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Assessing the PM_{10} emission potential of sandy, dryland soils in South Africa using the PI-SWERL

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ABSTRACT

The Free State has been identified as the region with the most dust sources in South Africa. These dust sources can be linked with the large, heavily cultivated cropland areas in this province, which leaves fields vulnerable to wind erosion after the harvest in the winter. For this study, the focus was on the factors that influence the emission from bare, flat surfaces on agricultural lands in this region. The Portable In-Situ Wind Erosion Laboratory (PI-SWERL) was used to measure the emission flux from adjacent crusted and loose surfaces, which was combined with shear strength, moisture, and soil texture measurements. Boosted regression tree (BRT) analyses were used to identify the variable with the highest relevance on the emission flux.

On the whole dataset, that the shear strength is the most important variable that controls the emission. This is reflected in the significantly lower emission from the crusted surfaces (0.49 mg m^{-2} s^{-1}) compared to that of loose surfaces (2.34 mg m^{-2} s^{-1}). However, for crusted surfaces, the presence of abraders appeared to be the most significant factor in emission, showing a power relationship between the abrader count and the emission flux ($R^2 = 0.76$). In the case of the loose surfaces, the presence of clay and silt was a major influence in emissivity, with a linear relationship between the two variables ($R^2 = 0.68$). This difference in factors depending on the agricultural disturbance, asks for a more holistic approach when predicting emission from such arid cropland areas.

1. Introduction

Dust emission is an important process that has an impact on climate (Boucher et al., 2013; Shao et al., 2011; Tegen et al., 1997), the global chemical flux (Lawrence & Neff, 2009; Mahowald et al., 2009), public health (Goudie, 2013; Sprigg, 2016), and the degradation of croplands (Bridges & Oldeman, 1999; Chappell et al., 2019; Chappell et al., 2012; Oldeman, 1992; Sterk et al., 1996; Visser & Sterk, 2007). Due to climate change, the emission of dust from disturbed soil surfaces from arid regions is expected to increase (Mahowald & Luo, 2003; Shepherd et al., 2016; Tegen et al., 2004; Woodward et al., 2005), which could enhance the on– and off-site effect of dust emission. Several studies have determined the sources of dust and the factors controlling the emissions. While remote sensing is suitable in the identification of emission hot spots (Vickery et al., 2013; von Holdt et al., 2017) small-scale factors that influence dust emission require detailed field observations (Bielders et al., 2001; Chappell et al., 2008; Goossens, 2004; von Holdt et al., 2019).

One region that has been recently identified as an important source for dust emissions, and is our focus here, is the central to north-western part of the Free State Province, South Africa (Eckardt et al., 2020) as seen from the MSG (Meteosat Second Generation) and SEVIRI (Spinning Enhanced Visible and Infrared Imager) imagery. It was reported that 71% of all South African dust sources in this record are situated in the Free State Province and are mainly associated with areas of extensive dryland crop farming, suggesting a strong anthropogenic origin of these dust emissions. This is in contrast to natural dust sources that have been identified as the dominant source areas for dust emissions in the rest of southern Africa, where the Etosha pan, the Makgadikgadi pan, coastal regions, and the Kalahari Desert are the main emitter of dust (Ginoux et al., 2012; Vickery et al., 2013; von Holdt et al., 2017). Despite the significant presence of pans in the Free State (Geldenhuys, 1982), the

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size of pans is still very small compared to the croplands area. Eckardt et al. (2020) described the land cover of a 10 km radius of the dust source points and found that less than 1% consists of pans, whereas 34% consist of agricultural land, and 55% of grassland and low shrubland.

Agricultural areas are predicted to be subjected to climatic changes, including an increase in wind velocities and a decrease in rainfall (Archer & Tadross, 2009; Mahowald & Luo, 2003; Thomas et al., 2005), which would enhance dust emission. The impact of soil degradation by wind erosion, due to the loss of nutrients and organic carbon from agricultural lands, leads to reduced land productivity (Sterk et al., 2001; Visser & Sterk, 2007). The dust sources identified from MSG (Eckardt et al., 2020) revealed a dust season from August till November (late winter and spring) which correlated with the crop cycle and farming practices. The dust season was particularly pronounced during the drought cycle in 2016, which left many of the fields fallow and without wind protection. However, significant dust emission patterns between fields and years were noted in the decade long dust record (Eckardt et al., 2020) which raises questions regarding factors that control the dust emission from South Africa's maize production areas.

