Influence of soil type and soil moisture on PM emissions from soils during tillage

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Abstract

Tillage is an important cause of PM emissions from soils. Measurements in rural areas in Germany indicated many times higher fine dust emissions by tillage operations than by wind erosion. The main controlling factor is the soil moisture, or the vertical distribution of moisture in a soil profile at the moment of tillage. As the emission is a result of some parameters which can not be controlled in field experiments, a stepwise analysis of the main influencing factors was chosen. First, a wind tunnel was used as cross-flow gravitational separator to investigate the relation between soil type, soil moisture and PM emission. Twelve soils of different texture (7 sandy, 2 silty, 1 clayey and 2 organic soils) were investigated with regard to their water content, ranging from 0 to 40 mass per cent. The results show that soils can emit dust over a certain range of moisture, but already a small increase in soil moisture causes a distinct reduction of dust emission. The threshold water content for fine dust emission of soils was between 2 to 5 mass per cent for sandy soils, 5 to 10 mass per cent for silty soils, about 30 mass per cent for the clayey soil and 25 to 45 mass per cent for organic soils.

The wind tunnel results were used to calculate the PM10 emission potential of a sandy soil in spring and late summer. In spring only the upper 2.5 cm were dry enough to emit PM10, whereas in summer the soil was desiccated to the entire tillage depth. The calculated PM10 emission potential for a tillage depth of 20 cm resulted in 13.4 g per m^2 for the soil moisture conditions in spring and 76.8 g per m^2 in summer.

Our results show the importance of the vertical soil moisture profile on the PM emission of soils during tillage. So, the emission factors resulting from field operations should preferably be related to the affected amount/volume of a soil, which is dry enough to emit PM, than to the affected area.

Keywords: soil moisture, particulate matter, emission, tillage

Introduction

Fine dust particles seldom emit directly from soil surfaces. They usually need a releasing process as wind erosion or tillage operations (Gillette D. 1977, Green F. H. et al. 1990, Clausnitzer H. et al. 1996, Alfaro S. C. 2001, Kjelgaard et al. 2004). Wind erosion is limited to a certain extent because a susceptible soil surface and a given erosivity of the climate have to coincide. It is temporally restricted to the spring months and constrained spatially by the acreages of root crops, corn and summer cereals, which amount to about 20 per cent of the agricultural land area in Northern Germany (Federal Statistical Office Germany 2006).

Dust emission resulting from tillage operations affects all soils, even those which are considered to be non-erodible. This is mainly caused by higher contents of silt and clay particles, which support the formation of aggregates or crusts. On the other hand these soils have a higher potential for dust emission when they are disturbed by the impact of tillage tools. On the North European plains dust emission induced by tillage was measured as being four to six times higher than the dust emission by wind erosion events (Goossens D. et al. 2001, Goossens D. 2004). The correlations between soil tillage and dust emission have been investigated in many studies, ranging from effects on human health to the effects of losses of fine material on soil fertility and air quality (Louhelainen K. et al. 1987, Clausnitzer H. et al. 1996, Nieuwenhuijsen M. J. et al. 1998, Nieuwenhuijsen M. J. Schenker M. B. 1998, Schenker M. B. 2000, Holmen B. A. et al. 2001a/b, Trzepla-Nabaglo K. et al. 2002, Cassel T. et al. 2003, Goossens D. 2004). Most of these studies contain no or only general information about the soil texture and soil water content, so that is not possible to derive the potential of soils as a source for dust emission from these concentration measurements. The main controlling factor is the soil moisture, or more precisely the vertical distribution of moisture in a soil profile at the moment of tillage. Soil moisture is one of the most important factors which limits wind erosion and therefore dust emission as well (Chepil W. S. 1956, Weinan Ch. et al. 1996). The influence of soil moisture on erodibility has been investigated well in empirical or physically-based studies (ChepilW. S. 1956, Bisal F. et al. 1966, Mc Kenna-Neumann C. et al. 1989, Saleh A. et al. 1995, Weinan Ch. et al., 1996, Cornelis W., Gabriels D. 2003, Cornelis W. et

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al. 2004). In most cases increasing water content results in decreasing wind erosion and dust emissions. Although most of the processes responsible for dust emission of soils are known in detail, there are still some deficits in implementing this knowledge to obtain a more soil-related balance of dust emission caused by tillage. The objective of our study was therefore to derive a soil-related emission factor, which also considers the actual conditions in the field.

