal	Difference	Factor
Rain	14.27	59.26	19.34	44.99	4.15
WDR	141.27	283.69	178.16	142.42	2.01

Slope (loam, plane)	7° down	0°	7° up	Difference	Factor
Rain	14.27	3.47	3.03	11.24	4.71
WDR	141.27	95.47	91.29	49.98	1.55

properties determining resilience to particle detachment (Savat and DePloey, 1982).

Despite some laboratory studies with detachment rates and physical formulas derived from wind-driven rain erosion measurement results, actual detachment amounts are rarely given. Lyles et al. (1968) measured 69% more erosion by WDR compared to windless rain, which is quite in the range of the here derived "wind-driven rain coefficient" for natural soil surfaces except sand, although they applied a much higher wind-velocity (48 km/h). On mulched surfaces, they found a factor of 2.7 (Lyles et al. 1974) which is a greater effect than was measured on autochthonous surfaces but less than on the sandy substrate.

4.2. Objective 2: assessment of the potential of wind-driven rain erosion as a natural hazard for different environments

Three different soil surfaces corresponding to three types of environments were tested. With the support of findings from the laboratory experiments, general assumptions concerning the impact of wind-driven rain erosion on different surface characteristics can be proposed.

On all tested soil surfaces, wind-driven rain generates higher erosion and runoff than rain.

The "Mediterranean" plots are more affected by WDR than by windless rain erosion. The susceptibility of the substrates of semi-arid Spain to runoff generation and erosion is to a great extent determined by specific surface characteristics like crusts, stone cover, roughness and vegetation (e.g. Cerdà et al., 2016; Martínez-Murillo et al., 2013), and aggressive agricultural management practices lead to dramatic erosion and runoff values (Keesstra et al., 2016; Prosdocimi et al., 2016; Cerdà et al., 2009; Rodrigo Comino et al., 2015; 2016). Runoff generation is also increased by WDR, which might be particularly hazardous on the crusted surfaces, where it can accelerate quickly and thus gain even more erosive power. This is all the more the case in combination with the impact on rain splash erosion, which can be derived from laboratory tests: the factor combination loamy substrate and downward slope lead to a strongly enhanced erosion of substrate by rain splash and a very strong erosion by wind-driven rain splash. Another factor is the effect of climate change on Mediterranean weather systems: Most projections show a very likely decrease of cyclones and windstorms (Nissen et al., 2014), promoting the relative impact of wind-driven rain erosion, which can be supposed to be highest at low to medium wind intensities. At higher wind speeds, the drops are destroyed and downsized, thus losing a great part of their impact energy.

On "humid/agricultural" plots, the difference between rain and WDR-erosion is equally accentuated. The corresponding factor-combination from laboratory tests was a loamy substrate on a downward slope with rills lengthwise to the airstream, which produced in laboratory tests highest rain splash and high WDR-splash values. Runoff is only slightly increased, probably due to the high runoff rates on the waterlogged test plots.

On sandy substrate, the difference between windless rain and WDR erosion is particularly pronounced. Compared to windless conditions, under wind-driven rain 113–1100% more erosion was measured. This finding is supported by the laboratory results that highlight WDR –splash as a particularly powerful force to erode sand fractions, even on surfaces without inclination or upslope. If these results are transferred on the respective landscape units, valuable information for management of coastal, dune and drift-sand areas can be derived.

Table 8
Impact of tested factors in combination with the respective agent of erosion for a range of test conditions. Values are given in g m^{-2}. Given in brackets are conditions, from which values were derived: e.g. values presented for "Substrate" (7° down, plane) include the conditions "slope: 7° down" and "roughness: plane".

	Substrate (7° down, plane)		Slope (sand, plane)			Roughness (loam, 0°)		
	Loam	Sand	7° down	0°	7° up	Plane	Rills lengthwise	Rill transversal
Rain	14.27	1.56	1.53	1.56	1.15	3.47	33.04	4.22
WDR	141.27	201.52	201.52	155.59	158.28	95.47	145.54	104.19
Difference	+127.00	+154.03	+199.99	+154.03	+157.13	+92.00	+112.50	+99.97
Factor	10	129	132	100	138	28	4	25
	Substrate (0°, plane)		Slope (loam, plane)			Roughness (loam, 7° down)		
	Loam	Sand	7° down	0°	7° up	Plane	Rills lengthwise	Rill transversal
Rain	3.47	1.56	14.27	3.47	3.03	14.27	59.26	19.34
WDR	95.47	155.59	141.27	95.47	91.29	141.27	283.69	178.16
Difference	+92.00	+154.03	+127.00	+92.00	+88.25	+127.00	+224.43	+158.82
Factor	27	100	10	27	30	10	5	9

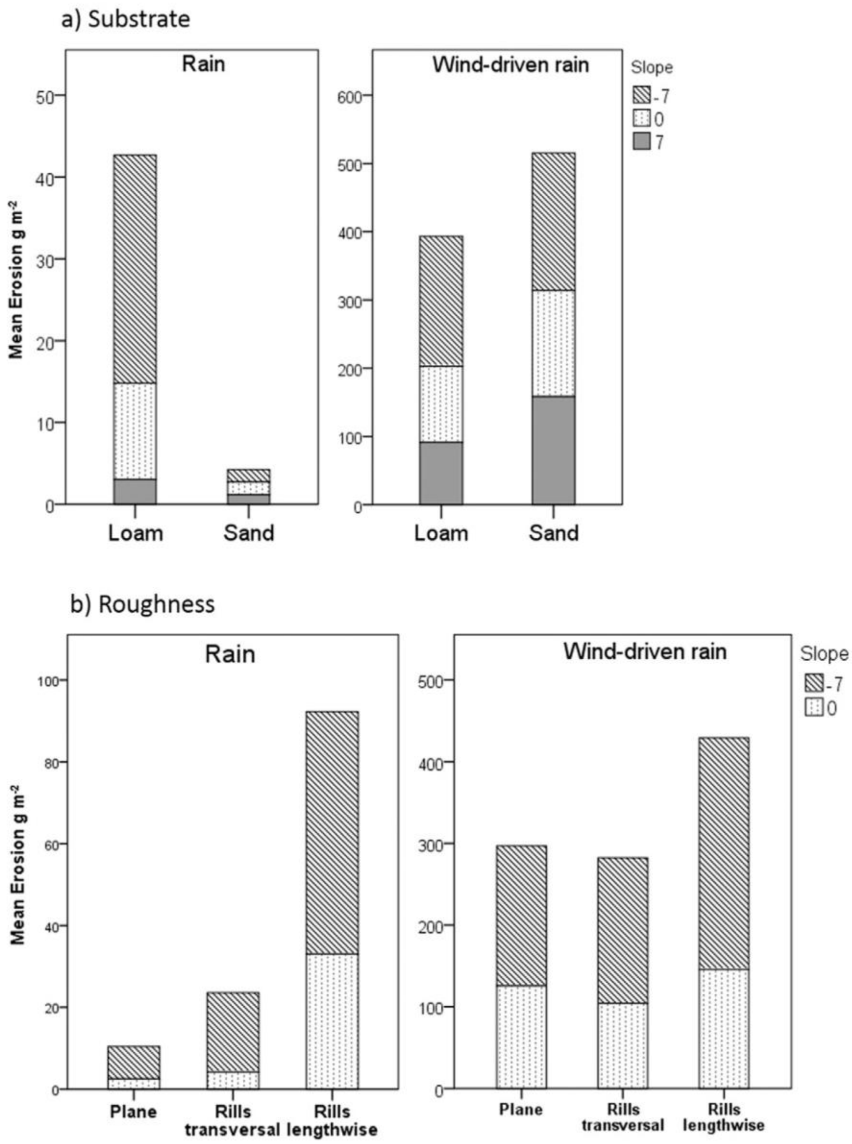

Fig. 5. Comparison of erosion by rain splash and wind-driven rain splash on different substrates (a) and surface roughnesses (b) for different slopes.