The main characteristics that control the emissivity from a surface include soil composition, surface cohesion, and surface roughness and cover (Fryrear et al., 1998; McKenna Neuman et al., 2005; Shao et al., 2011; Webb et al., 2013; Webb & Strong, 2011). These parameters are determined by the soil texture and chemistry, the moisture content, the presence and characteristics of crusts, the aggregate content, the presence of clods, the roughness from tillage practices, and the presence of crops or stubble cover, among others (Funk & Engel, 2015; Gillette, 1988; Leys et al., 1996; Munkhtsetseg et al., 2017; Sterk, 2003). Two studies from the Free State provide some preliminary characteristics. Wiggs and Holmes (2011) described the importance of aerodynamic roughness on the threshold friction velocity, by monitoring a disturbed, bare field, where the roughness was the result of ridges and clods. The crusts that form on the croplands are expected to be physical crusts since biological crusts are sensitive to disturbance and develop slowly, a process that can take multiple decennia (Belnap et al., 2001). Vos et al. (2020) developed and tested physical soil crusts in the laboratory from soils sampled in the Free State. The study described a strong reducing effect of the soil crusts on the emission of dust, in comparison to the emission from surfaces with Loose Erodible Material (LEM) (Zobeck, 1991). Furthermore, Vos et al. (2020) found that even with the presence of abraders, dust emission from crusted sand and loamy sand surfaces is lower than from loose surfaces by a factor of 10. These recent findings contradict previous studies that described physical crusts on these soil types as weak, with little potential to minimize wind erosion (Rajot et al., 2003; Rice et al., 1999) due to the lack of fines. However, the soils in the Free State could have a range of soil textures, chemistry, cohesion, and abrasion conditions compared to those used in the laboratory. Furthermore, cropland crusts could have experienced more degradation and might have formed under different rainfall conditions. Therefore, it is important to compare the results from the laboratory study to dust emission measurements from croplands.

To determine the emissivity of a surface, wind tunnels have been used in many studies since this offers a precise indication of the losses from a surface and response to measured wind velocity (Belnap et al., 2007; Fister & Ries, 2009; Leys & Eldridge, 1998; Li et al., 2015; Liu et al., 2006; McKenna Neuman & Scott, 1998). The disadvantage of wind tunnels is their large size, which makes it time-consuming to deploy the instrument and to measure on smaller surfaces. An alternative method is the Portable In-Situ Wind Erosion Laboratory (PI-SWERL) (Etyemezian et al., 2007). The PI-SWERL consists of a 30 cm diameter chamber that is placed on a surface, with an annular blade that exerts a controlled friction velocity to the surface. The particles with a diameter below 10 μm (PM_{10}) that are emitted as a response is measured with a DustTrak 8530. The advantage of the PI-SWERL, in comparison to wind tunnels, are its small size, lower weight, and high frequency of measurement runs, which enables many repeated measurements in a relatively short time. The major disadvantage of the PI-SWERL is its shallow annular blade (at 5 cm height) and lack of a naturally developed logarithmic wind profile, making it less representative of natural wind erosion and determining the influence of surface roughness then requires a separate assessment (Bacon et al., 2011; Etyemezian et al., 2014). Despite these disadvantages, the PI-SWERL was successfully used under laboratory conditions to assess dust emissions from crusts and loose substrates (van Leeuwen et al., 2021; Vos et al., 2020) and on different surface types in various regions of the world. Field studies have been performed on grasslands (Munkhtsetseg et al., 2017; Munkhtsetseg et al., 2016); alluvial landscapes (von Holdt et al., 2017; von Holdt et al., 2019); mining areas (Wang et al., 2015), and a variety of desert landforms (Bacon et al., 2011; Cui, Lu, Wiggs, & et al., 2019; Cui, Lu, Etyemezian, & et al., 2019; Sweeney et al., 2016; Sweeney & Mason, 2013). Despite this large number of PI-SWERL studies, agricultural lands have received little attention so far, with the exception of Cui et al. (2019a). As emissions from agricultural surfaces represent between 10% (Tegen et al., 2004) and 25% (Ginoux et al., 2012) of global dust sources, it is paramount to understand such areas and the PI-SWERL presents the perfect opportunity to assess these surfaces.