Material and Methods

Wind tunnel investigations

The experimental setup in the laboratory was intended to reproduce the basic processes in the field during tillage in a simple and repeatable way. These processes can be described as follows: soil particles will be lifted and accelerated by the action of the tillage tools and the tyres of the tractor into the direction of the operation. Then gravity and the pull of the moving tractor result in a vertical and horizontal component of the separation process depending on size and density of single particles or aggregates and the speed of the tillage tool.

Dust emission measurements took place in the wind tunnel of the Institute of Soil Landscape Research in Müncheberg (Funk R. 2000). The wind tunnel is generally used to investigate wind erosion processes, but it can also be applied as a cross-flow gravitational separator according to standardised particle size analysis by air classification (DIN 66118). A wind tunnel is a suitable tool to carry out a separation in this way because height of fall, sedimentation distance and wind speed can be adjusted to optimise

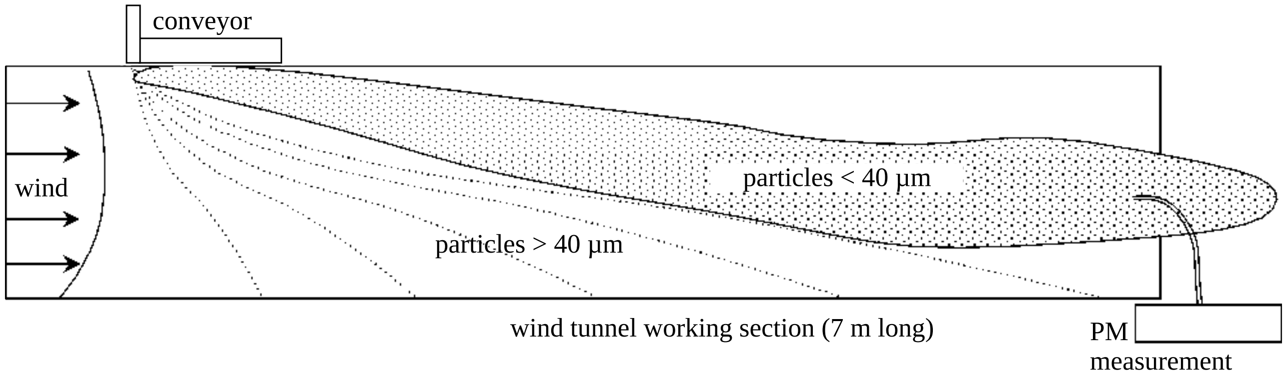

Figure 1:
The experimental setup in the wind tunnel for cross-flow gravitational separation

Table 1:
Soil texture, humus content and water contents of the investigated soils

Site	Code	Sand 2000-63µm %	Silt 63-2µm %	Clay < 2 µm %	Humus %	SWC 60 °C* M%	SWC air-dry** M%
Klockenhagen	KLOC	91.8	7.4	0.8	1.31	0.19	0.61
Siggelkow	SIGG	89.4	8.3	2.3	1.32	0.29	0.66
Gottesgabe	GOGA	87.3	6.9	5.8	1.33	0.15	0.56
Muencheberg	MUEB	82.5	14.1	3.4	0.90	0.23	0.46
Sandhagen	SAHA	81.2	15.7	3.1	1.13	0.21	0.75
Penkow	PENK	73.8	22.4	3.8	1.35	0.25	1.41
Gross Kiesow	GRKI	72.8	24.7	2.5	1.28	0.28	1.04
Hildesheim	HILD	2.1	81.9	16.0	0.94	0.46	1.85
Bad Lauchstedt	BALA	11.0	65.0	24.0		0.75	2.85
Seelow	SEEL	14.3	28.6	57.1	2.18	2.63	4.15
Heinrichswalde	HEIN	74.4	15.0	10.6	23.3	3.33	6.91
Rhinluch	RHIN				40.9	9.86	21.2

* SWC 60 °C – gravimetric soil water content (mass per cent) after 24 hours oven drying at 60 °C

** SWC air-dry – gravimetric soil water content after drying in the laboratory (21°C, 60% rH) the separation process for certain particle sizes. The working section of our wind tunnel has a length of 7 m and a cross section area of 0.7 x 0.7 m. The wind speed in the centre of the tunnel was set to 3 m/s. In contrast to regular tests in the wind tunnel we minimised the boundary layer below 10 cm height and adjusted a more laminar flow.

