Application of a modeling approach to designate soil and soil organic carbon loss to wind erosion on long-term monitoring sites (BDF) in Northern Germany

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Abstract

Soil organic carbon (SOC) loss is a serious problem in maize monoculture areas of Northern Germany. Sites of the soil monitoring network (SMN) "Boden-Dauerbeobachtung" show long-term soil and SOC losses, which cannot be explained neither by conventional SOC balances nor by other non-Aeolian causes. The main objective was to determine whether these losses can be explained by wind erosion shown on the use of a process-based model.

In the long-term context of 10 years wind erosion was not measured directly but often observed. A suitable estimation approach was linking high-quality soil/farming monitoring and wind speed data with modeling results. The model SWEEP, validated for German sandy soils, was used. Two similar local SMN study sites were compared. Site A was characterized by high SOC loss and often affected by wind erosion; the reference site B was not.

At site A soil mass and SOC stock decreased by 49.4 and 2.44 kg m⁻² from 1999 to 2009. Using SWEEP, a total soil loss of 48.9 kg m⁻² resulted for 16 erosion events (max. single event 12.6 kg m⁻²). A share of 78 % was transported by suspension with a SOC enrichment ratio (ER) of 2.96 (saltation ER 0.98), comparable to the literature. At the reference site measured and modeled topsoil losses were minimal.

The good agreement between measurements and modeling results suggested that wind erosion caused significant long-term soil and SOC losses. The approach uses results of prior studies and is applicable to similar well-studied sites without other noteworthy SOC losses.

Keywords: long-term soil monitoring; BDF; SOC loss; wind erosion modeling; SWEEP; Northern Germany

1 Introduction

1.1 Background and research gap

Soil organic carbon (SOC¹) loss of arable soils is one of the main impacts of land degradation, triggered by a variety of physical and chemical factors, but finally caused by inappropriate land use (FAO & ITPS, 2015; Lal, 2014, 2003; Louwagie et al., 2009; Verheijen et al., 2009). Wind erosion can be a reason of gradual soil degradation, but the processes themselves are difficult to recognize or measure in the field.

In the flat sandy lowlands of Schleswig-Holstein in Northern Germany wind erosion is also a common process (Hassenpflug, 1998; Duttmann and Bach, 2006; Duttmann et al., 2011). SOC-rich sandy soils were developed on formerly heathland by Plaggen fertilization of livestock residues from stables (Giani et al., 2014; Blume, 2004; Springob et al., 2001; Springob and Kirchmann, 2002), characterized as Plaggic Anthrosols (IUSS, 2006). Used as arable land these sites are highly susceptible to wind erosion (Riksen and Graaff, 2001). Quantitative and qualitative effects of wind erosion on these soils were investigated sporadically only in a few studies. Direct field measurements of wind erosion are sparsely available for the region (Funk et al., 2004; Goossens and Gross, 2002; Goossens, 2004), even less is known about the amount of SOC loss by wind erosion (Bach, 2008) and nothing about the long-term losses over decades. For the latter, the most plausible reasons are the high technical and organizational efforts to measure wind erosion over long periods.

However, some soils exhibit decreased soil mass and SOC stock in the topsoil, i.e. the Ap horizon (LLUR, 2010; Ad-Hoc-AG Boden, 2005). Several authors recommend to consider these changes for estimating erosion losses in combination with modeling approaches (e.g. Post et al., 2001; Kibblewhite et al., 2012; Lal, 2005). Kibblewhite et al. (2012) state that soil erosion reduces topsoil depth, soil mass and SOC in the Ap horizon and suggests the use of long-term soil monitoring data to identify these changes. Even without direct measurements of wind erosion, the long-term monitoring of these soil parameters enables the assessment of the changes over decades (Post et al., 2001). Chappell & Viscarra Rossel (2013) and Chappell & Baldock (2016) describe the importance

¹ Abbreviation list:

BDF	Boden-Dauerbeobachtungsfläche (long-term soil monitoring site)
DIN	German Industry Standard (Deutsches Institut für Normung)
DWD	German Meteorological Service (Deutscher Wetterdienst)
ER	Enrichment ratio
GMD	Geometric mean diameter
GSD	Geometric standard deviation
LAI	Leaf area index
LLUR	State Agency
SAI	Stem area index
SMN	Soil monitoring network
SOC	Soil organic carbon
SWEEP	Single-event Wind Erosion Evaluation Program
TEAM	Texas Tech Erosion Analysis Model
WEPS	Wind Erosion Prediction System

of soil monitoring, sampling design on the detection of wind erosion and the absence of aeolian SOC losses from management-focused SOC balances. To conclude all these studies; reproducing measured SOC changes with a process-based wind erosion model may help to identify the contribution of wind erosion on SOC losses, which is not included in SOC balances so far. Using this approach, it is necessary to exclude other possible sources of SOC loss. Dust emission by tillage, was considered negligible for typical soil moisture conditions in the periods of wind erosion (Öttl and Funk, 2007; Funk et al., 2008), and water erosion has no relevance in the flat lowlands. A possible thinning effect resulting of an intrusion of subsoil material by tillage can lead to an underestimation of SOC in the topsoil. Therefore, topsoil and tillage depths need to be observed to exclude such causes of detected SOC changes.

To link topsoil measurements with Aeolian losses previous region-specific direct wind erosion measurements and other erosion studies are advantageous to define a range of usual soil and SOC loss. Bach (2008) measured soil and SOC losses by saltation in laboratory wind tunnel experiments investigating sandy top soil material from the same erosion-affected site as reported in this study. Using the TEAM model (Gregory et al., 2004) the author determined a high erodibility of that soil material resulting in a total soil loss of 13.08 kg m^{-2} within four days in March 1969, and a maximum single-event loss of 5.49 kg m^{-2} . Hassenpflug (1998) estimated a total soil loss of $10.0\text{--}15.0 \text{ kg m}^{-2}$ by aerial photograph analysis for the same erosion events and in the same area. In Northwestern Germany Goossens (2004) found $> 5 \text{ kg soil m}^2$ eroded at a sandy field (lengths $125\text{--}200 \text{ m}$) during an erosion event of 11 h. Studying an alluvial sandy soil in Northeastern Germany Funk et al. (2004) determined surface roughness and measured and simulated up to 10.5 kg m^{-2} of single-event total soil loss blown by erosive west winds. The study used the process-based erosion model SWEEP (Hagen et al., 1995) which was validated successfully for German sandy soils (Funk et al. 2004). Measurements and modeling on a 150 m long field resulted in 35 and 46 % of suspension, respectively. It was possible to show, that after setting the initial conditions very carefully, changing soil surface conditions and corresponding soil losses could be modelled by SWEEP with good accuracy. The studies of Bach (2008) and Funk et al. (2004) are the only available comparisons between measured and modelled soil losses by wind erosion in Germany.

To avoid wind erosion, the surface application of cattle slurry is a widely used erosion control method in agricultural areas with high wind erosion risk in Northern Germany (Duttmann et al., 2011; Bach, 2008; Riksen et al., 2003). Especially liquid cattle manure contains many fibers and adhesive substances forming a stable crust after drying (Riksen et al. in Warren, 2003). Heavy rainfall can destroy the protective effect of these crusts.