Combining the need to further understand the relevance of crusts for reducing dust emissions from sandy dryland soils, the respective soil and surface properties, the processes that influence emissions in real-world conditions, and the suitability of the PI-SWERL to determine emissivity on cropland, the aims of this study were:

1. Determine to which extent physical soil crusts minimize dust emissions from cropland.
2. Determine the main factors that influence the emissivity of croplands from loose erodible material and crusted surfaces.
3. Determine how the emission from field surfaces compare to the emissions from laboratory surfaces.

In order to achieve these aims, this study combines dust emission measurements using PI-SWERL, data and observations, describe soil surface properties, such as moisture content, soil texture, carbon content, and surface cohesion. In addition, the emission from a pan and an adjacent grassland were measured to generate a reference emission value for dominant land cover and known dust sources. The research was carried out from August to October 2019 (the winter dust season) in the Free State province of South Africa. Measurements were made on crusted and loose erodible material surfaces at different fields with different agricultural management.

2. Methods

2.1. Study area

The study area is in the north-western part of the Free State, 100 km north of the State capital, Bloemfontein (Fig. 1). This area has been identified as a hotspot for dust emission (Eckardt et al., 2020) in southern Africa. This region was also chosen because it enables the investigation of two different soil types that are predominant in the region and known for sustaining agriculture: Luvisols and Arenosols (Jones et al., 2013). Both soil types are characterised by their sandy texture, which makes them highly suitable for water storage under the local climatic conditions (Hensley et al., 2006) and therefore suitable for dryland cropping.

The Free State has a semi-arid climate, with annual rainfall ranging from 400 to 600 mm (Hensley et al., 2006), 80% of which takes place between November to April (summer). During the dust event months, which is mainly between August and November, the average daily maximum wind velocity is 5.4 m s^{-1} and 10% of the days have a maximum wind speed above 7.7 m s^{-1}. The rainfall is on average 104 mm in total during the main dust season. The climate in the study area has been described in more detail by Vos et al. (2020). The main crop