The results indicate that during dry conditions, wind erosion is the major factor controlling total erosion. During rainy periods, only minor erosion takes place, but only if the air is calm. In case of wind accompanying rain, the WDR-erosion is very powerful and transports considerable amounts of substrate. The erosion event could start with a powerful entrainment of particles by splash-creep, splash-saltation and splash-drift, followed by, with continuing duration of the storm event, shallow runoff could further transport the material that was already entrained or is already in motion. This idea confirms Cornelis et al. (2004), who found the impact of wind-driven rain on total soil loss budget most notably in the case of low winds. In some very specific cases as for conservation of inland drift-sand areas in the Netherlands and Belgium, this might be good news that are in contrast to Riksen and Goossens (2007) who found transport by wind-driven rain splash marginal during one wind-driven rain event. WDR events could here support the preservation of this valuable environment by enhanced disturbance of substrate surface and a suppression of stable revegetation, without the complete loss of eroded material like during wind erosion.

Concerning prediction and risk assessment of the effect of WDR adding to the impact of hydrological extremes, an underestimation of the WDR effect can lead to a severe miscalculation of erosion and runoff. Wind-driven rain might lead to erosion rates exceeding those obtained conventionally by means of experimental studies or numerical models (van Dijk et al., 1996). That is caused by the fact that the erosive effect of wind-driven rain is not accounted for sufficiently by simply applying a higher kinetic energy as is generally the case in models simulating soil erosion and runoff generation.

Beyond a higher kinetic energy, the erosive potential of wind-driven rain includes

- additional direct transport of airborne particles by the air stream
- directed transport of particles in wind direction
- stronger impulse induced by the oblique impact angle of the wind-driven raindrop.

Wind-driven rain might thusly alter hydrological systems with respect to discharge peaks and sediment supply.

5. Conclusion

Wind-driven rain (WDR) is found an important factor controlling soil erosion and runoff generation, particularly in the combination of heavy rainfall with low to moderate wind.

We deem wind-driven rain a crucial factor for natural hazard risk assessment for following reasons:

- WDR has a great potential to increase soil erosion
- WDR has a considerable impact on runoff generation
- Absolute and relative influence of WDR seems to be particularly powerful in the combination heavy rainfall with low to moderate wind.

We introduced the wind-driven rain coefficient to show that total soil erosion is severely underestimated for all types of tested soil surfaces including different substrates and surface characteristics. The enhanced runoff generation should be acknowledged as an important factor adding to the general increase in erosive potential of wind-driven rains. The wind-driven rain processes might thusly alter hydrological systems with respect to discharge peaks and sediment supply. It could lead to erosion and runoff rates exceeding those obtained conventionally by means of experimental studies or numerical models. That is caused by the fact that the erosive effect of wind-driven rain is not accounted for sufficiently by simply applying a higher kinetic energy as is generally the case in models simulating soil erosion and runoff generation.

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References

Angulo-Martínez, M., Beguería, S., Navas, A., Machín, J., 2012. Splash erosion under natural rainfall on three soil types in NE Spain. Geomorphology 175–176, 38–44.
Al-Awadhi, J.M., Willetts, B.B., 1999. Sand transport and deposition within arrays of non-erodible cylindrical elements. Earth Surf. Process. Landf. 24, 423–435.
Beguería, S., Angulo-Martínez, M., Gaspar, L., Navas, A., 2015. Detachment of soil organic carbon by rainfall splash: experimental assessment on three agricultural soils of Spain. Geoderma 245–246, 21–30.
Berg, P., Haerter, J.O., 2013. Unexpected increase in precipitation intensity with temperature - a result of mixing of precipitation types? Atmos. Res. 119, 56–61.
Blocken, B., Poesen, J., Carmeliet, J., 2006. Impact of wind on the spatial distribution of rain over micro-scale topography: numerical modelling and experimental verification. Hydrol. Process. 20, 345–368.
Bromirski, P.D., Flick, R.E., Cayan, D.R., 2003. Storminess variability along the California Coast: 1858–2000. J. Climate 16, 982–993.
Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32, 385–415.
Casalí, J., Gastesi, R., Álvarez-Mozos, J., De Santisteban, L.M., de Lersundi, J.D.V., Giménez, R., Larrañaga, A., Goñi, M., Agirre, U., Campo, M.A., López, J.J., Donézar, M., 2008. Runoff, erosion, and water quality of agricultural watersheds in central Navarre (Spain). Agric Water Manag 95, 1111–1128.
Casalí, J., López, J.J., Giráldez, J.V., 1999. Ephemeral gully erosion in southern Navarra (Spain). Catena 36, 65–84.
Cerdà, A., González-Pelayo, Ó., Giménez-Morera, A., Jordán, A., Pereira, P., Novara, A., Brevik, E.C., Prosdocimi, M., Mahmoodabadi, M., Keesstra, S., Orenes, F.G., Ritsema, C.J., 2016. Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency–high magnitude simulated rainfall events. Soil Research 54, 154–165.
Cerdà, A., Morera, A.G., Bodí, M.B., 2009. Soil and water losses from new citrus orchards growing on sloped soils in the western Mediterranean basin. Earth Surf. Process. Landf. 34, 1822–1830.
Corella, J.P., Valero-Garcés, B.L., Serrano, S.M.V., Brauer, A., Benito, G., 2016. Three millennia of heavy rainfalls in Western Mediterranean: frequency, seasonality and atmospheric drivers. Sci. Rep. 6, 38206.
Cornelis, W.M., Oltenfreiter, G., Gabriels, D., Hartmann, R., 2004. Splash-saltation of sand due to wind-driven rain: vertical deposition flux and sediment transport rate. Soil Sci. Soc. Am. J. 68, 32–40.
de Lima, M.I.P., Santo, F.E., Ramos, A.M., Trigo, R.M., 2015. Trends and correlations in annual extreme precipitation indices for mainland Portugal, 1941–2007. Theor. Appl. Climatol. 119, 55–75.
de Lima, J.L.M.P., 1989. Raindrop splash anisotropy: slope, wind and overland flow velocity effects. Soil Technol. 2, 71–78.
de Lima, J.L.M.P., Singh, V.P., de Lima, M.I.P., 2003. The influence of storm movement on water erosion: storm direction and velocity effects. Catena 52, 39–56.
de Lima, J.L.M.P., Singh, V.P., Isidoro, J.M.G.P., de Lima, M.I.P., 2011. Incorporating the Effect of Moving Storms into Hillslope Hydrology: Results from a Multiple-Slope Soil Flume, in: World Environmental and Water Resources Congress 2011. American Society of Civil Engineers, pp. 1398–1407.
de Lima, M.I.P., Santo, F.E., Ramos, A.M., de Lima, J.L.M.P., 2013. Recent changes in daily precipitation and surface air temperature extremes in mainland Portugal, in the period 1941–2007. Atmos. Res. 127, 195–209.
de Lima, J.L.M.P., van Dijk, P.M., Spaan, W.P., 1992. Splash-saltation transport under wind-driven rain. Soil Technology 5, 151–166.
Diodato, N., Bellocchi, G., 2014. Landscape scales of erosive storm hazard across the Mediterranean Region. In: Diodato, N., Bellocchi, G. (Eds.), Storminess and Environmental Change, Advances in Natural and Technological Hazards Research. Springer Netherlands, pp. 101–116.
Disrud, L.A., Krauss, R.K., 1971. Examining the process of soil detachment from clods exposed to wind-driven simulated rainfall. Trans. ASAE 14, 90–92.
Dunne, T., Malmon, D.V., Dunne, K.B.J., 2016. Limits on the morphogenetic role of rain splash transport in hillslope evolution. J. Geophys. Res. Earth 121 (2015JF003737).
Dunne, T., Malmon, D.V., Mudd, S.M., 2010. A rain splash transport equation assimilating field and laboratory measurements. J. Geophys. Res. 115, F01001.
Erpul, G., Gabriels, D., Norton, L.D., 2005. Sand detachment by wind-driven raindrops. Earth Surf. Process. Landf. 30, 241–250.
Erpul, G., Gabriels, D., Norton, L.D., 2004. Wind effects on sediment transport by raindrop-impacted shallow flow: a wind-tunnel study. Earth Surf. Process. Landf. 29, 955–967.
Erpul, G., Gabriels, D., Norton, L.D., Flanagan, D., Huang, C., Visser, S.M., 2011. Interactions between raindrop impact and shallow interrill flow under wind-driven rain. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment- Wind Erosion, Interrill Erosion, Gully Erosion. Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 9–18.
Erpul, G., Norton, L., Gabriels, D., 2002. Raindrop-induced and wind-driven soil particle transport. Catena 47, 227–243.
Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.-G., 2012. A portable wind and rainfall simulator for in situ soil erosion measurements. Catena 91, 72–84.
Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.G., 2011. Comparison of rainfall characteristics of a small portable rainfall simulator and a portable wind and rainfall simulator. Zeitschrift für Geomorphologie 55, 109–126.
Fister, W., Schmidt, R.-G., 2008. Concept of a single device for simultaneous simulation of wind and water erosion in the field. In: Gabriels, D., Cornelis, W. (Eds.), Proceedings of Conference on Desertification. Gent, Belgium, pp. 106–113.
Foulds, S.A., Warburton, J., 2007. Significance of wind-driven rain (wind-splash) in the erosion of blanket peat. Geomorphology 83, 183–192.
Funk, R., Reuter, H.I., Hoffmann, C., Engel, W., Öttl, D., 2008. Effect of moisture on fine dust emission from tillage operations on agricultural soils. Earth Surf. Process. Landf. 33, 1851–1863.
Furbish, D.J., Hamner, K.K., Schmeeckle, M., Borosund, M.N., Mudd, S.M., 2007. Rain splash of dry sand revealed by high-speed imaging and sticky paper splash targets. J. Geophys. Res. 112, F01001.
Gabriels, D., Erpul, G., Vermang, J., 2011. The "Erosion Component"of WEPP (Water Erosion Prediction Project) for wind driven rain. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment - Wind Erosion, Interrill Erosion, Gully Erosion. Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 9–18.
Gao, Y., Dang, X., Yu, Y., Li, Y., Liu, Y., Wang, J., 2016. Effects of tillage methods on soil carbon and wind erosion. Land Degrad. Dev. 27, 583–591.
Geißler, C., Kühn, P., Böhnke, M., Bruelheide, H., Shi, X., Scholten, T., 2012. Splash erosion potential under tree canopies in subtropical SE China. Catena 91, 85–93.
Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. 33, L08707.
Goossens, D., Poesen, J., Gross, J., Spaan, W., 2000. Splash drift on light sandy soils: a field experiment. Agronomie 20, 271–282.
Govers, G., Poesen, J., 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. Geomorphology 1, 343–354.
Hassenpflug, W., 1998. Bodenerosion durch Wind. In: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems. Wissenschaftliche Buchgesellschaft, Darmstadt, pp. 69–82.
Helming, K., 2001. Wind speed effects on rain erosivity. In: Stott, D.E., Mohtar, R.H., Steinhardt, G.C. (Eds.), Sustaining the Global Farm, Selected Papers from the 10th International Soil Conservation Organization Meeting 1999. Int. Soil Conservation Organization in Cooperation with the USDA and Purdue University, West Lafayette, pp. 771–776.
Hoffman, O., Yizhaq, H., Boeken, B.R., 2013. Small-scale effects of annual and woody vegetation on sediment displacement under field conditions. Catena 109, 157–163.
Iserloh, T., Fister, W., Marzen, M., Seeger, M., Kuhn, N.J., Ries, J.B., 2013a. The role of wind-driven rain for soil erosion – an experimental approach. Zeitschrift für Geomorphologie Suppl. Issues 57:193–201. http://dx.doi.org/10.1127/0372-8854/2012/S-00118.
Iserloh, T., Ries, J.B., Cerdà, A., Echeverría, M.T., Fister, W., Geißler, C., Kuhn, N.J., León, F.J., Peters, P., Schindewolf, M., Schmidt, J., Scholten, T., Seeger, M., 2013b. Comparative