Alternatively, erosion control by surface-applied solid manure or dung (Blanco-Canqui and Lal, 2008; de Rouw and Rajot, 2004b) can be used.

1.2 SOC and wind erosion

Wind erosion is a very effective material sorting and SOC-removing process; as a result, fine particles in the suspension transport can be enriched in organic matter (Zobeck and Fryrear, 1986). This is expressed through enrichment ratios (ERs), the ratio of SOC content in the eroded material to the SOC content in the parent soil (Sterk et al., 1996). ERs for SOC are expected to be ≤ 1 in the saltation layer ($< \approx 30$ cm) and ≥ 1 in the suspension layer ($> \approx 30$ cm). Bach (2008) derived an ER of 0.98 in the saltation layer by wind tunnel studies using soil material of site A and surroundings.

A comprehensive overview of the importance of SOC enrichment in dust emissions on a continental scale was provided by Chappell et al. (2013). The authors present results from soil sampling and modeling. In the semiarid Canadian prairies Larney et al. (1998) reported ERs for saltation ranging between 1.02 and 1.05 (25 cm height). At semiarid environments in southwest Niger Sterk et al. (1996) found a saltation ER of 1.33 at 5 cm height. Funk et al. (2004) described increasing ER with height, ranging from 0.92 to 1.7 from 5 to 45 cm height at a sandy test site of low SOC stock in Eastern Germany. Similar was observed by Mendez et al. (2011) presenting measured ERs of 0.97 (5 cm height), 1.03 (15 cm), 3.7 (45 cm) and 4.6 (80 cm). Sterk et al. (1996) stated ERs of 2.39 and 3.02 for heights of 26 and 50 cm, respectively. They remarked that those heights include material transported by both, saltation and suspension processes.

Studying the arid region of southern New Mexico Li et al. (2007) found ERs (1.2 m height) between 3.24 without coverage, increasing continuously to 6.33 (75% cover). Ramsperger et al. (1998) measured ERs of SOC of 3 - 4 for dust samples trapped in 2 and 4 m height, Funk (1995) estimated an ER of 5 for dust sampled in 6 m height. ERs depend as well of the parent material's SOC content. For Australia Webb et al. (2012) reported suspension ERs (2 m height) of 1.67 in grass downs, 3.63 at a sand plain and ~ 7 at a dune.

Analyzing the SOC losses per area requires greater efforts and is based on flux measurements with a high spatial resolution (Buschiazzo and Funk, 2015) or indirect evidences as radionuclide concentration of ^{137}Cs (Funk et al., 2012). For Australian soils Harper et al. (2010) found average losses of 0.36 and 0.51 kg C m⁻² eroded by wind, for 1 or 2 years, respectively.

1.3 Soil monitoring

The soil properties affected by environmental impacts, e.g. wind erosion, have been observed on long-term soil monitoring sites ("Boden-Dauerbeobachtungsflächen", BDF sites) in Germany since 1985 (Nerger et al., 2016; Prechtel et al., 2009; Schröder et al., 2004; Barth et al., 2001). A detailed description of the BDF-SH SMN (Boden-Dauerbeobachtung Schleswig-Holstein soil monitoring network) methods and quality was provided in Nerger et al. (2016). The BDF-SH SMN was evaluated as highly suitable to detect long-term changes in soil and in farming management.

The BDF sites are part of larger fields and managed by farmers with contractual obligation to report all realized management actions. The top soil material of the BDF is sampled and analyzed at regular time intervals. These sites offer the unique opportunity to study long-term effects on soil properties, especially the gradual degradation by wind erosion, which is difficult to detect at a site itself through short-term measurements. On an international scale, comprehensive wind erosion monitoring networks which include soil and farming monitoring are still in the build-up phase (Webb et al., 2016). Thus, the already existing soil monitoring networks could be used to study the past impact of wind erosion on the soil.

1.4 Objectives

The main objective of this study was to investigate whether long-term soil and SOC losses measured at sites of a high-quality soil monitoring network can be explained by wind erosion shown on the use of a process-based wind erosion model. In this long-term context of 10 years wind erosion events were often observed but continuous direct measurements were not possible. Instead, measured long-term soil monitoring and farming data of the peer-reviewed BDF-SH SMN were used for study sites without other noteworthy causes of soil and SOC losses, except wind erosion. As the data situation was adequate the use of a physical based wind erosion model, considering both saltation and suspension transport process, was possible. The most important input parameters were determined in the field, including high-resolution wind speed data. Finally, the potentials, uncertainties and limitations of the approach will be discussed.

2 Material and Methods

2.1 Description of the study sites

The monitoring site Leck (site A) was characterized by high SOC losses, possibly due to wind erosion, and therefore selected as a study site. The reference site Schuby (site B) was selected because it features similar soil properties and farming management. Both sites are located in the Geest region in Northern Germany (Table 1 and Figure 1).

Table 1: Basic geographical and management characteristics of the monitoring sites A and B (LLUR, 2010)

site	A	B
location	Leck	Schuby
short coordinates (GK) ^a	35066, 60621	35282, 60452
landscape unit	Geest (Schleswiger Vorgeest)	Geest (Schleswiger Vorgeest)
annual mean temp. (°C) 1981-2010	8.2	8.6
parent material	Weichselian glaciuvial sands	Weichselian sandur sands
soil texture ^b	sandy sand (93% sand, 4% silt, 2% clay)	sandy sand (87% sand, 9% silt, 4% clay)
soil type ^c	Plaggic Anthrosol	Plaggic Anthrosol
historic land use	heathland / plaggen	heathland / plaggen
present land use	maize monoculture	crop rotation (maize, grain crops)

^a Gauß-Krüger system, Bessel, Potsdam: easting and northing, ^b (Ad-Hoc-AG Boden, 2005), ^c (IUSS, 2006)

Figure 1: Natural landscape units of Schleswig-Holstein (Northern Germany) and localization of the long-term soil monitoring sites. The study sites A and B are the sites 4 and 9 in the figure (triangle symbols)

The monitoring sites with a size of 0.1 ha are managed in the same manner as the larger field of which they are part of (Figure 2). The boundaries of the BDF are geodetically marked positions of rocks and magnets in the deeper subsoil. Thus, at the surface there is a continuous transition of the soil from the monitoring sites to the surrounding field.

Figure 2: Monitoring sites A (left), B (right) and surrounding areas

Site A is located in the center of a sandy maize monoculture field. The effective field length to the east, the direction where the erosive winds are from, is 125 m. Adjacent to the east there is pasture and finally wind barriers; the total length from site A to the wind barriers in the east is 545 m. Site B has a similar soil texture, more wind barriers close to the monitoring site and tillage perpendicular to the main erosive wind directions. The field length to the east is 340 m. The surrounding situation of both sites remained constant over the time periods considered for modeling.