The soil material was supplied by a conveyor which was placed at the beginning of the working section on top of the wind tunnel (figure 1). A plate, 0.5 cm thick and with a cut-out of 10 x 20 cm, was placed at the conveyor belt. Cut-out and thickness of the plate result in a volume of 100 cm³ which was filled with the soil material, smoothed and covered by a plastic plate to minimise moisture losses during the runs. After starting the conveyor the soil material fell off through a 10 cm wide slot into the working section at a constant rate in 6 minutes.

The soils were taken from the plough-horizon of seven sandy soils, two silt loam soils, two organic soils and one clay soil. The soils were air-dried in an air-conditioned laboratory (temperature: 21 °C, relative humidity: 60 %) and sieved for the fraction less than 2 mm. One part of each soil was dried at 105 °C to obtain the amount of hygroscopic water which had remained in the air-dried soil. Samples of 300 g each was moistened with distilled water. Soil water contents of the following gradations were set: 105 °C dried, 60 °C dried, air-dried and depending on the texture in 6 to 10 further steps of about a half mass per cent up to a distinctly visible moist condition of the sample. The samples were stored in hermetically sealed Erlenmeyer flasks for 24 hours. The next day the soil samples were placed on the conveyor, covered and supplied to the wind tunnel.

The dust fraction was measured with a dust monitor (Grimm #107 Spectrometer), which continuously detects all particles between 0.3 to 30 µm and registers these in three classes as particle mass PM10, PM2.5 and PM1.0 in µg per m³. The threshold water content for dust emission was appointed when, compared with the base load in the wind tunnel, no increase in the PM10 concentration could be measured. Multiple regression calculations were performed using WinStat software (R. Fitch Software).

Field measurements

The field measurements were conducted on loamy sand in Muencheberg (Brandenburg, Germany), which was ploughed under typical moisture conditions, such as in spring and in summer. The field measured 50 m x 50 m. Before tillage, the vertical soil moisture profile was measured in steps of 1 cm at several points by a near Infrared-Reflexion-Photometer (Pier-Electronic GmbH).

For ploughing we used a 100 kW tractor with a 3-share plough and a working width of 1.25 m and a working depth of 0.2 m. The tillage direction was perpendicular to the wind direction (figure 2). The dust monitor (GRIMM #107) was positioned in combination with a meteorological station two meters away from the leeward field boundary with the air inlet at a height of 2 meters. PM10, PM2.5 and PM1.0 were measured every 6 seconds simultaneously with wind speed (cup anemometers in two heights, 2 m and 0.5 m), wind direction, temperature and relative humidity. The aim was to measure only that dust which leaves the field and to get a horizontal intersection of the dust cloud, which was obtained by the repeated passage of the tractor and the increasing distance with any passage.

A Lagrangian dispersion model GRAL (Graz Lagrangian Model) was used to obtain PM area related emission factors from the concentration measurements. GRAL is a well-validated short range numerical model and applicable to a wide range of wind speeds and atmospheric stabilities (Oettl D. et al. 2001). Emission factors of PM were obtained by modelling the dispersion from the test field, treating it as an area source. In the simulations it was assumed that the PM emissions are initially mixed up to 2 m above ground level due to the tractor-induced turbulence (Oettl D. et al. 2005).

