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Investigations with a field wind tunnel to estimate the wind erosion risk of row crops

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ABSTRACT

Soil protection against wind erosion on arable land has mostly been investigated in the field with plant residues – as practiced in reduced and no-tillage systems or in wind tunnels with artificial roughness elements. Results from growing plants, such as row crops in conventional tillage systems, are rare, despite these fields being the most affected by wind erosion. Wind tunnel investigations were carried out at the field scale on an Arenic Gleysol with sugar beet (*Beta vulgaris*) and maize (*Zea mays*). These crops were chosen because they are the preferred row crops in Germany, and are cultivated predominantly in conventional tillage systems, and represent examples of mono- and dicotyledonous plants. The influence of the plants on wind erosion was calculated as the ratio between the measured soil flux of a plot covered by plants and the soil flux of the same plot without plants (soil flux ratio, R_Q). This ratio was then tested for correlation with vegetative soil cover, silhouette area or dry mass, and row orientation. As a new approach, an empirical vegetation parameter was introduced into a sand transport equation of the form $q = A(u_* - u_{*t})\, u_*^2$, which was used to compare the measured with the modeled soil fluxes.

The results demonstrate the high susceptibility of row crops in conventional tillage systems to wind erosion. The results also show significant differences in erosion rates between mono- and dicotyledonous plants. The row orientation only has influence in the case of sugar beet. To describe the reductive effects of vegetation on the soil fluxes over a wide range of wind velocities, an empirical soil cover parameter can be integrated into a sand transport equation.

1. Introduction

Soil protection against wind erosion on arable land has mostly been investigated with plant residues commonly found in reduced tillage systems or with artificial plants and cover material (Armbrust and Bilbro, 1997; Bilbro and Fryrear, 1985; Hagen, 1996; Hagen and Casada, 2013; Lyles and Allison, 1981; Marshall, 1971; Mendez and Buschiazzo, 2008; Sterk, 2000). A few investigations with live plants have used grass tussocks (Burri et al., 2011; Walter et al., 2012), which can be found scattered at beaches or early succession areas and develop a dense canopy very quickly under regular cultivation conditions. However, most wind erosion in agricultural lands occurs on fields of row crops with conventional tillage systems. In these systems protection against wind erosion is limited by the sparse spacing of the crop. The susceptibility of these fields to wind erosion is enhanced by a smooth, fine-textured soil surface with insufficient soil cover. This condition is caused by the seedbed preparation in combination with the wide distance between the rows, at the time of the highest climatic erosivity in spring. The problem has become more relevant in Germany during the last decade due to the increase in the acreage of maize used for bioenergy from 1.5 to 2.5 million ha (StBA, 2012). The time between sowing, germination, and early stages of plant development for row crops is also when most pesticides are applied. Particularly pre-emergent herbicides have a high risk of being lost (Gaynor and MacTavish, 1981; Larney et al., 1997). Due to wind erosion up to 50% of an agent absorbed by soil particles can be removed by one erosion event (Fritz, 1993). Besides the loss of agents from the field site, the concentrated deposition at the field boundary can induce environmental problems in shelter belts or ditches, and dust contaminated by pesticides can cause serious impacts on human health (Larney et al., 2002).

The effect of soil protection by young plants is caused by the absorption of flow momentum rather than by direct soil coverage (Wolfe and Nickling, 1993). Previous investigations even indicated an increase of wind erosion risk for newly emerged crops or plant residues of low quantities (Morgan and Finney, 1987; Funk, 1995; Sterk, 2000). This effect was explained by an increase of turbulence induced exchange close to the ground, with only a low absorption

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of momentum or local peaks of shear stress. Furthermore, plants react differently from rigid obstacles by being flexible in the air stream, which results in decreasing silhouette areas and changing drag coefficients (Morgan et al., 1988; Funk and Frielinghaus, 1998). Fluttering leaves can also initiate additional release of particles by hitting the surface (Burri et al., 2011).

In contrast to cover material that is randomly distributed, young row crops can affect wind erosion to a very different degree, depending on the row orientation to the wind direction. The planting systems for maize and sugar beet arrange the plants in rows, with a consistent spacing between plants in a row. This spacing is considerably smaller than between the rows, so a different effect should result from this arrangement and changing wind directions.

Measures to prevent or reduce wind erosion without additional efforts in conventional tillage systems are limited. Recommended measures include leaving a rough seedbed and orienting the rows perpendicular to the prevailing wind direction (Liu et al., 2006; Wilson et al., 2013). As soil roughness has been thoroughly investigated, there are only a few studies about the effects of the crop's row orientation on wind erosion (Skidmore et al., 1966; Abtew et al., 1989; Hagen and Armbrust, 1992 Zhang et al., 2004). In these studies the best (perpendicular) and the worst (parallel) cases were predominantly investigated with the assumption that all other orientations would be a gradient in between the two extremes. It can be supposed, that the effect of row orientation will be low at the beginning of the plant development, increase with growth of the plants, and decline again until the crops form a dense canopy. Therefore, the row orientation is of particular importance during the most critical time of plant development. This includes their effect as roughness element influencing the intensity of the wind erosion and the plants themselves, because they are easily damaged by saltating sand particles at that time (Skidmore, 1966; Armbrust, 1984). The protective effect of plants against wind erosion can be expressed by:

- the reduction of the wind speed close to the ground,
- the reduction of eroded/transported soil in comparison to a bare surface,
- the increase of the threshold wind (u_t) or friction velocity (u_{*t}),
- the partition of drag between plants and soil surface,
- the physical cover of the surface from saltating sand grains.