Erosion control measures were realized using the crust formation effect of surface-applied slurry at site A (Table 2). In some years, the slurry was not applied immediately after sowing, thus, on a few days high wind speeds coincided with uncovered soil. Heavy rainfall was able to destroy the adhesive effect, as documented by the farmer in the management database (LLUR, 2010) and regarded in the calculations. Referring to German Meteorological Service (DWD) heavy rainfall is defined as daily precipitation amount exceeding 25 mm, a value which was used in the study to consider the slurry crust as ineffective. After harvest crop residues remained on the field. In addition to the natural weed infestation it formed a soil cover until stubble cultivation in spring. Since 2007 solid cattle manure was surface-applied as erosion control at site A. This cover was not affected by heavy rainfall (LLUR, 2010). In contrast, at site B no erosion control took place and the farming management was partly different (Table 2).

Table 2: Selected major management characteristics of the monitoring sites A and B from 1991 – 2009 (LLUR, 2010)

site	A	B
main crops	silage maize monoculture	crop rotation including maize; years 2002 to 2005 and 2008: wintercrops only, no crop cultivation in spring
catch crops and mulch	none	none
crop residues	remained on the field in winter; incorporated in spring by cultivator or disk harrow (before ploughing)	surface-applied in autumn
ploughing	annually, from 2007 conservation tillage	1-2 times per year
ploughing depth	30 cm until 2002; 25 cm since 2003	25 cm in spring, 30 cm in autumn (some years)
sowing time	1-5 days after seedbed preparation	2-6 days after seedbed preparation
tillage spacing and orientation	75 cm, WNW-ESE	75 cm, N-S
incorporated organic fertilizer	35-45 m ³ ha ⁻¹ a ⁻¹	35-40 m ³ ha ⁻¹ a ⁻¹
erosion control after sowing	always on the same day or 1 day after sowing; surface fixation by cattle slurry (5-15 m ³ ha ⁻¹ a ⁻¹) until 2006; from 2007 surface application of solid manure	none
potential erosion exposure	spring: time from stubble cultivation, ploughing, sowing, until 2 months after; in total about 2.5 to 3 months; coincides with dry and strong eastern winds	

2.2 Soil sampling strategy and laboratory work within the SMN

All laboratory results are obtained from the long-term soil monitoring program BDF-SH SMN (LLUR, 2010). Data of three sampling campaigns between October to November in 1990, 1999 and 2009 were used for the analysis. The sampling and measurement procedure followed standardized and scientific soil monitoring techniques and was described in detail in Nerger et. al. (2016). Basically, three composite samples were taken from 18 single points per campaign and study site. Only topsoil material was taken and depths documented. The rock fraction was determined by volume in the field and converted to mass fractions using conversion tables in Ad-Hoc-AG Boden (2005). SOC stock calculation, uncertainty determination and laboratory procedures were as described in Nerger et al. (2016). Additionally, saturated hydraulic water conductivity was measured in constant-head mode after DIN 19683-9:1998-05.

2.3 Calculation of management SOC balances

Conventional management SOC balances were calculated annually using the site-adjusted method of Kolbe (2010). The calculation is based on the management documentation of main crops, residue management and organic amendments. Cultivated

crops are considered as a SOC-draining factor whereas catch crops, organic amendments and residues left on the field increase SOC balance. The method offers default values for these factors, derived from German long-term field trials.

The method was chosen because it is a substantial improvement to former methods and has been site-specific adjusted. SOC/N_{tot} ratio and texture as soil-borne input are considered, referring to Springob and Kirchmann (2003) who stated this ratio as an indicator for the high inert SOC pool of sandy soils of heathland and Plaggen history which are present at the study sites A and B.

2.4 The wind erosion model SWEEP

2.4.1 Brief description of the model and its application

To reproduce the measured topsoil loss, the model SWEEP (Single-event Wind Erosion Evaluation Program; version 1.2.12; Hagen, 2004) was chosen, because it was validated successfully for sandy soils of Northeastern Germany by Funk et al. (2004), which are comparable to those of Schleswig-Holstein. SWEEP is an advancement of the stand-alone erosion submodel of WEPS (Hagen et al., 1995, 1991; Hagen, 2004; Li et al., 2014). The site-specific total soil loss and deposition are modelled and creep/saltation and suspension transport are distinguished. Data input and output is from sub-hourly (e.g. wind speed) to daily (e.g. erosion results) time steps.

The model runs cover the time periods of topsoil measurements from 1999 to 2009. Each year the relevant model period started at the first day of tillage in the year and lasted until 60 days after sowing, thus up to 75 days per year in total. Days featuring erosion control measures were not erosive (LLUR, 2010) and thus not modeled. Dust emissions by tillage were excluded, because they were considered as negligible (cf. section 1.1).

2.4.2 Field geometry and wind barriers

The entire field, neighboring areas and wind barriers of the study sites (Figure 2) were included in the spatial model setup. A grid size was chosen in which each BDF site was represented of nine grid cells (3x3) as part of the total modeling area. As modeling results solely the grid cells of the monitoring sites (0.1 ha) were used. The different height, length, width and porosity of wind barriers were also characterized. For grass, tree lines and shrubs the porosity was set to 0.5, according to Vigiak et al. (2003) and Hagen et al. (1981); farm buildings, wood and solid barriers were considered with lesser porosities or were set to zero. Height, length and width of hedges and trees were determined in field campaigns. The wind

barriers were constantly present over the monitored time period, although tree growth was not considered in this study.

2.4.3 Weather related parameters

The weather station in Leck (distance: 14 km) was selected for site A, data from the urban station in Schleswig (distance: 7 km) were used at site B. The stations are equivalent for the study sites as the comparison with verified and region-specific data of wind maps of a 200 m resolution (DWD, 2010) revealed that both sites and stations are characterized by a long-term average annual wind speed of 5.1 - 5.4 m/s.

Wind speed data were available as 10-minute- and wind direction as hourly averages supplied by the German Meteorological Service (DWD). Aerodynamic roughness was estimated according to the classification of Traup and Kruse (1996) and aerial photos of the surroundings of the station.

The surface water content was calculated hourly from precipitation data of both weather stations. According to the very sandy soil texture and high soil hydraulic conductivity values of both sites (2.2–8.8 cm h⁻¹), precipitation was assumed to infiltrate immediately (Blume et al., 2002) and the soil surface to be dried up within two hours from the surface. Surface water content of the upper 5 mm (Hagen et al., 1995) of soil layer was calculated as follows:

$$SWC = \frac{0.1 * CUMP_h}{0.5 * DBD} \quad (1)$$

Where: SWC = surface water content [g g⁻¹]; CUMP_h = hourly precipitation amount [mm] equivalent to [l m⁻²] or [kg m⁻²]; DBD = dry bulk density [g cm⁻³]

2.4.4 Soil layer, surface and biomass parameters

Many constant SWEEP input parameters (Table 3) were determined in the field or in the laboratory, others calculated due to reliable sources. The study of Funk et al. (2004) for German sandy soils was important to confirm the field-determined range of initial random roughness and oriented roughness (ridge height) as well as the description of their declines after precipitation and erosion events.