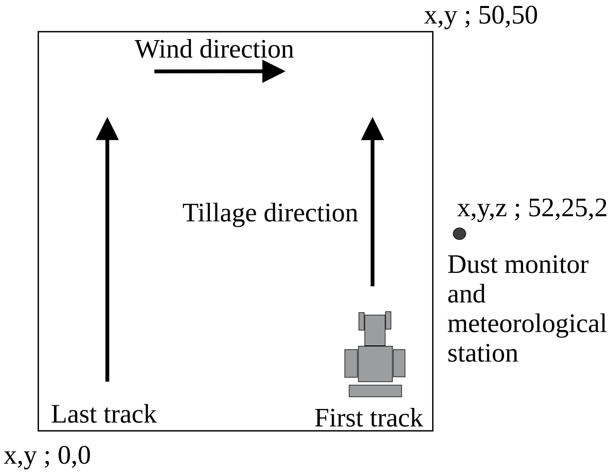

Figure 2:
Sketch of the field measurements of tillage induced PM emissions

Results

Wind tunnel investigations

Our results show that soils can emit particulate matter over a certain range of moisture. Great differences in the PM10 emission were already measured between the 105°C-, 60°C- and air-dried soil samples (figure 3). The water content of the 105°C-dried samples was assumed to be zero, the water contents of the 60°C- and air-dried samples are listed in table 1. Sandy and silt soils had the highest fine dust emission rates of both oven-dried samples and the lowest of the air-dried sample. The clay soil does not show such a difference. The PM10 emission of the oven-dried samples resulted in: sandy > silty > clay, whereas the emission of the air dried samples was: sandy < silty < clay. This opposing trend can be explained by the small contact areas between the particles in the sand and clay fraction in sandy soils, which result in weak bonding forces mostly caused by the adsorptive water between the contact points. Water films resulting from molecular adsorption only appear on particles of the clay size, which are attached to the outside of the sand and silt grains and form a large surface for evaporation (figure 4).

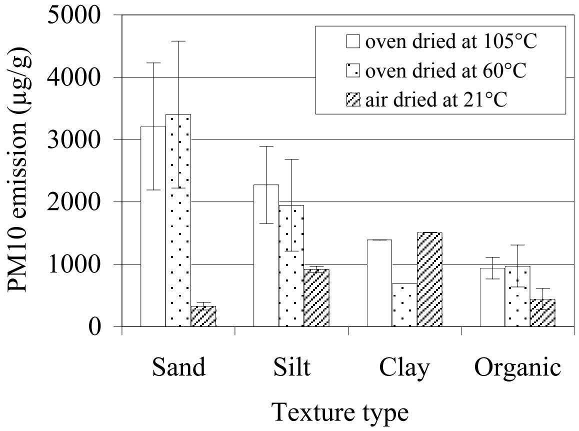

Figure 3:
Dust emission of sandy (n = 7), organic (n = 2), silty (n = 2) and clay (n = 1) soils using different drying intensities (oven dried at 105°C and 60°C, air dried at 21°C)

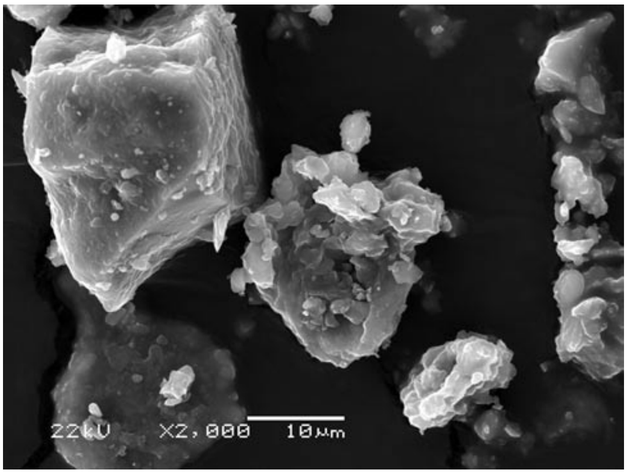

Figure 4:
Scanning electron microscopy of a mineral dust sample

Figure 5 shows the relationship between the PM10 emissions of all investigated soils to the content of particles of this size in the soil. These are all particles in the clay and fine silt fraction (< 6.3 µm in diameter) according to the German Standard for soil texture classification, which are nearest to the PM10 size. The PM10 emission potential of a soil is closely related to the content of these particle sizes.

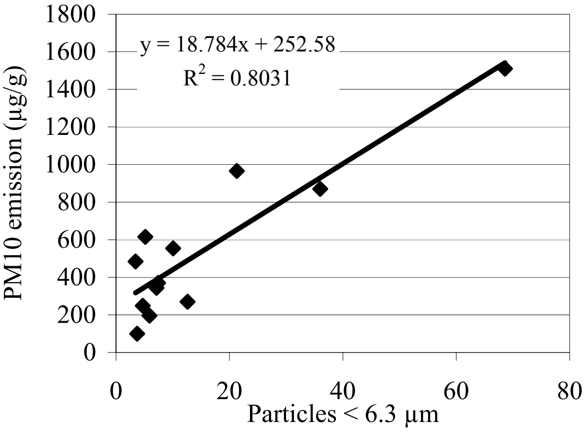

Figure 5:
Relationship between the content of particles < 6.3 µm (clay and fine silt) and the PM10 emission of the air dried samples (all investigated soils)