measurements with seven rainfall simulators on uniform bare fallow land. Zeitschrift für Geomorphologie Suppl. Issues 57, 11–26.
Kaiser, A., Neugirg, F., Schindewolf, M., Haas, F., Schmidt, J., 2015. Simulation of rainfall effects on sediment transport on steep slopes in an Alpine catchment, in: Sediment Dynamics from the Summit to the Sea. IAHS-AISH Publication. IAHS Press, New Orleans, pp. 43–50.
Keesstra, S., Pereira, P., Novara, A., Brevik, E.C., Azorin-Molina, C., Parras-Alcántara, L., Jordán, A., Cerdà, A., 2016. Effects of soil management techniques on soil water erosion in apricot orchards. Sci. Total Environ. 551–552, 357–366.
Kinnell, P.I.A., 1990. The mechanics of raindrop induced flow transport. Soil Research 28, 497–516.
Kinnell, P.I.A., 2005. Raindrop-impact-induced erosion processes and prediction: a review. Hydrol. Process. 19, 2815–2844.
Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., Soussana, J.-F., 2014. Europe, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267–1326.
Lyles, L., Dickerson, J., Schmeidler, N., 1974. Soil detachment from clods by rainfall: effects of wind, mulch cover, and initial soil moisture. Transactions of the ASAE 17, 697–700.
Lyles, L., Disrud, L.A., Woodruff, N.P., 1968. Effects of soil physical properties, rainfall characteristics, and wind velocity on clod disintegration by simulated rainfall. Soil Sci. Soc. Am. J. 33, 302–306.
Madsen, H., Lawrence, D., Lang, M., Martinkova, M., Kjeldsen, T.R., 2014. Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. Journal of Hydrology 519, 3634–3650 Part D.
Martínez-Murillo, J.F., Nadal-Romero, E., Regüés, D., Cerdà, A., Poesen, J., 2013. Soil erosion and hydrology of the western Mediterranean badlands throughout rainfall simulation experiments: a review. Catena 106, 101–112.
Marzen, M., Iserloh, T., Casper, M.C., Ries, J.B., 2015. Quantification of particle detachment by rain splash and wind-driven rain splash. Catena 127, 135–141.
Marzen, M., Iserloh, T., de Lima, J.L.M.P., Ries, J.B., 2016. The effect of rain, wind-driven rain and wind on particle transport under controlled laboratory conditions. Catena 145, 47–55.
Marzolff, I., Ries, J.B., Poesen, J., 2011. Short-term versus medium-term monitoring for detecting gully-erosion variability in a Mediterranean environment. Earth Surf. Process. Landf. 36, 1604–1623.
Nissen, K.M., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2014. Mediterranean cyclones and windstorms in a changing climate. Reg. Environ. Chang. 14, 1873–1890.
Nouwakpo, S.K., Williams, C.J., Al-Hamdan, O.Z., Weltz, M.A., Pierson, F., Nearing, M., 2016. A review of concentrated flow erosion processes on rangelands: fundamental understanding and knowledge gaps. International Soil and Water Conservation Research 4, 75–86.
Nunes, J.P., de Lima, J.L.M.P., Singh, V.P., de Lima, M.I.P., Vieira, G.N., 2006. Numerical modeling of surface runoff and erosion due to moving rainstorms at the drainage basin scale. J. Hydrol. 330, 709–720.
Pedersen, H.S., Hasholt, B., 1995. Influence of wind speed on rainsplash erosion. Catena 24, 39–54.
Poesen, J., 1985. An improved splash transport model. Z. Geomorphol. 29, 193–211.
Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91–133.
Poreh, M., Mechrez, E., 1984. The combined effect of wind and topography on rainfall distribution. J. Hydrol. 72, 1–23.
Prosdocimi, M., Cerdà, A., Tarolli, P., 2016. Soil water erosion on Mediterranean vineyards: a review. Catena 141, 1–21.
Rajczak, J., Pall, P., Schär, C., 2013. Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. J. Geophys. Res. Atmos. 118, 3610–3626.
Ries, J.B., 2010. Methodologies for soil erosion and land degradation assessment in Mediterranean-type ecosystems. Land Degrad. Dev. 21, 171–187.
Ries, J.B., 2003. Landnutzungswandel und Landdegradation in Spanien – eine Einführung. In: Marzolff, I., Ries, J.B., De La Riva, J., Seeger, M. (Eds.), Landnutzungswandel und Landdegradation in Spanien. Universität Frankfurt a. M. and Universidad de Zaragoza, pp. 11–31.
Ries, J.B., Hirt, U., 2008. Permanence of soil surface crusts on abandoned farmland in the Central Ebro Basin/Spain. Catena 72, 282–296.
Ries, J.B., Iserloh, T., Seeger, M., Gabriels, D., 2013. Rainfall simulations – constraints, needs and challenges for a future use in soil erosion research. Zeitschrift für Geomorphologie Suppl. Issues 57, 1–10.
Ries, J.B., Andres, K., Wirtz, S., Tumbrink, J., Wilms, T., Peter, K.D., Burczyk, M., Butzen, V., Seeger, M., 2014a. Sheep and goat erosion – experimental geomorphology as an approach for the quantification of underestimated processes. Zeitschrift für Geomorphologie Suppl. Issues 58, 23–45.
Ries, J.B., Marzen, M., Iserloh, T., Fister, W., 2014b. Soil erosion in Mediterranean landscapes - experimental investigation on crusted surfaces by means of the Portable Wind and Rainfall Simulator. J. Arid Environ. 100–101, 42–51.
Riksen, M.J.P.M., Goossens, D., 2007. The role of wind and splash erosion in inland driftsand areas in the Netherlands. Geomorphology 88, 179–192.
Rodrigo Comino, J., Brings, C., Lassu, T., Iserloh, T., Senciales, J.M., Martínez Murillo, J.F., Ruiz Sinoga, J.D., Seeger, M., Ries, J.B., 2015. Rainfall and human activity impacts on soil losses and rill erosion in vineyards (Ruwer Valley, Germany). Solid Earth 6, 823–837.
Rodrigo Comino, J., Iserloh, T., Lassu, T., Cerdà, A., Keestra, S.D., Prosdocimi, M., Brings, C., Marzen, M., Ramos, M.C., Senciales, J.M., Ruiz Sinoga, J.D., Seeger, M., Ries, J.B., 2016. Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. Sci. Total Environ. 565, 1165–1174.
Routschek, A., Schmidt, J., Kreienkamp, F., 2015. Climate change impacts on soil erosion: a high-resolution projection on catchment scale until 2100. In: Lollino, G., Manconi, A., Clague, J., Shan, W., Chiarle, M. (Eds.), Engineering Geology for Society and Territory - Volume 1. Springer International Publishing, pp. 135–141.
Saleh, A., 1993. Soil roughness measurement: chain method. J. Soil Water Conserv. 48, 527–529.
Samray, H., Erpul, G., Gabriels, D., 2011. Raindrop detachment and raindrop-induced flow transport (RD-RIFT) under different fall trajectories of wind-driven raindrops. In: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment- Wind Erosion, Interrill Erosion, Gully Erosion. Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 9–18.
Santo, F.E., Ramos, A.M., de Lima, M.I.P., Trigo, R.M., 2014. Seasonal changes in daily precipitation extremes in mainland Portugal from 1941 to 2007. Regional Environmental Change 14, 1765–1788.
Savat, J., DePloey, J., 1982. Sheetwash and rill development by surface flow. In: Bryan, R.B., Yair, A. (Eds.), Badland Geomorphology and Piping. Geobooks, Norwich, pp. 113–126.
Schmidt, J., Werner, M.v., Schindewolf, M., 2017. Wind effects on soil erosion by water - a sensitivity analysis using model simulations on catchment scale. Catena 148, 168–175.
Seeger, M., 2007. Uncertainty of factors determining runoff and erosion processes as quantified by rainfall simulations. Catena 71, 56–67.
Sharon, D., 1980. The distribution of hydrologically effective rainfall incident on sloping ground. J. Hydrol. 46, 165–188.
Smith, R.E., Quinton, J., Goodrich, D.C., Nearing, M., 2010. Soil-erosion models: where do we really stand? Earth Surf. Process. Landf. 35, 1344–1348.
Umback, C., Lembke, W., 1966. Effects of wind on falling water drops. Transactions of the ASAE 9, 805–808.
van Dijk, P.M., Stroosnijder, L., de Lima, J.L.M.P., 1996. The influence of rainfall on transport of beach sand by wind. Earth Surf. Process. Landf. 21, 341–352.
Wainwright, J., Parsons, A.J., Cooper, J.R., Gao, P., Gillies, J.A., Mao, L., Orford, J.D., Knight, P.G., 2015. The concept of transport capacity in geomorphology. Rev. Geophys. 53, 1155–1202.
Warburton, J., 2003. Wind-splash erosion of bare peat on UK upland moorlands. Catena 52, 191–207.
Westra, S., Alexander, L.V., Zwiers, F.W., 2012. Global increasing trends in annual maximum daily precipitation. J. Climate 26, 3904–3918.
Wirtz, S., Iserloh, T., Rock, G., Hansen, R., Marzen, M., Seeger, M., Betz, S., Remke, A., Wengel, R., Butzen, V., Ries, J.B., 2012. Soil erosion on abandoned land in Andalusia: a comparison of interrill- and rill erosion rates. ISRN Soil Science 2012:1–16. http://dx.doi.org/10.5402/2012/730870.