314 Table 3: Setup of selected constant input parameters in SWEEP of the monitoring sites A and B

constant parameters	unit	site A	site B	calculation/estimation method; source
initial random roughness	mm	4	6	field observation; Funk et al. (2004)
initial ridge height	mm	25	35	
row spacing	m	0.75	0.75	LLUR (2010)
ridge orientation	deg	109	0	
ridge spacing	mm	150	150	LLUR (2010), Hagen et al. (1995)
ridge width	mm	100	100	
aerodynamic roughness	mm	40	300	estimation according to Traup and Kruse (1996) and aerial photos
rock volume fraction	m ³ m ⁻³	0	0.15	field measurement
initial very fine sand fraction	Mg Mg ⁻¹	0.2	0.1	estimation from grain-size distribution curve (Blume et al. 2002)
initial aggregate density	Mg m ⁻³	1.80	1.80	Skidmore and Layton (unpub.) in: Hagen et al. (1995)
initial dry aggregate stability	ln (J kg ⁻¹)	1.17	1.42	Skidmore and Layton (1992) in: Hagen et al. (1995)
initial GMD of aggregate sizes	mm	1.02	3.19	Farres (1978) in: Hagen et al. (1995)
initial GSD of aggregate sizes	mm mm ⁻¹	10.30	14.76	
initial minimum aggregate size	mm	0.01	0.01	
initial maximum aggregate size	mm	16.44	75.20	
adjusted sand fraction (after prev. erosion event = a.p.e.e.)	Mg Mg ⁻¹	1.00	1.00	equations (2; 3) of this study
adjusted very fine sand fraction (a.p.e.e.)	Mg Mg ⁻¹	0	0	
adjusted aggregate density (a.p.e.e.)	Mg m ⁻³	1.80	1.80	
adjusted dry aggregate stability (a.p.e.e.)	ln (J kg ⁻¹)	0.85	0.85	
adjusted GMD of aggregate sizes (a.p.e.e.)	mm	1.00	1.00	
adjusted GSD of aggregate sizes (a.p.e.e.)	mm mm ⁻¹	1.01	1.01	
adjusted minimum aggregate size (a.p.e.e.)	mm	0.10	0.10	
adjusted maximum aggregate size (a.p.e.e.)	mm	2.00	2.00	
Soil wilting point water content	Mg Mg ⁻¹	0.09	0.16	LLUR (2010), field measurement
effective crust after applying slurry as erosion control (until 2006)	m ² m ⁻²	1.0	-	LLUR (2010), field observation; soil cover of solid manure comparable to Wagner and Nelson (1995)
residue flat cover after applying solid manure as erosion control (from 2007)	fraction	1.0	-	
residue flat cover of flat maize stubbles	fraction	0.25	-	Skidmore and Layton (unpub.) in: Hagen et al. (1995)
surface crust density	Mg m ⁻³	1.80	1.80	
surface crust stability	ln (J kg ⁻¹)	1.17	1.42	Zobeck (1991) in: Hagen et al. (1995)

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316 Some variable parameters (Table 4) were determined following the contributions of
317 various authors as documented in the WEPS technical manual (Hagen et al., 1995). Events
318 of erosion and precipitation >10 mm affect soil layer and surface properties. Thus, after each
319 event some soil layer and surface parameters had to be updated (Hagen, 2008) using the
320 SWEEP update function.

Table 4: Sources of selected variable input parameters in SWEEP for the monitoring sites A and B

variable parameters	unit	calculation/estimation method; source
decline of random roughness (after precipitation)	mm	Potter (1990) in: Hagen et al. (1995)
decline of ridge height (after precipitation)	mm	Lyles and Tatarko (1987) in: Hagen et al. (1995)
decline of random roughness (after erosion event)	mm	SWEEP subdaily results (update function)
decline of ridge height (after erosion event)	mm	
initial surface crust thickness	mm	Farres (1978) in: Hagen et al. (1995)
initial surface crust fraction	m ² m ⁻²	Zobeck and Popham (1992) in: Hagen et al. (1995)
initial loose erodible fraction	m ² m ⁻²	
initial loose erodible mass	kg m ⁻²	
decline of surface crust thickness	mm	SWEEP subdaily results (update function)
decline of surface crust fraction	m ² m ⁻²	
decline of loose erodible fraction	m ² m ⁻²	
decline of loose erodible mass	kg m ⁻²	
changed loose erodible mass	kg m ⁻²	equations (2; 3) of this study
residue flat cover	m ² m ⁻²	Wagner and Nelson (1995); field observation
growing crop height	m	sowing and yield data of the management database (LLUR, 2010); growth stages of maize plants of Armbrust and Lyles (1985); growing degree days concept of Hagen et al. (1995)
SAI (incl. stem diameter, plants per m ²)	m ² m ⁻²	
growing crop leaf area index	m ² m ⁻²	

However, not all necessary updates for the needs of this study are included in the update function, e.g. the changed texture in the uppermost centimeter after erosion events. If such events were characterized by high suspension loss and low saltation loss, soil texture near surface shows depletion of material susceptible to suspension transport (López, 1998; de Rouw and Rajot, 2004a). These losses were subtracted from soil stocks of those materials. As a first step material susceptible for suspension was defined according to Hagen et al. (1995) as the clay, silt and very fine sand fraction (Table 5).

Table 5: Estimated stocks of process-specified susceptible material for the uppermost layer of 1 cm from Ap horizon of the monitoring sites A and B

	unit	site	value
stock of material susceptible for suspension (very fine sand, silt, clay) of the uppermost layer of 1 cm	kg m ⁻²	A	3.47
		B	3.10
stock of material susceptible for saltation (sand without very fine sand) of the uppermost layer of 1 cm	kg m ⁻²	A	9.53
		B	10.20

The SWEEP model is actually not applicable for multiple soil layers. Thus, the resulting superficial sand layer was modeled as loose erodible mass (LEM) above an impermeable crust (L.E. Wagner, 2011, personal communication). The calculation for the thickness of the remaining pure sand layer and the LEM was derived as follows:

$$T_{LAYER} = \frac{SOIL_LOSS_{SUSP}}{SOIL_STOCK_{SUSP}} - \frac{SOIL_LOSS_{SALT}}{SOIL_STOCK_{SALT}} \quad (2)$$

$$LEM = SOIL_STOCK_{SUSP} * T_{LAYER} \quad (3)$$

Where: T_{LAYER} = Thickness of remaining pure sand layer [fraction of 1 cm], $SOIL_LOSS_{SUSP}$ = soil loss by suspension [$kg\ m^{-2}$], $SOIL_STOCK_{SUSP}$ = soil stock of material susceptible to suspension [$kg\ m^{-2}$], $SOIL_LOSS_{SALT}$ = soil loss by creep/saltation [$kg\ m^{-2}$], $SOIL_STOCK_{SALT}$ = soil stock of material susceptible to creep/saltation [$kg\ m^{-2}$], LEM = loose erodible mass of remaining pure sand layer [$kg\ m^{-2}$]

2.5 Comparing SOC losses from measurement, balances and modeling results

As a first step topsoil SOC stocks at the beginning and the end of the test period were calculated as described in section 2.2. The annually calculated SOC balances were cumulated for the test period and added to the topsoil SOC stock losses (Equation 4) resulting in the total SOC loss through wind erosion. Calculating SOC transport by saltation of each event the ER of 0.98 derived from wind tunnel experiments for local soil material from Bach (2008) was multiplied with the modeled soil losses (Equation 5). The resulting sum of SOC loss by saltation of the whole test period was subtracted from overall SOC loss (Equation 6). The remaining SOC loss was regarded to be lost by suspension.