(Armbrust and Bilbro, 1997; Funk and Frielinghaus, 1998; Morgan, 1990; Okin, 2008; Raupach, 1981; Raupach et al., 1993; van de Ven et al., 1989; Walter et al., 2012; Wolfe and Nickling, 1993).

Parameters used to define plant development stages are fresh or dry mass, height, soil cover, leaf area, frontal area, or some combinations of these (Fryrear, 1985; Morgan et al., 1988; van de Ven et al., 1989; Bilbro, 1991). The soil cover is often used because it is easy to determine, enables comparison of different crop types, and has a strong correlation to other morphometric parameters. However, from the perspective of fluid dynamics the soil cover is not practical for plants (Leys, 1991). Parameters like frontal area or lateral cover (also termed as roughness density) are much better suited for wind erosion studies but their determination requires considerable effort. The effects of stems and leaves should be regarded separately because stems are 10 times more effective at depleting the wind energy (Retta and Armbrust, 1995; Skidmore et al., 1994).

A common method for quantifying the effect of plants or residues on wind erosion is the estimation of the ratio between the soil loss or soil flux of a covered plot and the soil loss or flux of a plot without cover by field or wind tunnel experiments (Fryrear, 1985; Armbrust and Bilbro, 1997; Leys, 1991; Sterk, 2000; Maurer et al., 2006). This ratio can be linked to parameters describing cover material like soil cover, silhouette area or plant density (Fryrear, 1985; van de Ven et al., 1989; Mendez and Buschiazzo, 2008; Burri et al., 2011).

Comparisons of adjacent covered and uncovered plots in field experiments are labour-intensive and time-consuming, need a sufficiently large area, depend on the weather conditions, and are therefore relatively unreliable. Investigations in the field with a mobile wind tunnel enable more flexibility with a high rate of replications. A further advantage of these wind tunnel experiments is that secondary effects on the absolute soil loss, such as the influence of soil texture, water content of the soil, aggregates or roughness, can be disregarded if they are kept constant. In stationary wind tunnel experiments, homogenized soil can be used. Whereas in field experiments, constant conditions of the soil material cannot be fully guaranteed. Thus, all affecting parameters should be documented very carefully. The disadvantage is that the soil flux q has an exponential relationship to the friction velocity $u_*(q \approx f(u_*^3))$ and small variations between the initial conditions of the wind tunnel runs can produce great differences in the final results (Greeley and Iversen, 1985). In most cases the soil flux is measured as a mean or sum for a certain time, with a range of wind speeds. Another approach is to simultaneously record the fluxes and the wind speed with a high temporal resolution, which allows a more process related analysis of the results.

Since wind tunnels are closed systems height and width are important parameters influencing the formation of the boundary layer and the transport characteristics (Feng et al., 2009; Owen and Gillette 1985). The height (H) is important for a proper simulation of saltation and is included in the Froude number (Fr) calculation. It indicates a reducing effect of the tunnel height on the saltation flux when $Fr > 20$ (Hagen, 2001; Maurer et al., 2006). The side walls also have an effect and thus soil fluxes are generally measured in the center of the tunnel. That approach is reasonable if the investigated parameter is distributed randomly, such as random roughness or soil coverage by residues, but a regular arrangement can cause preferred paths of the fluxes between the roughness elements and lead to poor results. The flux is also the highest at the center line and total soil losses can be overestimated by using this value without considering the variability over the wind tunnel's width (Dong et al., 2004).

The eroded soil material is usually trapped by active or passive samplers at the end of a measuring section of the wind tunnels. Stationary wind tunnels can be equipped with active isokinetic traps, which were developed for a specific application. In contrast, traps in mobile wind tunnels for passive sampling are already available, such as the BSNE (Big Spring Number Eight) or MWAC (Modified Wilson and Cooke) (Maurer et al., 2006). Both the BSNE and MWAC traps can be used to measure the vertical profile, but they integrate the trapped amount over the collection time. Due to the small inlet opening, it can reasonably be concluded that each sampler measures at a specific point. Another passive trap for field measurements is the SUSTRA (Suspension Sediment Trap, Janssen and Tetzlaff, 1991), which enables the weighing and recording of the trapped amounts with a high temporal resolution of 0.5 Hz. The SUSTRA was developed to measure suspension transport. For this purpose, the device has a relatively large inlet opening with a diameter of 5 cm. This sampler can be regarded as a single measuring point in the suspension height (>50 cm), but in the saltation layer, the inlet opening has to be regarded as a height range instead.

The aim of this study was to estimate the erosion risk for two of the most common row crops in Germany, in conditions as close as possible to the real growing environment. This study also seeks to quantify the effect of row orientation at the most critical time in the plant development and to investigate the influence of vegetation on the soil fluxes. The results of our measurements