References

Auerswald, K., 1998. Bodenerosion durch Wasser, in: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems. Wissenschaftliche Buchgesellschaft, Darmstadt, pp. 33–42.

Bagnold, R.A., 1941. The physics of blown sand and desert dunes. William Morrow, New York.

Belnap, J., Gillette, D.A., 1998. Vulnerability of desert biological soil crusts to wind erosion: the influences of crust development, soil texture, and disturbance. Journal of Arid Environments 39, 133–142.

Blocken, B., Poesen, J., Carmeliet, J., 2006. Impact of wind on the spatial distribution of rain over micro-scale topography: numerical modelling and experimental verification. Hydrological Processes 20, 345–368.

Blume, H.-P., Brümmer, G.W., Horn, R., Kandeler, E., Kögel-Knabner, I., Kretzschmar, R., Stahr, K., Wilke, B.-M., 2010. Scheffer/Schachtschabel: Lehrbuch der Bodenkunde, 16th ed. Spektrum Akademischer Verlag, Heidelberg.

Bork, H., 1988. Bodenerosion und Umwelt-Verlauf und Folgen der mittelalterlichen und neuzeitlichen Bodenerosion. Landschaftsgenese und Landschaftsökologie 13, Braunschweig.

Breshears, D.D., Whicker, J.J., Johansen, M.P., Pinder, J.E., 2003. Wind and water erosion and transport in semi-arid shrubland, grassland and forest ecosystems: quantifying dominance of horizontal wind-driven transport. Earth Surface Processes and Landforms 28, 1189–1209.

Brevik, E.C., Cerdà, A., Mataix-Solera, J., Pereg, L., Quinton, J.N., Six, J., Van Oost, K., 2015. The interdisciplinary nature of SOIL. SOIL 1, 117–129.

Brodie, I., Rosewell, C., 2007. Theoretical relationships between rainfall intensity and kinetic energy variants associated with stormwater particle washoff. Journal of Hydrology 340, 40–47.

Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32, 385–415.

Bullard, J.E., McTainsh, G.H., 2003. Aeolian-fluvial interactions in dryland environments: examples, concepts and Australia case study. Progress in Physical Geography 27, 471–501.

Cammeraat, E.L.H., 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. Agriculture, Ecosystems & Environment, 104, 317–332.

Cappelle, A., Lüders, R., 1981. Erfassung und Beurteilung der Erosionsgefährdung des Bodens durch Wind anhand bodenkundlicher und meteorologischer Parameter.—Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 30, 307–317.

Chepil, W., 1945. Dynamics of wind erosion: I. Nature of movement of soil by wind. Soil Science 60, 305.

Chepil, W.S., 1956. Influence of Moisture on Erodibility of Soil by Wind. Soil Science Society of America Journal 20, 288–292.

Cooke, R.U., Warren, A., Goudie, A., 1993. Desert geomorphology. CRC, London.

Cornelis, W.M., Gabriels, D., 2003. The effect of surface moisture on the entrainment of dune sand by wind: an evaluation of selected models. Sedimentology 50, 771–790.