Assigning the entire measured topsoil SOC loss to wind erosion was possible as all other causes of SOC loss could be excluded (cf. section 1.1).

SOC loss by suspension was allocated weighted to the suspension soil loss of each erosion event. Thus, a suspension ER resulted for the whole test period whereas SOC loss was pointed out for single events considering reduced SOC contents after every erosion event.

$$SOC_LOSS_{TOTAL} = SOC_CHANGE_{Ap;1999\ to\ 2009} + \sum_{year=1}^{year=10} SOC_BALANCE_{ANNUAL} \quad (4)$$

$$SOC_LOSS_{SALT} = \sum_{i=1}^n SOIL_LOSS_{SALT} * (SOC_CONC_{Ap;1999} * ER_{SALT}) \quad (5)$$

$$SOC_LOSS_{SUSP} = SOC_LOSS_{TOTAL} - SOC_LOSS_{SALT} \quad (6)$$

Where:

SOC_LOSS_{TOTAL} = sum of total SOC loss of the test period [t]; $SOC_CHANGE_{Ap;1999\ to\ 2009}$ = topsoil SOC stock change of the test period, means from 1999 to 2009 [t]; $SOC_BALANCE_{ANNUAL}$ = annual SOC balances of the test period [t]; SOC_LOSS_{SALT} = sum of SOC loss by saltation of the test period [t]; $SOIL_LOSS_{Salt}$ = soil loss by saltation as SWEEP result of one event [t]; SOC_CONC = initial SOC concentration measured at the beginning of the test period [%]; ER_{SALT} = enrichment ratio saltation (=0.98; Bach (2008)); SOC_LOSS_{SUSP} = sum of SOC loss by suspension of the test period [t]

2.6 Modeling variations

Modeling variations were assessed for the most sensitive parameters mentioned in Hagen et al. (1999) and Feng & Sharratt (2005) for site A. Using the SWEEP threshold friction speed of 8 m s^{-1} the effect of wind speed variations of $\pm 5\%$ on wind values was calculated, whose relation is similar between wind speed and soil loss (Fryrear et al., 1998). The resulting wind value deviations represent the potential total soil loss deviations. In a second run, random and oriented roughness were varied by 25 and 20%, respectively. Finally, the time needed to dry up the soil surface after an erosion event was varied from two hours to four hours.

3 Results

3.1 Results of topsoil measurements

The results of the topsoil measurements (LLUR, 2010) are listed in Table 6. Grain size distribution shows an erosion-susceptible fine sand fraction of 50 % at site A. It declined from 1999 to 2009. In accordance with the very sandy texture of the sites, hydraulic water conductivity was high and reached $2.2\text{--}8.8 \text{ cm h}^{-1}$.

Table 6: Laboratory characterization of topsoil samples of the monitoring sites A and B. Measurement campaigns in October/November of the years 1990 (1st), 1999 (2nd) and 2009 (3rd)

soil property	unit	site	1 st campaign		2 nd campaign		3 rd campaign	
			mean	$\pm$ SD	mean	$\pm$ SD	mean	$\pm$ SD
Ap horizon soil mass (excluding rocks)	kg m^{-2} (for 0.1 ha)	A	429.3	15.82	390.0	23.43	340.6	14.25
		B	344.3	0.00	338.3	10.31	335.9	3.46
SOC concentration	%	A	2.53	0.10	2.27	0.09	1.88	0.04
		B	3.64	0.32	4.02	0.22	3.70	0.25
SOC/N _{tot} ratio	dimension- less	A	13.9	-	15.2	-	13.4	-
		B	15.5	-	20.5	-	17.4	-
sand (63 - <2000 μm)	Vol%	A	92.63	0.48	93.23	0.38	90.67	0.55
		B	87.13	0.78	86.73	0.68	87.93	0.40
fine sand (63 - <200 μm)	Vol%	A	49.97	2.51	51.07	1.42	47.13	2.15
		B	29.63	1.66	31.50	2.04	28.10	1.25
silt (2 - <63 μm)	Vol%	A	4.52	0.44	4.40	0.36	-	-
		B	8.50	0.55	9.30	0.26	8.07	0.47
clay (<2 μm)	Vol%	A	2.85	0.36	2.27	0.64	-	-
		B	4.37	0.37	4.03	0.81	4.00	0.10
silt+clay (<63 μm)	Vol%	A	-	-	-	-	9.33	0.55
		B	-	-	-	-	-	-
dry bulk density	g cm^{-3}	A	1.37	-	1.30	0.08	1.21	0.05
		B	1.35	-	1.33	0.04	1.33	0.05
topsoil depth	cm	A	31.3	1.2	30.0	1.3	28.2	1.2
		B	30.0	0.3	30.0	0.3	29.8	0.3
hydraulic water conductivity	cm h^{-1}	A	-	-	8.8	7.3	6.3	2.4
		B	-	-	2.2	0.4	2.5	1.2

SD = standard deviation

Originally both sites were characterized by high SOC stocks of over 10.0 kg m⁻² (Figure 3). From 1999 to 2009 averaged topsoil depth, dry bulk density and SOC concentration declined at site A. Thus, soil mass declined by 49.37 kg m⁻² and SOC stocks significantly by 2.44 kg m⁻². Considering standard deviation minimum, loss of SOC stock was 1.76 kg m⁻². Already prior to the modeling period (1990 to 1999) the significant loss of SOC stock was 2.01 kg m⁻². At the reference site B the averaged topsoil depths and dry bulk density remained nearly constant. Thus, only a very small soil loss of 2.42 kg m⁻² was measured; SOC changes were insignificant.

Figure 3: SOC stocks in kg m⁻² for the study sites A and B. Measurement campaigns in October/November of the years 1990 (1st), 1999 (2nd) and 2009 (3rd)

3.2 Results of management SOC balances

Table 7 shows calculated conventional annual farming management SOC balances based on main crops of the study sites. The total sum of SOC balances for all years was 0.15 kg m⁻² at site A and 0.35 kg m⁻² at site B. The method of site-adjusted SOC balance (Kolbe, 2010) implies that SOC-consuming crops influence sandy sites to a lesser extent because they have a high turnover of organic carbon. Additionally, organic fertilizers were applied regularly by the farmers. Therefore, these sites mostly feature neutral or positive SOC balances. Compared to the SOC losses the applied amount of organic carbon by liquid and solid manure is low (<0.05 kg m⁻² a⁻¹).