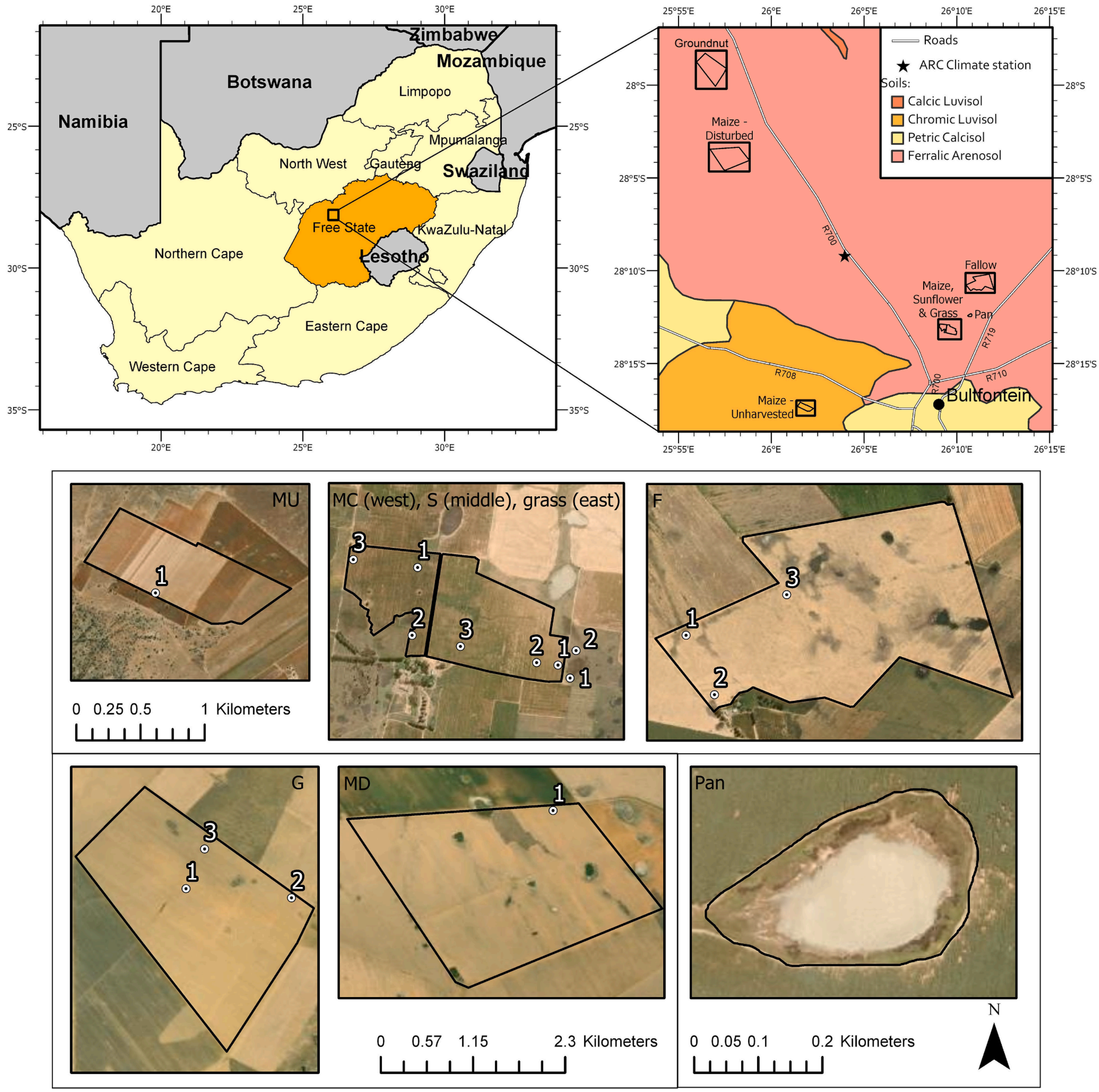

Fig. 1. Maps depicting South Africa and the Free State province (top left) and the selected study area and test fields with dominant soil types (top right). The aerial images below illustrate the individual fields that were selected for emissivity measurements with respective positions of test plots. Soil data from the Soil and Terrain Database (SOTER) for South Africa (FAO-ISRIC-2).

produced in this region is corn (maize) with about 82% of the total crop production in the Free State (DAFF, 2018). This is followed by sunflower (7%), soybean (6%), wheat (4%), and groundnuts (1%). Most of these crops are planted at the beginning of the rainy season and harvested between May and August. There are few exceptions from this cycle, for example, winter wheat, which is planted at the end of July as a cool-season fodder crop.

2.2. Field description

Six agricultural fields were selected for the field measurements: a fallow field (F), a harvested groundnut field (G), a harvested sunflower field (S), an unharvest maize field (MU), and two harvested maize fields (maize-crusted (MC) and maize-disturbed (MD)) (Figs. 1, 2, and Table 1). Furthermore, a pan and two grassland plots were selected for comparison measurements. All the agricultural fields were situated on Arenosols, apart from the unharvested maize field that was on a Luvisol. These fields were chosen for their variety of agricultural management practices, which resulted in a range of different surface characteristics, such as regarding soil crusts, roughness, cohesion and aggregate content. It should be noted that the crop type on each field can be alternated each year so that the used names are only a descriptor for the crops and agricultural management in the specific season preceding the fieldwork. The sunflower field was harvested at the end of July. Bordering on the west of the sunflower field is the crusted maize field, which was a field with crusted surfaces and tire tracks. On the disturbed maize field, the removal of loose plant material resulted in the disturbance of the crust. The peanut field was harvested by removing the entire plant, leaving no