Cornelis, W.M., Oltenfreiter, G., Gabriels, D., Hartmann, R., 2004. Splash-saltation of sand due to wind-driven rain: vertical deposition flux and sediment transport rate. Soil Science Society of America Journal 68, 32–40.

de Lima, M.I.P. de, Santo, F.E., Ramos, A.M., Trigo, R.M., 2015. Trends and correlations in annual extreme precipitation indices for mainland Portugal, 1941–2007. Theoretical Applied Climatology 119, 55–75.

de Lima, J.L.M.P., 1990. The effect of oblique rain on inclined surfaces: A nomograph for the rain-gauge correction factor. Journal of Hydrology 115, 407–412.

de Lima, J.L.M.P., 1989. Raindrop splash anisotropy: Slope, wind and overland flow velocity effects. Soil Technology 2, 71–78.

de Lima, J.L.M.P., van Dijk, P.M., Spaan, W.P., 1992. Splash-saltation transport under wind-driven rain. Soil Technology 5, 151–166.

de Lima, M.I.P., Santo, F.E., Ramos, A.M., de Lima, J.L.M.P., 2013. Recent changes in daily precipitation and surface air temperature extremes in mainland Portugal, in the period 1941–2007. Atmospheric Research 127, 195–209.

de Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. Earth-Science Reviews 71, 95–125.

de Vente, J., Poesen, J., Arabkhedri, M., Verstraeten, G., 2007. The sediment delivery problem revisited. Progress in Physical Geography 31, 155–178.

de Vente, J., Poesen, J., Verstraeten, G., Van Rompaey, A., Govers, G., 2008. Spatially distributed modelling of soil erosion and sediment yield at regional scales in Spain. Global and Planetary Change 60, 393–415.

Disrud, L.A., Lyles, L., Skidmore, E., 1969. How wind affects the size and shape of raindrops. Agricultural Engineering 50, 617.

Dunne, T., Malmon, D.V., Dunne, K.B.J., 2016. Limits on the morphogenetic role of rain splash transport in hillslope evolution. Journal of Geophysical Research: Earth Surface 121, 2015JF003737.

Dunne, T., Malmon, D.V., Mudd, S.M., 2010. A rain splash transport equation assimilating field and laboratory measurements. Journal of Geophysical Research 115, F01001.

Duttmann, R., 2001. Bodenfeuchte als Steuergröße der Bodenerosion. Geographische Rundschau 53, 24–32.

Düwel, O., Schäfer, W., Kuntze, H., 1994. Der Einfluß der Bodenrauhigkeit auf den Sedimenttransport durch Wind. Mitteilungen der Deutschen Bodenkundlichen Gesellschaft 74, 85–88.

Erpul, G., Gabriels, D., Janssens, D., 2000. Effect of wind on size and energy of small simulated raindrops : A wind tunnel study. International Agrophysics 14, 1–7.

Erpul, G., Gabriels, D., Norton, L.D., Flanagan, D., Huang, C., Visser, S.M., 2011. Interactions between raindrop impact and shallow interrill flow under wind-driven rain, in: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment- Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 9–18.

Fécan, F., Marticorena, B., Bergametti, G., 1999. Parametrization of the increase of the aeolian erosion threshold wind friction velocity due to soil moisture for arid and semi-arid areas. Annales Geophysicae 17, 149–157.

Field, J.P., Breshears, D.D., Whicker, J.J., 2009. Toward a more holistic perspective of soil erosion: Why aeolian research needs to explicitly consider fluvial processes and interactions. Aeolian Research 1, 9–17.

Fiener, P., Seibert, S.P., Auerswald, K., 2011. A compilation and meta-analysis of rainfall simulation data on arable soils. Journal of Hydrology 409, 395–406.

Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.-G., 2012. A portable wind and rainfall simulator for in situ soil erosion measurements. Catena 91, 72–84.

Fister, W., Iserloh, T., Ries, J.B., Schmidt, R.G., 2011. Comparison of rainfall characteristics of a small portable rainfall simulator and a portable wind and rainfall simulator. Zeitschrift für Geomorphologie 55, 109–126.

Fister, W., Schmidt, R.-G., 2008. Concept of a single device for simultaneous simulation of wind and water erosion in the field., in: Gabriels, D., Cornelis, W. (Eds.), Proceedings of Conference on Desertification. Gent, Belgium, pp. 106–113.

Funk, R., Frielinghaus, M., 1998. Winderosion, in: Blume, H.P. (Ed.), Handbuch der Bodenkunde. Berlin, pp. 1–22.

Furbish, D.J., Hamner, K.K., Schmeeckle, M., Borosund, M.N., Mudd, S.M., 2007. Rain splash of dry sand revealed by high-speed imaging and sticky paper splash targets. Journal of Geophysical Research 112, F01001.

Furbish, D.J., Fathel, S.L., Schmeeckle, M.W., Jerolmack, D.J., Schumer, R., 2017. The elements and richness of particle diffusion during sediment transport at small timescales. Earth Surface Processes and Landforms 42, 214–237.

Gillette, D.A., Adams, J., Endo, A., Smith, D., Kihl, R., 1980. Threshold Velocities for Input of Soil Particles Into the Air by Desert Soils. Journal of Geophysical Research 85, 5621–5630.

Govers, G., Poesen, J., 1988. Assessment of the interrill and rill contributions to total soil loss from an upland field plot. Geomorphology 1, 343–354.

Guy, B., Dickinson, W., Rudra, R., 1987. The roles of rainfall and runoff in the sediment transport capacity of interrill flow. Transactions of the ASAE 30, 1378–1387.

Hassenpflug, W., 1998. Bodenerosion durch Wind., in: Richter, G. (Ed.), Bodenerosion Analyse und Bilanz eines Umweltproblems. Wissenschaftliche Buchgesellschaft, Darmstadt, pp. 69–82.

Holcombe, T.L., Ley, T., Gillette, D.A., 1997. Effects of Prior Precipitation and Source Area Characteristics on Threshold Wind Velocities for Blowing Dust Episodes, Sonoran Desert 1948–78. Journal of Applied Meteorology 36, 1160–1175.

Iserloh, T., Fister, W., Marzen, M., Seeger, M., Kuhn, N.J., Ries, J.B., 2013. The role of wind-driven rain for soil erosion – an experimental approach. Zeitschrift für Geomorphologie, Supplementary Issues 57, 193–201.

Iserloh, T., Ries, J.B., Arnáez, J., Boix-Fayos, C., Butzen, V., Cerdà, A., Echeverría, M.T., Fernández-Gálvez, J., Fister, W., Geißler, C., Gómez, J.A., Gómez-Macpherson, H., Kuhn, N.J., Lázaro, R., León, F.J., Martínez-Mena, M., Martínez-Murillo, J.F., Marzen, M., Mingorance, M.D., Ortigosa, L., Peters, P., Regüés, D., Ruiz-Sinoga, J.D., Scholten, T., Seeger, M., Solé-Benet, A., Wengel, R., Wirtz, S., 2013. European small portable rainfall simulators: A comparison of rainfall characteristics. Catena 110, 100–112.

Jiongxin, X., 2000. The wind-water two-phase erosion and sediment-producing processes in the middle Yellow River Basin, China. Science in China, Series D 43, 176–186.

Kinnell, P., 2005. Raindrop-impact-induced erosion processes and prediction: a review. Hydrological Processes 19, 2815–2844.

Kovats, R.S., Valentini, R., Bouwer, L.M., Georgopoulou, E., Jacob, D., Martin, E., Rounsevell, M., Soussana, J.-F., 2014. Europe, in: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1267–1326.

Kuhn, N.J., Greenwood, P., Fister, W., 2014. Chapter 5.1 - Use of Field Experiments in Soil Erosion Research, in: Thornbush, M.J., Allen, C.D., Fitzpatrick, F.A. (Eds.), Geomorphological Fieldwork. Elsevier, Amsterdam, pp. 175–200.

Lal, R., Lawson, T.L., Anastase, A.H., 1980. Erosivity of tropical rains, in: De Boodt, M., Gabriels, D. (Eds.), Assessment of Erosion. Wiley, Chichester, pp. 143–151.