The relationship between the PM10 emission and the increasing gravimetric water content of the sandy soils is shown in figure 6, that of silt, clay and organic soils in figure 7. The results show the reduction of dust emission with increasing soil moisture. Even small differences in soil moisture caused distinct changes in dust emission, resulting in an exponential curve progression for all soil types. In an attempt to relate the PM emission to soil moisture and parameters of the soil texture and humus content, a multiple regression analysis was performed. Table 2 summarizes the coefficients of the regression equations, which have effected the best r². Above a certain water content no dust was emitted. This can be regarded as the texture related threshold of soil moisture. These threshold values of soil moisture are between 2 to 5 % for sandy soils, 5 to 10 % for silty soils, up to 20 % for the clay soil and 25 to 45 % for organic soils. The share of PM2.5 amounts to about 6 per cent, the portion of PM1.0 to about 1 per cent of the PM10 mass. These relations were relatively constant for all investigated soils and did not change with increasing soil moisture.

Table 2.

Parameter of multiple linear regressions of the form:

ln PM (µgm^{-3}) = a + b SWC (M%) + c silt (%) + d clay (%) + e humus (%), Significance level p = 0.05

Soil textural class		a	b	c	d	e	r²
Sand	ln PM10	7.07	-1.182	0.115		-1.73	0.77
	ln PM2.5	5.35	-0.980	0.070		-2.35	0.54
	ln PM1.0	4.24	-0.955	0.054		-2.48	0.42
Silt + clay	ln PM10	4.95	-0.248		0.068		0.56
	ln PM2.5	2.10	-0.347		0.078		0.55
	ln PM1.0	1.22	-0.363		0.067		0.70
Organic soils	ln PM10	11.32	-0.117			-0.095	0.86
	ln PM2.5	9.67	-0.159			-0.125	0.87
	ln PM1.0	5.03	-0.145			-0.052	0.41

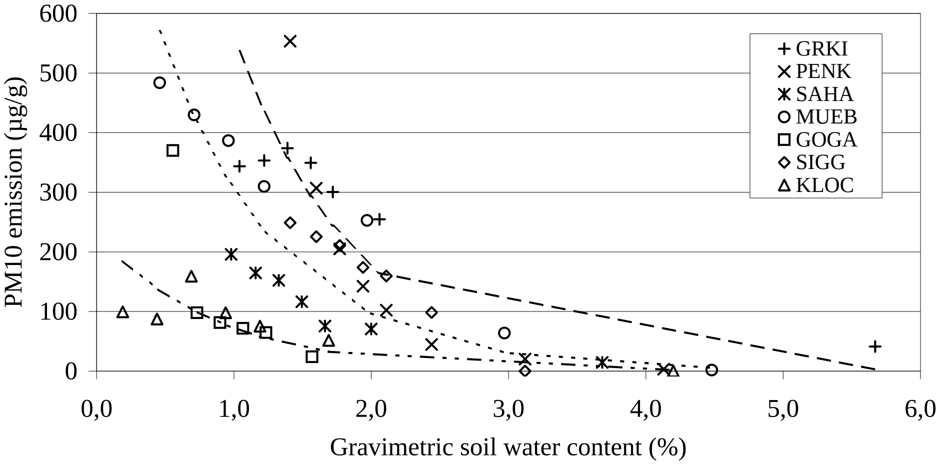

Figure 6:

PM10 emission of all sandy soils, curves are calculated with multiple regression (see table 2), shown curves are examples of GRKI (72.8% sand), MUEB (82.5% sand) and KLOC (91.8% sand)

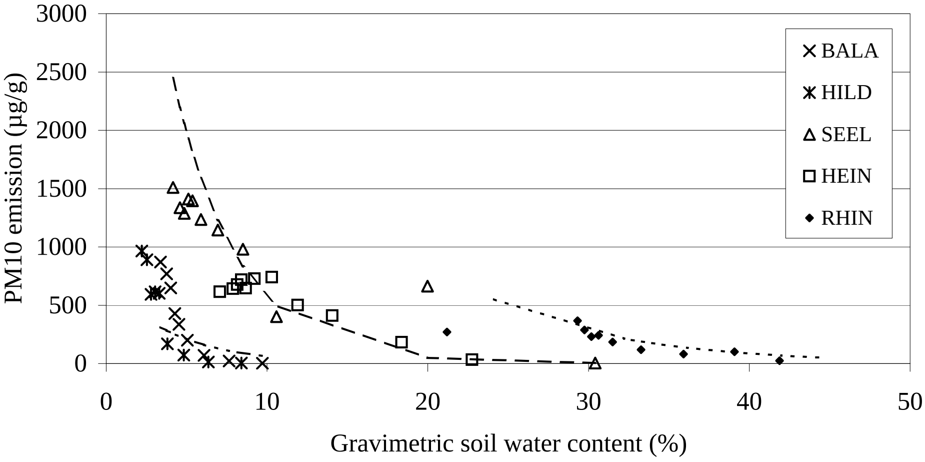

Figure 7:

PM10 emission of all silt, clay and organic soils, curves are calculated with multiple regression (see table 2), shown curves are examples of RHIN (organic soil), SEEL (clay soil) and BALA (silt soil)

Relevance for the derivation of emission factors

The relevance of our results for the derivation of emission factors is demonstrated by field measurements on a sandy soil in Muencheberg, which was ploughed in spring and in summer. The soil texture is given in table 1. The soil moisture of the first centimetre was approximately the same; only the soil moisture depth profile differed at both times and is shown in figure 8.

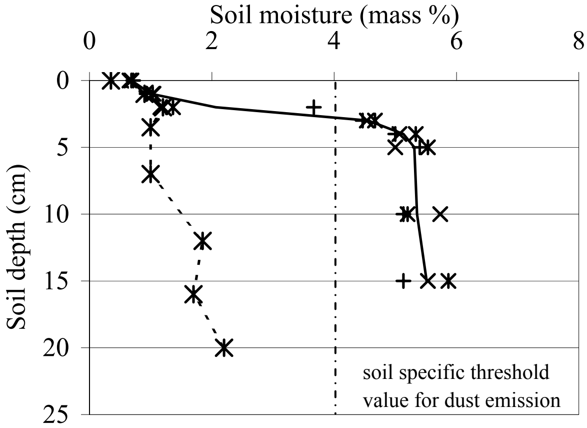

Figure 8:
Soil moisture depth profiles at two dates of ploughing

The soil specific threshold value of moisture for dust emission was estimated as about 4 %. Under the moisture conditions in spring only the uppermost 2.5 cm of the soil are dry enough to contribute to the emission of dust particles. The conditions in summer are characterised by soil moisture below the threshold value for the entire ploughing depth. We derived a PM10 emission potential (EP_{PM10}) of 13.4 g per m² (± 0.8 g) in spring and 76.8 g per m² (± 4.6 g) in summer for a ploughing depth of 20 cm, using the above determined soil moisture – dust emission relationship in steps of 1 cm.

$$EP_{PM10} = \sum_{i=1}^{20} TDE_i \cdot \rho \cdot V$$

with EP_{PM10} - PM10 emission potential (µg per m²)
TDE - total dust emission of the soil related to the water content (µg per g)
ρ - bulk density of the soil (g per cm³)
V - volume of the layer i per m² (10,000 cm³ per m²)

PM measurements and subsequent modelling with the dispersion model GRAL resulted in an emission of 0.12 g per m² of the moist soil in spring and 1.05 g per m² of the dry soil in summer (Oettl et al. 2005). The same tillage operation at the same soil resulted in about 9-times higher emissions in summer mainly induced by the lack of soil moisture. There is a close relationship to the affected volume or mass of the soil contributing to the dust emission, which is 8-times higher in summer (20 cm in summer, 2.5 cm in spring).

Conclusion

Dust emission from tillage operations are closely related to the soil moisture conditions. This aspect has not been considered in previous studies so far. In this study we followed a stepwise analysis of the main influencing factors of dust emission from tillage operations. Firstly, the basic relations between soil texture, humus content and soil water content were investigated by using a wind tunnel as cross-flow gravitational separator. It was possible to show that soils can emit PM over a certain range of moisture. The relationships of soil water content, soil texture and humus content on PM10, PM2.5 and PM1.0 emissions could be derived. Threshold values of soil moisture for PM emission were determined which ranged between 2 to 5 % for sandy soils, 5 to 10 % for silty soils, up to 20 % for the clay soil and 25 to 45 % for organic soils.

Applying these findings on moisture conditions in spring and in summer resulted in good correlations between the derived PM emission potentials of a soil and measured emissions while ploughing. Our results show the necessity of considering the soil water content and its vertical profile for the derivation of emission factors. So, the emission factors of field operations should be related to the affected amount/volume of a soil, which is dry enough to emit PM, rather than to the affected area.

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