Table 7: Main crops and SOC balances in kg m⁻² 1999-2009 for the monitoring sites A and B; calculated using the management data of LLUR (2010) with the side-adjusted method (Kolbe, 2010).

site A										
year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
main crop	sm ^a	sm	sm	sm	sm	sm	sm	sm	sm	sm
	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031	-0.031
catch crop										
crop residues										
solid manure								0.048	0.028	0.028
liquid manure	0.032	0.032	0.032	0.032	0.049	0.045	0.032	0.036	0.032	0.032
sewage sludge										
TOTAL	0.001	0.001	0.001	0.001	0.018	0.014	0.001	0.053	0.029	0.029
site B										
year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
main crop	sm	oa ^b	ww ^c	wb ^d	wr ^e	ww	sm	sm	wry ^f	sm
	-0.031	-0.003	-0.003	-0.003	-0.003	-0.003	-0.031	-0.031	-0.003	-0.031
catch crop										
crop residues			0.032	0.036	0.031					0.040
solid manure										
liquid manure	0.028	0.024	0.028	0.028	0.023	0.024	0.020	0.028	0.016	0.028
sewage sludge	0.056				0.045					
TOTAL	0.053	0.021	0.057	0.061	0.095	0.021	-0.011	-0.003	0.013	0.037

legend: ^a silage maize; ^b oat; ^c winter wheat; ^d winter barley; ^e winter rape; ^f winter rye

3.3 SWEEP modeling results

Model results for site A (Table 8) found 16 erosion days within a ten-year period. The majority of erosion events (10 out of 16) and the highest calculated single event soil loss of 12.64 kg m⁻² were related to easterly winds. In the whole test period 48.93 kg m⁻² of soil was estimated to be eroded by wind from the 0.1 ha monitoring site. This is in very good agreement with the balanced topsoil loss of 49.37 kg m⁻² for the ten-year period (1999–2009). Excluding negligible erosion events of 100 % creep/saltation transport, soil loss through easterly winds was transported between 61–99 % by suspension. Due to a smaller effective field length and/or more wind barriers saltation's share was higher (20-50%) at erosion events of southerly, westerly and northeasterly winds. The overall weighted creep/saltation to suspension ratio was 22:78.

454 Table 8: Estimated variable parameters, model results and projected SOC loss for the test period 1999-2009 of the monitoring sites A and B.

		soil surface properties					biomass properties				weather related properties			predicted soil loss for the study sites (0.1 ha)							est. SOC loss		
date	DALTO _a	random roughness	ridge height	surface crust fraction	loose erod. fraction	loose erod. mass	residue flat cover	grow. crop height	stem area index	leaf area index	CUMP _b	SWC _c	wind direction	mean total soil loss	grid variability	creep / saltation loss		suspension loss		T _{LAYER} _d	saltation ER= 0.98	suspension ER= 2.96	
DD/MM /YYYY		mm	mm	m ² m ⁻²	m ² m ⁻²	kg m ⁻²	m ² m ⁻²	m	m ² m ⁻²	m ² m ⁻²	mm	Mg Mg ⁻¹	deg	kg m ⁻²	%	kg m ⁻²	% of total	kg m ⁻²	% of total	cm	kg m ⁻²	kg m ⁻²	
site A - 2000 - 2009																							
09/05/2001	0	4.00	25.00	0	0	0	0	0	0	0	0	0	70	2.1	5.9	0.4	18	1.7	82	0.45	0.01	0.12	
09/05/2002	0	4.00	25.00	0	0	0	0	0	0	0	0	0	57	8.4	3.5	4.3	51	4.1	49	0.72	0.10	0.27	
10/05/2002	0	4.00	25.00	0	0	0	0	0	0	0	0	0	83	12.6	1.7	0.3	2	12.3	98	3.53	0.01	0.80	
03/05/2003	0	4.00	25.00	0	0	0	0.25	0	0	0	0.3	0.05	250	0.8	25.1	0.4	53	0.4	47	0.06	0.01	0.02	
09/06/2003	32	1.53	6.66	0.62	0.25	0.01	0	0.38	0.03	0.25	110	0	235	0.3	75.2	0.2	50	0.2	50	0.00	0.00	0.01	
11/06/2003	34	1.50	6.66	1.00	1.00	0.03	0	0.41	0.03	0.31	4.5	0	240	0.0	60.2	0.0	100	0.0	0	0.00	0.00	0.00	
29/04/2004	2	4.00	25.00	0	0	0	0.25	0	0	0	0	0	100	0.0	0.2	0.0	23	0.0	77	0.01	0.00	0.00	
30/04/2004	3	3.98	24.91	0	0	0	0.25	0	0	0	0	0	85	4.0	1.2	1.6	39	2.5	61	0.54	0.03	0.15	
09/05/2006	0	4.00	25.00	0	0	0	0	0	0	0	0	0	80	3.0	2.5	0.1	5	2.8	95	0.79	0.00	0.17	
19/04/2007	4	4.00	25.00	0	0	0	0.25	0	0	0	1.1	0	250	0.0	35.9	0.0	56	0.0	45	0.00	0.00	0.00	
20/04/2007	0	4.00	25.00	0	0	0	0	0	0	0	0.4	0.05	307	3.6	2.4	1.8	50	1.8	50	0.71	0.04	0.11	
22/04/2008	0	4.00	25.00	0	0	0	0	0	0	0	0	0	80	7.6	2.2	0.3	4	7.3	96	0.21	0.01	0.43	
23/04/2008	1	1.50	9.90	1.00	1.00	1.98	0	0	0	0	0	0	93	0.0	89.8	0.0	100	0.0	0	0.00	0.00	0.00	
25/04/2009	1	4.00	25.00	0	0	0	0	0	0	0	0	0	97	4.1	0.5	0.0	1	4.0	99	1.16	0.00	0.23	
27/04/2009	0	4.00	25.00	0	0	0	0	0	0	0	0	0	195	2.4	18.2	1.4	58	1.0	42	0.01	0.03	0.06	
28/04/2009	1	1.50	6.57	1.00	1.00	0.14	0	0	0	0	0.4	0	80	0.0	72.1	0.0	100	0.0	0	0.00	0.00	0.00	
TOTAL															48.9		10.8	22°	38.1	78°		0.226	2.369
																						2.595 ^f	
site B - 2000 - 2009																							
04/06/2006	24	2.85	13.99	0.53	0.21	0.64	0	0.13	0.00	0.04	72.5	0	310	0.4	97.7	0.3	73	0.1	27	0.00	0.01	0.01	
11/05/2007	19	2.88	20.04	0.38	0.39	0.17	0	0.09	0.00	0.02	2.7	0.02	250	0.0	75.0	0.0	80	0.0	20	0.00	0.00	0.00	
17/05/2007	25	1.85	14.15	0.40	0.16	0.64	0	0.13	0.00	0.04	14.6	0	300	0.4	89.9	0.3	75	0.1	25	0.00	0.01	0.01	
15/05/2009	25	3.49	21.53	0.40	0.16	0.64	0	0.14	0.00	0.05	0	0	90	0.0	27.5	0.0	73	0.0	27	0.00	0.00	0.00	
22/05/2009	32	2.46	16.99	0.40	0.56	0.61	0	0.22	0.01	0.10	21.6	0	260	0.0	72.9	0.0	80	0.0	20	0.00	0.00	0.00	
26/05/2009	36	1.90	14.69	0.40	0.57	0.60	0	0.28	0.01	0.14	4.1	0	250	0.1	51.3	0.1	79	0.0	21	0.00	0.00	0.00	
28/05/2009	38	1.87	14.56	0.40	0.49	0.46	0	0.31	0.02	0.17	6.1	0	300	0.0	119.4	0.0	75	0.0	25	0.00	0.00	0.00	
TOTAL															1.0		0.8	75°	0.3	25°		0.031	0.031