Lal, R., 1990. Erosion measurement and evaluation, in: Lal, R. (Ed.), Soil Erosion in the Tropics: Principles and Management. McGraw Hill, New York, pp. 183–223.

Le Bissonnais, Y., 1996. Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. European Journal of Soil Science 47, 425–437.

Legout, C., Leguédois, S., Le Bissonnais, Y., Malam Issa, O., 2005. Splash distance and size distributions for various soils. Geoderma 124, 279–292.

Leguédois, S., Planchon, O., Legout, C., Bissonnais, Y.L., 2005. Splash projection distance for aggregated soils: Theory and experiment. Soil Science Society of America Journal 69, 30–37.

Marzen, M., Iserloh, T., Casper, M.C., Ries, J.B., 2015. Quantification of particle detachment by rain splash and wind-driven rain splash. Catena 127, 135–141.

Marzen, M., Iserloh, T., de Lima, J.L.M.P., Ries, J.B., 2016. The effect of rain, wind-driven rain and wind on particle transport under controlled laboratory conditions. Catena 145, 47–55.

Mc Tainsh, G.H., Rose, C.W., Okzach, G.E., Paris, R.G., 1992. Water and wind erosion: similarities and differences, in: Hurni, H., Tarlo, K. (Eds.), Erosion: Conservation and Small Catchment Scale Farming. Marceline, Missouri, USA, pp. 109–119.

Morgan, R.P.C., 2005. Soil erosion and conservation, 3rd ed. Wiley-Blackwell, Maiden, Oxford, Carlton.

Moss, A., Green, P., 1983. Movement of solids in air and water by raindrop impact. effects of drop-size and water-depth variations. Soil Research 21, 257–269.

Mutchler, C.K., Larson, C.L., 1971. Splash Amounts from Waterdrop Impact on a Smooth Surface. Water Resources Research 7, 195–200.

Nearing, M.A., Pruski, F.F., O’Neal, M.R., 2004. Expected climate change impacts on soil erosion rates: A review. Journal of Soil and Water Conservation 59, 43–50.

Nissen, K.M., Leckebusch, G.C., Pinto, J.G., Ulbrich, U., 2014. Mediterranean cyclones and windstorms in a changing climate. Regional Environmental Change 14, 1873–1890.

Offer, Z.Y., Goossens, D., 2001. Ten years of aeolian dust dynamics in a desert region (Negev desert, Israel): analysis of airborne dust concentration, dust accumulation and the high-magnitude dust events. Journal of Arid Environments 47, 211–249.

Offer, Z.Y., Goossens, D., Shachak, M., 1992. Aeolian deposition of nitrogen to sandy and loessial ecosystems in the Negev Desert. Journal of Arid Environments 23, 355–363.

Paola, C., Straub, K., Mohrig, D., Reinhardt, L., 2009. The “unreasonable effectiveness” of stratigraphic and geomorphic experiments. Earth-Science Reviews 97, 1–43.

Planchon, O., Esteves, M., Silvera, N., Lapetite, J.-M., 2000. Raindrop erosion of tillage induced microrelief: possible use of the diffusion equation. Soil and Tillage Research 56, 131–144.

Poesen, J., Savat, J., 1981. Detachment and transportation of loose sediments by raindrop splash: Part II Detachability and transport ability measurements. Catena 8, 19–41.

Poesen, J.W., Boardman, J., Wilcox, B., Valentin, C., 1996. Water erosion monitoring and experimentation for global change studies. Journal of Soil and Water Conservation 51, 386–390.

Richter, G., 1965. Bodenerosion: Schäden und gefährdete Gebiete in der Bundesrepublik Deutschland, Forschungen zur deutschen Landeskunde. Bundesanstalt für Landeskunde und Raumforschung, Selbstrverlag, Bad Godesberg.

Richter, G., Negendank, J.F.W., 1977. Soil erosion processes and their measurement in the German area of the Moselle river. Earth Surface Processes 2, 261–278.

Ries, J., Langer, M., Rehberg, C., 2000. Experimental investigations on water and wind erosion on abandoned fields and arable land in the central Ebro Basin, Aragon, Spain. Zeitschrift für Geomorphologie, Supplementary Issues 121, 91–108.

Ries, J.B., 2011. Bodenerosion, in: Gebhardt, H., Glaser, R., Radtke, U., Reuber, P. (Eds.), Geographie- Physische Geographie Und Humangeographie. Spektrum, Heidelberg, pp. 506–515.

Ries, J.B., Iserloh, T., Seeger, M., Gabriels, D., 2013. Rainfall simulations – constraints, needs and challenges for a future use in soil erosion research. Zeitschrift für Geomorphologie, Supplementary Issues 57, 1–10.

Riezebos, H.T., Epema, G.F., 1985. Drop shape and erosivity part II: Splash detachment, transport and erosivity indices. Earth Surface Processes and Landforms 10, 69–74.

Rodrigo Comino, J., Iserloh, T., Lassu, T., Cerdà, A., Keestra, S.D., Prosdocimi, M., Brings, C., Marzen, M., Ramos, M.C., Senciales, J.M., Ruiz Sinoga, J.D., Seeger, M., Ries, J.B., 2016. Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. Science of the Total Environment 565, 1165–1174.

Roth, C.H., 1995. Physikalische Ursachen der Wassererosion, in: Blume, H.P., Felix-Henningsen, P., Fischer, W.R., Frede, H.-G., Guggenberger, G., Horn, R., Stahr, K. (Eds.), Handbuch der Bodenkunde. Wiley-VCH, Weinheim, p. 3584.

Roth, C.H., 1992. Die Bedeutung der Oberflächenverschlämmung für die Auslösung von Abfluss und Abtrag. Technische Universität Berlin.

Samray, H., Erpul, G., Gabriels, D., 2011. Raindrop detachment and raindrop-induced flow transport (RD-RIFT) under different fall trajectories of wind-driven raindrops, in: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment- Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 9–18.

Santo, F.E., Ramos, A.M., Lima, M.I.P. de, Trigo, R.M., 2014. Seasonal changes in daily precipitation extremes in mainland Portugal from 1941 to 2007. Regional Environmental Change 14, 1765–1788.

Sharon, D., 1980. The distribution of hydrologically effective rainfall incident on sloping ground. Journal of Hydrology 46, 165–188.

Stroosnijder, L., 2005. Measurement of erosion: Is it possible? Catena 64, 162–173.

Torri, D., Sfalanga, M., Chisci, G., 1987. Threshold conditions for incipient rilling. Catena Supplement 8, 97–105.

Toy, T.J., Foster, G.R., Renard, K.G., 2002. Soil erosion: processes, predicition, measurement, and control. Wiley New York 338 pp.

Umback, C., Lembke, W., 1966. Effects of wind on falling water drops. Trans. ASAE 9, 805–808.

Valentin, C., 1996. Soil erosion under global change, in: Walker, B., Steffen, W. (Eds.), Global Change and Terrestrial Ecosystems, International Geosphere-Biosphere Programme Book Series. pp. 317–340.

van Dijk, A.I.J.M., Bruijnzeel, L.A., Rosewell, C.J., 2002a. Rainfall intensity–kinetic energy relationships: a critical literature appraisal. Journal of Hydrology 261, 1–23.

van Dijk, A.I.J.M., Meesters, A.G.C.A., Bruijnzeel, L.A., 2002b. Exponential Distribution Theory and the Interpretation of Splash Detachment and Transport Experiments. Soil Science Society of America Journal 66, 1466.

van Dijk, P.M., Stroosnijder, L., de Lima, J.L.M.P., 1996. The influence of rainfall on transport of beach sand by wind. Earth Surface Processes and Landforms 21, 341–352.

van Heerden, W.M., 1964. Splash erosion as affected by the angle of incidence of raindrop impact. Purdue University, Lafayette, USA.

Visser, S.M., Erpul, G., Gabriels, D., Flanagan, D., Huang, C., Norton, L.D., Stroosnijder, L., 2011. Evaluation of interrill erosion under wind-driven rain evants in northern Burkina

Faso, in: Vermang, J., Gabriels, D., Cornelis, W.M., De Boever, M. (Eds.), Land Degradation Processes and Assessment- Wind Erosion, Interrill Erosion, Gully Erosion, Land Cover Features. UNESCO Chair of Eremology, Ghent, Belgien, pp. 25–31.