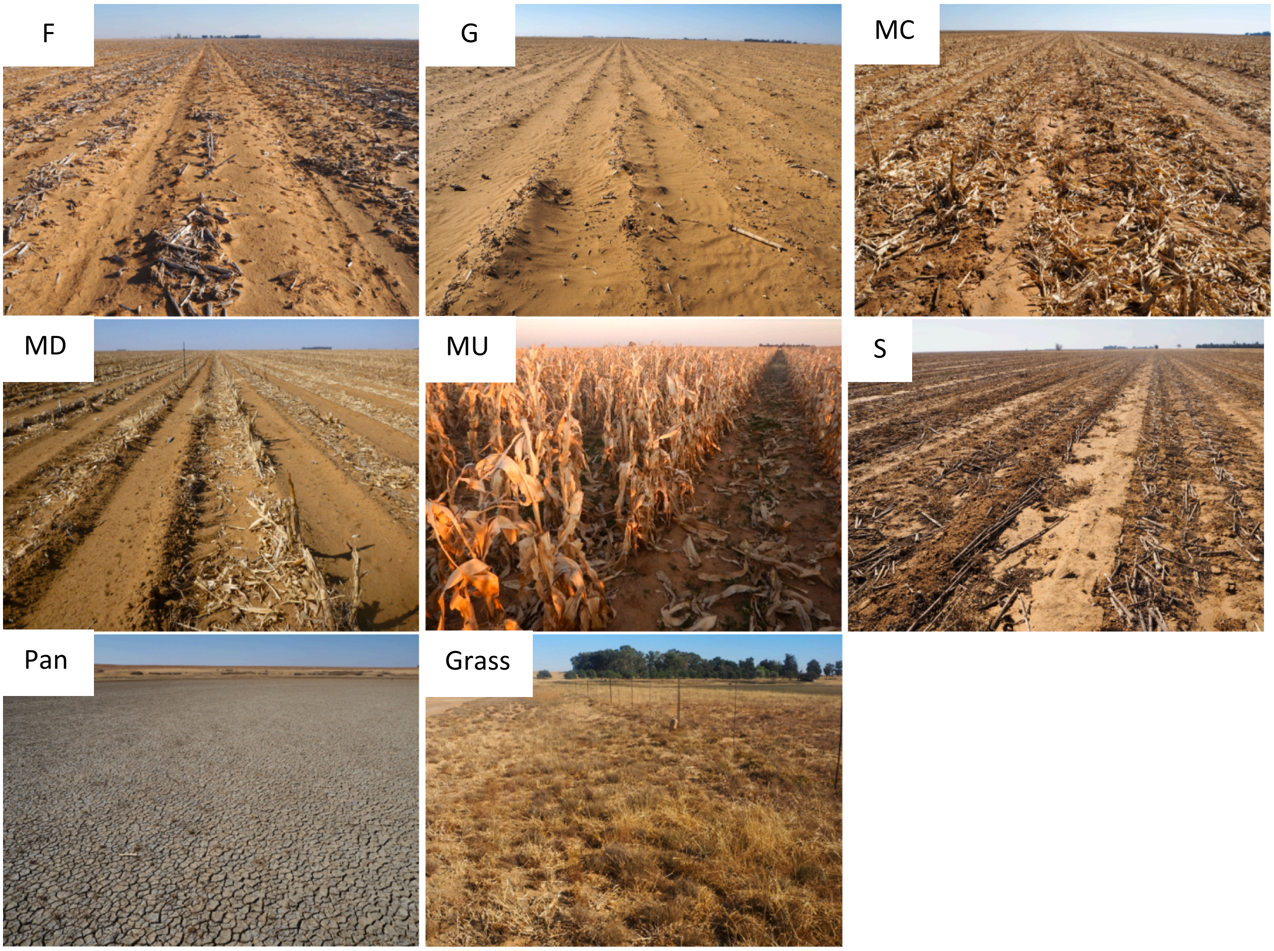

Fig. 2. Examples of the six fields that were selected for field measurements.

Table 1
Overview of the fields that were selected for this study. The plots, PI-SWERL runs, and surface types are explained in the text.

Field	Abbreviation	Plot count	PI-SWERL count	Surface types
Fallow field	F	3	48	Crust
Groundnut	G	3	48	Crust and sand deposits
Sunflower	S	3	40	Crust and loosened soil
Maize Unharvested	MU	1	2	Crust
Maize Crusted	MC	3	38	Crust and loosened soil
Maize Disturbed	MD	2	3	Loosened soil
Grassland surface	–	2	14	–
Pan	–	Cross-section	37	–

stubble on the ground, which made this field different from the maize and sunflower fields that still held some stubble. The peanut field showed sand deposits with ripple marks that covered the crusts, which is a sign of active movement by wind. The fallow land had not been planted the previous year and has been treated with herbicide (Roundup). Because this field has not been disturbed, it was fully covered with a soil crust. The selected Luvisol field carried unharvested maize and consisted fully of crusts. The selected grassland was not cultivated due to the high clay content in this area (personal communication with the farmer, Mr H. Prinsloo). The pan had a surface area of roughly 5 ha and consisted mainly of a clay surface, with salt deposits at the rim.