^a day after last tillage operation

^b cumulative depth of precipitation since last tillage or erosion event

^c relevant cumulated hourly surface water content during erosion event

^d thickness of new pure sand horizon after this event

^e calculation of creep/saltation-suspension ratio using total values of the test periods

^f Total SOC loss in test period: saltation + suspension = SOC loss Ap horizon ± ∑ SOC balances

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In years with more than one erosion event and without tillage random and oriented roughness decline was considered. As a consequence of the decline also less erosive winds were able to initiate erosion at site A. This was mostly the case when random roughness and ridge height were <2 mm and <10 mm, respectively. The crust caused by surface fixation by cattle slurry ($5 \text{ m}^3 \text{ ha}^{-1}$) was sufficient protective against wind erosion and no erosion was modeled. In 2003 the slurry crust was destroyed by heavy rainfall of 27.1 mm on 08/06/2003. Thus, the soil surface was susceptible to wind erosion and erosive winds could erode soil material on two days. As a consequence of 110 mm of precipitation since the last tillage operation, random and oriented roughness decreased to a minimum, so that erosion could take place even though wind speeds were relatively low. 0.32 kg m^{-2} of total soil loss through westerly winds was modeled at site A. In 2004 the slurry crust was destroyed again, but a new slurry layer was applied immediately. Therefore, more slurry was utilized ($15 \text{ m}^3 \text{ ha}^{-1}$) in 2005, which could resist heavy rainfall of 29.3 mm without losing the crust.

Precipitation was typically related to westerly winds reducing susceptibility to erosion by increased surface water contents. Mostly, precipitation sums after last tillage operations were quite low (<10 mm); thus, on 15 out of 16 days no surface crusts by precipitation developed. At five events of westerly winds a total soil loss of 4.74 kg m^{-2} occurred at site A, whereas at easterly wind events 41.81 kg m^{-2} were modeled. Three erosive days were characterized by pure sand layers which developed on the surface by high suspension loss, i.e. especially loss of parts of the fine sand and silt fractions (see Table 6). In each case model results of the following erosive day stated that these sand layers were not completely eroded; indicating that the underlying fine soil material was not susceptible to erosion.

At site B, featuring closer wind barriers to the northeast, the average total soil losses were much smaller and the variability of the SWEEP grid cells was higher. Most of the erosive days coincided with a crusted surface or growing crops. 7 erosive days were modeled, resulting in 1.0 kg m^{-2} of total soil loss and a saltation/suspension ratio of 75:25. This total soil loss of ten years corresponds to the measured topsoil loss (2.4 kg m^{-2}). The maximum total soil loss of a single event was 0.4 kg m^{-2} , eroded by northwesterly winds. All erosive days showed average loss in both creep/saltation and suspension. Some events were characterized by very small deposition at the western part of the monitoring site.

3.4 Comparing SOC losses from measurement, balances and modeling results

At site A a SOC stock decrease of 2.44 kg m^{-2} was measured in the topsoil within the period 1999–2009. The total conventional SOC balance method resulted in an increase of 0.15 kg m^{-2} . Based on the wind erosion modeling results SOC loss by creep/saltation was quantified to 0.23 kg m^{-2} for all 16 erosion events of the test period. Considering reduced SOC contents

in the uppermost layer after each erosion event the remaining sum of 2.37 kg m⁻² was estimated to be transported by suspension with an ER of 2.96. Highest SOC loss by creep/saltation was on 09/05/2002 (0.10 kg m⁻²) and by suspension on 10/05/2002 (0.80 kg m⁻²). SOC losses at site B were low. Developing ER's for site B from the present data of very few soil loss would feature a large uncertainty. Therefore, the same ERs as at site A were used, as it is geographically very close. Using these ERs, 0.031 kg m⁻² of SOC was eroded by creep/saltation and 0.031 kg m⁻² by suspension in the test period.

3.5 Modeling variations

The calculated soil losses using variations of sensitive parameters (Table 9) show that varying wind speed had the largest effect on the modeling results of site A (-44% and +62%). A roughness variation impacted the total soil loss also significantly (-33% and +11%) while a longer dry-up time had a negligible effect because most erosion events were days without rain close to the erosive hours (15 of 16).

Table 9: Calculated modeling soil losses using wind speed, surface roughness and surface dry-up variations for the test period 1999-2009 of the monitoring site A.

event no.	date	without variation	Wind speed variation		Roughness variation		Surface water drying up
		-	-5%	+5%	+20 to +25%	-20 to -25%	after 4 hours instead of 2 hours
		kg m ⁻²	kg m ⁻²	kg m ⁻²	kg m ⁻²	kg m ⁻²	kg m ⁻²
1	09/05/2001	2.1	0.4	4.4	0.0	3.1	2.1
2	09/05/2002	8.4	3.4	15.3	0.1	8.0	8.4
3	10/05/2002	12.6	8.2	18.1	12.3	12.8	12.6
4	03/05/2003	0.8	0.6	1.0	0.3	1.6	0
5	09/06/2003	0.3	0.2	0.4	0.3	0.4	0.3
6	11/06/2003	0.0	0.0	0.0	0.0	0.0	0.0
7	29/04/2004	0.0	0.0	0.0	0.0	0.3	0.0
8	30/04/2004	4.0	3.0	5.2	2.9	5.1	4.0
9	09/05/2006	3.0	1.3	5.3	2.2	3.2	3.0
10	19/04/2007	0.0	0.0	0.0	0.0	0.3	0.0
11	20/04/2007	3.6	0.8	10.0	2.7	4.1	3.6
12	22/04/2008	7.6	5.2	10.3	6.8	7.8	7.6
13	23/04/2008	0.0	0.0	0.0	0.0	0.0	0.0
14	25/04/2009	4.1	2.5	6.0	3.7	4.2	4.1
15	27/04/2009	2.4	1.7	3.2	1.5	3.7	2.4
16	28/04/2009	0.0	0.0	0.0	0.0	0.0	0.0
SUM		48.9	27.3	79.3	32.7	54.5	48.2
Differences in %		-	44	62	33	11	2

4 Discussion

4.1 Soil loss by wind erosion

The comparison of two study sites influenced by wind erosion to a different extent showed a very good agreement between measured and modeled topsoil loss. Within the ten-year-period the measured topsoil loss at site A corresponds almost exactly to the modeled soil loss. For the reference site B, the modeled very small soil and SOC losses are as well in accordance with the topsoil measurements.

The absolute loss of 49 kg m^{-2} over ten years ($4.9 \text{ kg m}^{-2} \text{ a}^{-1}$) at site A can be considered as very high but not unusual; Zhang et al. (2017) worked as well with SWEEP and determined 4-5 kg m^{-2} per year for an entire field.

The maximum single-event soil loss of 12.64 kg m^{-2} was caused by dry easterly winds, which is comparable to other measured very strong wind erosion events; e.g. 17 kg m^{-2} in German Lower Saxony (Schäfer and Neemann, 1990) at sites with similar soil and environmental conditions. Not focusing on the center part but on the entire field Bach (2008) modeled with another process-based model (TEAM, Gregory et al., 2004) a total soil loss of 13.08 kg m^{-2} for four days in March 1969 at the same area as in this study (site A).