Visser, S.M., Sterk, G., 2007. Nutrient dynamics—wind and water erosion at the village scale in the Sahel. Land Degradation & Development 18, 578–588.

Visser, S.M., Sterk, G., Ribolzi, O., 2004. Techniques for simultaneous quantification of wind and water erosion in semi-arid regions. Journal of Arid Environments 59, 699–717.

Wainwright, J., Parsons, A.J., Cooper, J.R., Gao, P., Gillies, J.A., Mao, L., Orford, J.D., Knight, P.G., 2015. The concept of transport capacity in geomorphology. Reviews of Geophysics 53, 1155–1202.

Wiggs, G., Baird, A., Atherton, R., 2004. The dynamic effects of moisture on the entrainment and transport of sand by wind. Geomorphology 59, 13–30.

Wirtz, S., Iserloh, T., Rock, G., Hansen, R., Marzen, M., Seeger, M., Betz, S., Remke, A., Wengel, R., Butzen, V., Ries, J.B., 2012. Soil Erosion on Abandoned Land in Andalusia: A Comparison of Interrill- and Rill Erosion Rates. ISRN Soil Science 2012, 1–16.

Wright, A.C., 1986. A physically-based model of the dispersion of splash droplets ejected from a water drop impact. Earth Surface Processes and Landforms 11, 351–367.

Yoon, Y.N., Wenzel, H.G., 1971. Mechanics of sheet flow under simulated rainfall. Journal of Hydraulics Division ASCE 97, 1367–1386.

Curriculum vitae

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School education:

08/2004	State-certified educator
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8/2000 - 7/2004	Leo-Sympher-Berufskolleg
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University education:

Since 01/2012	PhD Student at Trier University
10/2005 – 11/2011	Diploma-study of Applied Biogeography at Trier University Examination subjects: Biogeography, Soil Science, Physical Geography, Geobotany Diploma thesis: „Experimentelle Untersuchungen mit dem mobilen kombinierten Wind- Regenkanal (WiReKa) zur Erforschung von Bodenerosion durch windbeeinflussten Regen“ (in German)

Professional experience:

03/2014 – 2/2017	Research associate at the Department of Physical Geography (DFG-funded), Trier University [maternity leave & parental leave: 08/2015 - 05/2016 and 10/2016 – 11/2016]
10/2014 – 12/2014	Visiting researcher at the University of Coimbra (Dpt. of Civil Engineering)
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Publications (peer reviewed):

Marzen, M. & Iserloh, T. & De Lima, J.L.M.P. & Fister, W. & Ries, J.B. (2017): Impact of severe rain storms on soil erosion: Experimental evaluation of wind-driven rain and its implications for natural hazard management. Science of the Total Environment 590-591, 502-513.

Marzen, M. & Iserloh, T. & De Lima, J.L.M.P. & RIES, J.B. (2016): The effect of rain, wind-driven rain and wind on particle transport under controlled laboratory conditions. Catena 145, 47-55.

Rodrigo Comino, J. & Iserloh, T. & Lassu, T. & Cerdà, A. & Keesstra, S. & Prosdocimi, M. & Brings, C. & ***Marzen, M.*** & Ramos, M.C. & Senciales, J.M. & Ruiz Sinoga, J.D. & Seeger, M. & RIES, J.B. (2016): Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. Science of the Total Environment 565, 1165-1174.

Marzen, M. & Iserloh, T. & Casper, M.C. & Ries, J.B. (2015): Quantification of particle detachment by rain splash and wind-driven rain splash. Catena 127, 135-141.

Ries, J.B. & ***Marzen, M.*** & Iserloh, T. & Fister, W. (2014): Soil erosion in Mediterranean landscapes - Experimental investigation on crusted surfaces by means of the Portable Wind and Rainfall Simulator. Journal of Arid Environments 100-101, 42-51.

Iserloh, T. & Ries, J.B. & Arnáez, J. & Boix-Fayos, C. & Butzen, V. & Cerdà, A. & Echeverría, M.T. & Fernández-Gálvez, J. & Fister, W. & Geißler, C. & Gómez, J.A. & Gómez-Macpherson, H. & Kuhn, N.J. & Lázaro, R. & León, F.J. & Martínez-Mena, M. & Martínez-Murillo, J.F. & ***Marzen, M.*** & Mingorance, M.D. & Ortigosa, L. & Peters, P. & Regüés, D. & Ruiz-Sinoga, J.D. & Scholten, T. & Seeger, M. & Solé-Benet, A. & Wengel, R. & Wirtz, S. (2013): European small portable rainfall simulators: a comparison of rainfall characteristics. Catena 110, 100-112.

Iserloh, T. & Fister, W. & ***Marzen, M.*** & Seeger, M. & Kuhn, N.J. & Ries, J.B. (2013): The role of wind-driven rain for soil erosion – an experimental approach. Zeitschrift für Geomorphologie 57(1), 193-201.

Wirtz, S. & Iserloh, T. & Rock, G. & Hansen, R. & ***Marzen, M.*** & Seeger, M. & Betz, S. & Remke, A. & Wengel, R. & Butzen, V. & Ries, J.B. (2012): Soil erosion on abandoned land in Andalusia – a comparison of interrill- and rill erosion rates. ISRN Soil science, Volume 2012, Article ID 730870, 16 pages; DOI: 10.5402/2012/730870.

Publications (non peer-reviewed publications, conference presentations):

Fister, W. & Tresch, S. & ***Marzen, M.*** & Iserloh, T. (2017): Calculation of total runoff and sediment yield from aliquot sampling in rainfall experiments. Geophysical Research Abstracts, Vol. 19, EGU2017-18223.

Marzen, M. & Iserloh, T. & De Lima, J.L.M.P. & Fister, W. & Ries, J.B. (2017): Wind-driven rain and its implications for natural hazard management. Geophysical Research Abstracts, Vol. 19, EGU2017-9526.

Marzen, M. & Iserloh, T. & de Lima, J.L.M.P. & Ries, J.B. (2016): Wichtige Faktoren der Erosion durch Tropfenschlag (Splash) mit und ohne Windeinfluss. Oral at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 06.-07.10.2016, Jena, Germany.

Rodrigo Comino, J. & Iserloh, T. & Lassu, T. & Cerdà, A. & Keesstra, S. & Prosdocimi, M. & Brings, C. & ***Marzen, M.*** & Ramos, M.C. & Senciales, J.M. & Ruiz Sinoga, J.D. & Seeger, M. & Ries, J.B. (2016): Vergleich von Erosionsanfälligkeit und Oberflächenabflussentstehung in spanischen und deutschen Weinbergen. Poster at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 06.-07.10.2016, Jena, Germany.

Iserloh, T. & Peter, K.D. & Fister, W. & Wirtz, S. & Butzen, V. & Brings, C. & ***Marzen, M.*** & Casper, M.C. & Seeger, M. & RIES, J.B. (2015): Rainfall simulation experiments with a small portable rainfall simulator: research on runoff generation and soil erosion. Geophysical Research Abstracts, Vol. 17, EGU2015-15608.

Marzen, M. & Iserloh, T. & de Lima, J.L.M.P. & RIES, J.B. (2015): Particle transport patterns of short-distance soil erosion by wind-driven rain, rain and wind. Geophysical Research Abstracts, Vol. 17, EGU2015-6075. Also presented at 9th International Workshop of Young Geomorphologists, 8.05.-10.05.2015, Heimbach-Hergarten, Germany. Also presented at Desertland Conference", 16.06.-17.06.2015, Gent, Belgium.

Marzen, M. & Iserloh, T. & de Lima, J.L.M.P. & RIES, J.B. (2015): Initialer Partikeltransport über kurze Distanzen durch windbeeinflussten Regen, Regen und Wind. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 03.-04.10.2015, Berlin, Germany.