The measurement sites were chosen using a stratified randomized approach. For each field, one to three plots which covered roughly a 10 × 10 m area, were selected for measurements (Fig. 1). These plots were selected based on a textural gradient or, when no clear texture gradient was initially visible, a spatial distribution. Fig. 3 illustrates that a significant variation in grain size exists, both, between and within the fields. In general, the peanut field, sunflower field, and maize-disturbed field had the lowest concentration of clay and silt, whereas the

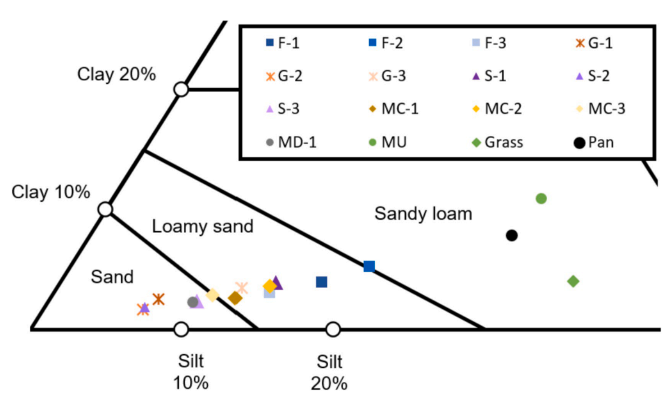

Fig. 3. Average soil texture of the field plots (F = Fallow, G = Groundnut, S = Sunflower MC = Maize Crusted, MD = Maize Disturbed, MU = Maize Unharvested, Grass = Grassland surface).

unharvested maize field with the Luvisol soil has the largest concentration. The within-field variation in texture appears to be the most significant in the peanut and sunflower fields, which were the fields where a texture gradient was present. For the pan, a cross-section was made along which was measured to capture the heterogeneity of the pan.

Within each plot, crusted and LEM surfaces that held less than 5% clods were randomly selected for PI-SWERL measurements. The LEM surfaces consisted of sand deposits and soil that was loosened by tracks (Fig. 4 and Table 1). In the field, clod content was estimated based on charts for surface proportion estimates. Later, the surface areas of the clods were determined by measuring the diameter and counting the number of clods in an image of the areas sampled by the PI-SWERL. Surfaces with more than 5% clods were excluded because the quality of PI-SWERL measurements on surfaces with high roughness is not well understood (Bacon et al., 2011; Etyemezian et al., 2014). Since the aim of this study was to understand the emissions of loose substrates and crusts in the field, this omission did not limit the scope of this study.

2.3. PI-SWERL measurements

The PI-SWERL is an instrument that has been used by many different studies to assess the emissivity of small, flat surfaces, which can then give insight into the emission potential of different landforms and the controlling factors and processes (Etyemezian et al., 2007; Sweeney et al., 2016; von Holdt et al., 2019). The PI-SWERL used for this study has a diameter of 30 cm. The instrument was placed on representative areas, avoiding large stubble and clods that could disturb the airflow inside the PI-SWERL (Fig. 5). A PI-SWERL run consisted of 30 s at 0 RPM, after which the RPM was increased to 2250 RPM in 120 s, where it was kept for 5 min. At the end of the run, the RPM was brought back to zero in 10 s. An RPM of 2250 is in accordance with a friction velocity of 0.56 m s^{-1} assuming an alpha value of 0.90 as described by Etyemezian et al. (2014). This is a friction velocity that is similar to the one used in most PI-SWERL (Sweeney et al., 2011; Sweeney et al., 2008; Sweeney & Mason, 2013; von Holdt et al., 2019). It represents a wind velocity of approximately 11 m s^{-1} at 2 m height, a common velocity during wind events in the Free State and has been linked with observed dust events (Eckardt et al., 2020; Vos et al., 2020). This friction velocity can mobilize particles above 1 mm diameter, according to models from both Bagnold (1941) and Greeley and Iversen (1985). For each run, a DustTrak 8530 measured the PM_{10} concentration from which the emission flux, E_{PI} in mg m^{-2} s^{-1} can be calculated using the formula from Sweeney et al. (2008):

$$E_{PI,i} = \frac{\sum_{begin,1}^{end} {}^{*}C^{*}F^{*}1s}{\left(t_{end,i} - t_{begin,i}\right)^{*}A_{eff}}$$