The relatively long field length to the east, in main wind direction, explains proportions of 99 % suspension in some erosion events at the monitoring site in this study. After a field length of approx. 100 m the maximum transport capacity of saltation is reached – erosion and deposition are in equilibrium – whereas suspension transport is constantly increasing and never reaches saturation (Hagen et al., 1995).

The results of Funk et al. (2004) are supporting the modeling results of this study. For their validation of the SWEEP model in Germany the authors reported an excellent agreement between measured and simulated soil loss, especially for large erosion events. Model results confirm that wind erosion is much higher at site A compared to site B. Without erosion control by cattle slurry and solid manure (cf. Funk & Riksen, 2007; Riksen et al., 2003) soil and SOC loss would have been extraordinary high at site A.

The strong decline of the topsoil mass at site A over ten years shows the erosion impact, whereas soil mass at site B (less affected by erosion) remained nearly constant. This relation is in accordance with the literature (cf. Ellert and Bettany, 1995; Kibblewhite et al., 2012). Another indication for the wind erosion impact is the declined fine sand fraction at site A from 1999 to 2009 (cf. Li et al., 2009). Particles of this size are preferably transported in wind erosion events (Hagen et al., 1995).

The analytical and modeling results bear also given uncertainties. This was shown e.g. in Table 6 and Table 9. In the recent literature for SWEEP the model was evaluated to

overestimate the threshold friction velocity, which is necessary to initiate wind erosion (Zhang et al., 2017; Pi et al., 2014; Feng & Sharratt, 2007, 2009). This is especially important for smaller erosion events. However, most of the soil and SOC loss reported in this study was caused by large erosion events of high wind speeds. Smaller events could be affected; this might be the reason for the difference of 1.4 kg m^{-2} between measured topsoil loss and modeled loss at site B. Once SWEEP detected erosion it overpredicted the modeled soil loss in the Columbia Plateau (USA) by 200-700 kg ha^{-1} (Feng & Sharratt, 2007) which translates to 0.02-0.07 kg m^{-2} and is therefore negligible for this study, as 48.9 kg m^{-2} were modeled and its aim was to designate the main part of the measured topsoil SOC loss to wind erosion.

4.2 SOC loss by wind erosion

The SOC loss determined by measurements and modeling at site A corresponds to the high soil loss. The SOC loss of 2.44 kg m^{-2} in ten years is an important degradation factor reducing soil fertility at the study site.

The determination of a considerable change of SOC (10 – 15 %) in soils requires an adequate sample size. This size was determined as $n=16$ (Garten and Wulfschleger, 1999). Considering the 18 sampling points in the BDF program, each containing two cores, this size is clearly reached (cf. Nerges et al., 2016). Using standardized sampling and laboratory methods all three composite samples of site A showed significantly declined SOC stocks.

To assign the estimated SOC losses to wind erosion other possible SOC losses have to be excluded. Water and tillage erosion were not relevant (cf. sections 1 and 2.4.1). Tillage depth changed 2003 at site A from 30 to 25 cm as documented in the management data base. Thus, a possible thinning effect from subsoil material intermixed with topsoil material can be excluded.

SOC losses were considered separately by using different ER for the saltation and suspension part of the soil losses. ERs can vary in space and time as indicated by Webb et al. (2012) or in consecutive measurements as well by sampler type (Funk, 1995). Nevertheless, over a long-term period these variations are minimized (Figure 4).

ERs for saltation transport were derived from wind tunnel experiments (Bach, 2008) with soil material from Site A. The chosen ER of 0.98 for saltation fits very good to the function derived from data of several authors (Fig. 4). The same applies to the suspension ER found in this study (2.96). It is very similar to the ER of 3.02 found by Sterk et al. (1996) and the ERs of 3.02 and 3.63 of Webb et al. (2012) and can therefore be considered as a reasonable value for SOC loss mainly by suspension.

Figure 4: Comparison of the enrichment ratios found in the present study with those of the literature

4.3 Significance and limitations of the study approach

The results are of relevance for evaluating long-term soil and SOC losses by wind erosion. Wind erosion measurements are not feasible for such long-term periods, therefore, approaches using modeling (Post et al. 2001), long-term soil monitoring (Lal, 2005) or soil sampling and modeling (Chappell et al., 2013; Chappell & Viscarra Rossel, 2013) may be more appropriate. The selected approach to combine topsoil measurements, detailed management data and process-based modeling allows to quantify the impact of wind erosion as land degradation process. To date there is no similar approach quantifying these long-term impacts of wind erosion. The presented approach is limited to sites without noteworthy SOC changes due to other processes such as water erosion and without presence of a thinning effect.

Adequate region-specific and characterization studies are necessary if the SWEEP model is applied without direct measurements of wind erosion. The estimation of all main input parameters in the model setup is based on field observations or measurements of the study site or on adequate validation studies (Funk et al., 2004; Hagen, 1995; Bach, 2008; references in Table 3). This covers the most sensitive parameters mentioned in Hagen et al. (1999) and Feng & Sharratt (2005) and enables to conclude that the study reconstructs reasonable erosion events and SOC loss even without direct erosion measurements in

sandy soils of Northern Germany. However, the exact results bear also an uncertainty. This was shown in Table 6 and chapter 3.5. Especially wind speed variations may have a large impact on the result, therefore, this study benefits from the used official and quality-proved 10-minute wind speed data set. Although a given uncertainty remains, the importance of the presented study lies more in the reliable designation of the main part of the measured SOC losses to wind erosion.

5 Conclusions

The applied approach, combining high-quality long-term monitoring data of soil and farming management as well as high-resolution wind speed data with a process-based wind erosion model, was successful. The measured SOC losses could be designated to wind erosion and confirms the impact of this soil degradation in arable sandy soils of Northern Germany. Although based on measured data it is an indirect estimation approach as wind erosion was not measured directly. However, it seems to be an adequate method to estimate wind erosion induced soil and SOC loss, especially for long-term periods (decades) where continuous erosion measurements are not possible

The key data is the BD-SH SMN using consistent sampling and laboratory methods of standardized monitoring routines allowing the determination of uncertainties and thus significant changes in time for long-term periods (Nerger et al., 2016). Although the results are limited to the study sites in Northern Germany, the presented procedure could be interesting for similar environments when long-term soil monitoring data are available and non-Aeolian causes for SOC loss can be excluded. The application of ER factors for SOC losses by saltation and suspension could improve carbon accounting systems and wind erosion models, following the recommendation of Webb et al. (2012).

6 Acknowledgments

We would like to thank both the Department Geology and Soil, Soil Conservation of the State Agency of Agriculture, Environment and Rural Areas of the Federal State Schleswig-Holstein (LLUR) and the Ministry of Energy, Agriculture, the Environment and Rural Areas of the Federal State Schleswig-Holstein (MELUR) for the financial support (LLUR grant number: 4121-3-2007-440F), the good cooperation and the data supply. We would also like to thank Larry E. Wagner from the Wind Erosion Research Unit (WERU) of the United States Department of Agriculture (USDA) for his good advice on some technical details of the SWEEP model.

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