Marzen, M. & Iserloh, T. & RIES, J.B. (2015): Theoretische und praktische Aspekte der modernen experimentellen Geomorphologie am Beispiel „Regentropfenerosion“: von der Entwicklung der Fragestellung bis zur Interpretation der Ergebnisse. Oral at Deutscher Kongress für Geographie, Session " DI-FS-19: Beobachten, forschen, abstrahieren – und zurück: Geomorphologisches Experimentieren in Schule und Hochschule ", 01.-06.10.2015, Berlin, Germany.

Tresch, S. & Fister, W. & ***Marzen, M.*** & Kuhn, N.J. (2015): Comparison of different methods to calculate total runoff and sediment yield based on aliquot sampling from rainfall simulations. Geophysical Research Abstracts, Vol. 17, EGU2015-15642.

Fister, W. & ***Marzen, M.*** & Iserloh, T. & Seeger, M. & Heckrath, G. & Greenwood, P. & Kuhn, N.J. & Ries, J.B. (2014): Die Bedeutung von windbeschleunigtem Regen für die zukünftige Bodenerosionsforschung. Oral at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 02.10.-04.10.2014, Kiel.

Fister, W. & ***Marzen, M.*** & Iserloh, T. & Seeger, M. & Heckrath, G. & Greenwood, P. & Kuhn, N.J. & Ries, J.B. (2014): The relevance of wind-driven rain for future soil erosion research. Geophysical Research Abstracts, Vol. 16, EGU2014-12859.

Marzen, M. & Iserloh, T. & Fister, W. & Brings, C. & Seeger, M. & Ries, J.B. (2014): Experimentelle Erfassung von Bodenerosion durch wind-driven rain: eine Studie auf landwirtschaftlichen Nutzflächen in Nordspanien. Oral at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 02.10.-04.10.2014, Kiel.

Marzen, M. & Iserloh, T. & Brings, C. & Fister, W. & Seeger, M. & Ries, J.B. (2014): Experimental wind-driven rain erosion study on agricultural soils. Geophysical Research Abstracts, Vol. 16, EGU2014-8424.

Seeger, M. & Gronz, O. & Klaes, B. & Becker, K. & ***Marzen, M.*** & Remke, A. (2014): The effect of object characteristics and image quality on 3D-modelling by Structure-from-Motion. Geophysical Research Abstracts, Vol. 16, EGU2014-7293.

Fister, W. & Iserloh, T. & ***Marzen, M.*** & Seeger, M. & Kuhn, N.J. & Heckrath, G. & Ries, J.B. (2013): Variability of the wind-driven rain effect on soil erosion in different landscapes. Geophysical Research Abstracts, Vol. 15, EGU2013-14109.

Ries, J.B. & Becker, K. & Bielen, R. & Brings, C. & Butzen, V. & Iserloh, T. & ***Marzen, M.*** & Peter, K.D. & Remke, A. & Schimpchen, J. & Seeger, M. & Tumbrink, J. & Wengel, R., Wilms, T. & Wirtz, S. (2013): Feldmethoden zur Quantifizierung aktueller Bodenerosionsprozesse. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 07.10.-09.10.2013, Eichstätt.

Seeger, M. & Gronz, O. & ***Marzen, M.***, Beiske, J. & Remke, A. & Ries, J.B. (2013): Bestimmung der Oberflächenrauheit mittels fotographischer Bildauswertung und Radarsignalen. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 07.10.-09.10.2013, Eichstätt.

Fister, W. & Iserloh, T. & ***Marzen, M.*** & Seeger, M. & Kuhn, N.J. & Heckrath, G. & Schmidt, R.-G. & Ries, J.B. (2012): Soil erosion rates by wind-driven rain on soils with different soil conditions and slope angle. Oral at Eurosoil 2012, Session 03.02: "Soil erosion and degradation on agriculture land", 02.-06.07.2012, Bari, Italien.

Marzen, M. & Iserloh, T. & Seeger, M. & Ries, J.B. (2012): Quantification of Splash and Splash-Saltation. Geophysical Research Abstracts, Vol. 14, EGU2012-6246. *(also as presentation at "4. Conference on Desertification and Land Degradation. UNESCO Chair on Eremology, 19 June 2012, Ghent, Belgium.)*

Wirtz, S. & Iserloh, T. & Rock, G. & Hansen, R. & ***Marzen, M.*** & Seeger, M. & Betz, S. & Remke, A. & Wengel, R. & Butzen, V. & Ries, J.B. (2012): Bodenerosion auf einer Brachfläche in Andalusien – ein Vergleich von Rinnenerosion und flächenhafter Erosion. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 10.10.-13.10.2012, Freising.

Iserloh, T. & Fister, W. & ***Marzen, M.*** & Seeger, M. & Ries, J.B. (2011): Der Einfluss von windbeschleunigtem Regen auf Erosionsraten. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 28.09.-01.10.2011, Leipzig.

Marzen, M. & Iserloh, T. & Ries, J.B. (2011): Experiment zur Quantifizierung von Splash und Splash-Saltation. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 28.09.-01.10.2011, Leipzig.

Fister, W. & Iserloh, T. & ***Marzen, M.*** & Seeger, M. & Schmidt, R.-G. & Ries, J.B. (2011): Experimental investigation of in situ soil erosion rates by wind-driven rain. Presentation at Rainfall Simulator Workshop, 30.06.-01.07.2011, Trier.

Iserloh, T. & Fister, W. & ***Marzen, M.*** & Seeger, M. & Ries, J.B. (2011): The influence of wind-driven rain on soil detachment rates on homogenous sandy substrate. Geophysical Research Abstracts, Vol. 13, EGU2011-9400.

Fister, W. & Iserloh, T. & ***Marzen, M.*** & Ries, J.B. & Schmidt, R.-G. (2010): Experimental measurement of wind and water erosion in Aragón and Andalusia, Spain. Geophysical Research Abstracts, Vol. 12, EGU2010-12982.

Fister, W. & Ries, J.B. & Iserloh, T. & ***Marzen, M.*** & Schmidt, R.-G. (2010): Erosion by wind, windless rain, and wind-driven rain - Experimental in situ measurements with a portable simulator. Oral at 5th I.A.G./A.I.G. SEDIBUD workshop: Sediment budgets in cold environments, "Qualitative and quantitative analysis of sedimentary fluxes and budgets in changing cold climate environments: Field-based approaches and monitoring, 19.-25.09.2010, Saudarkrokur, Iceland.

Iserloh, T. & Ries, J.B. & Fister, W. & ***Marzen, M.*** (2010): Windbeschleunigter Regen als eine neue Herausforderung für in-situ- Niederschlagssimulationen. Presentation at the annual conference of Deutscher Arbeitskreis für Geomorphologie, 07.-08.10.2010, Frankfurt a.M./Schmitten.

Ries, J.B. & Fister, W. & Iserloh, T. & ***Marzen, M.*** (2010): Wind driven rain as a new challenge for in situ rainfall simulation experiments. Geophysical Research Abstracts, Vol. 12, EGU2010-2747.

Wirtz, S. & Iserloh, T. & Butzen, V. & Wengel, R. & ***Marzen, M.*** & Rock, G. & Seeger, M. & Fister, W. & Ries, J.B. (2010): Method ensemble for quantification of soil erosion processes in the field. Geophysical Research Abstracts, Vol. 12, EGU2010-4013-1.

Iserloh, T. & Fister, W. & ***Marzen, M.*** & Ries, J.B. & Schmidt, R.-G. (2009): Wind and water erosion on abandoned land in High Andalusia - First results of a portable combined wind and rainfall simulator. Geophysical Research Abstracts, Vol. 11, EGU2009-10511.

Declaration / Erklärung

Hiermit erkläre ich, dass mir die derzeitige Promotionsordnung bekannt ist und ich die vorliegende Dissertation selbständig verfasst sowie keine anderen als die angegebenen Quellen und Hilfsmittel verwendet habe. Ergebnisse anderer Beteiligter sowie die inhaltlich und wörtlich aus anderen Werken entnommenen Stellen und Zitate sind als solche kenntlich gemacht. Die vorliegende Dissertation hat in ähnlicher oder gleicher Form noch keiner anderen Prüfungsbehörde vorgelegen oder wurde von dieser als Teil einer Prüfungsleistung angenommen.

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Ort/Datum Miriam Britt Marzen