Whereby C is the PM_{10} concentration in mg m^{-3}, F is the blow rate in m^3 s^{-1} which was approximately 0.1 m^{-3} s^{-1} throughout the run, t_{begin} is the start time and t_{end} is the end time in seconds of the aimed RPM step *i* (in this case 2250 RPM), and the A_{eff} is the effective surface which was 0.035 m^2. The PI-SWERL is also equipped with four Optical Gate Sensors (OGS), which measured the number of saltating particles passing the sensor, expressed in Hz, as described by Etyemezian et al. (2017). The count of the four sensors was averaged for the analyses on the abrader quantity during the PI-SWERL run.

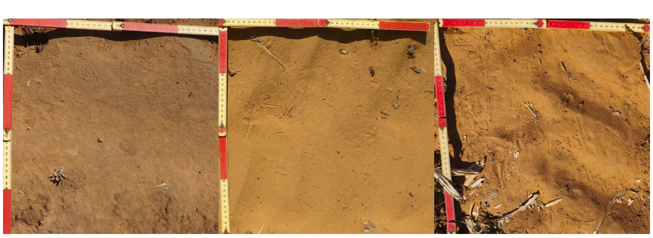

Fig. 4. Examples of the surface types: left crust (S), middle sandy deposit (G), and right loosened soil (MC).

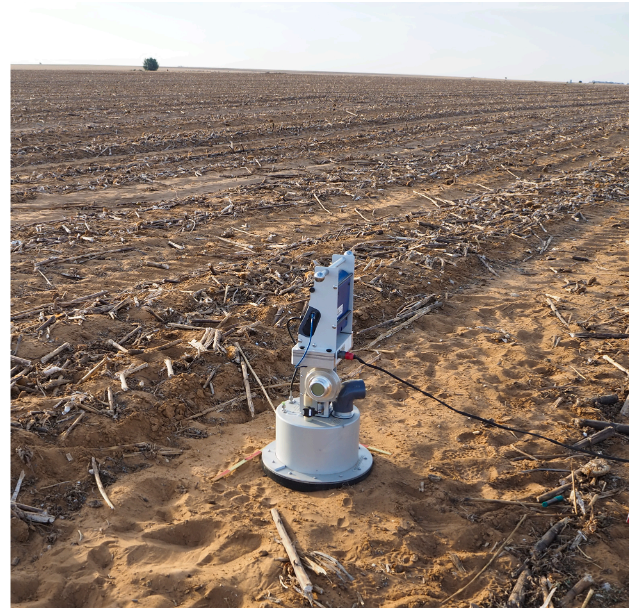

Fig. 5. The PI-SWERL performing a measurement in the sunflower field.

Multiple PI-SWERL runs were conducted at each test plot on the six different fields. In order to increase the number of PI-SWERL measurements, without simultaneously increasing the time necessary to describe the positions and to take samples, pairwise test runs were chosen as the best solution. It was assumed that soil moisture, texture and roughness did not change significantly between the two directly adjacent positions. Therefore, only the surface strength measurements were done individually for all test runs.

2.4. Surface characterisation

For each PI-SWERL run, the soil surfaces were characterised to determine which factors control their emissivity. The soil properties that were measured are the surface strength, soil texture, moisture, and aggregate content. The surfaces were furthermore classified based on their morphology and structure into crusts or LEM surfaces, from which the latter can be split into loosened soil or sand deposits.

The surface strength was regarded as the most important indicator for the emission potential, both for crusted surfaces (Feng et al., 2013; Goossens, 2004; Houser & Nickling, 2001; Rice et al., 1996; Rice & McEwan, 2001; Sharratt & Vaddella, 2014), as well as non-crusted surfaces (Goossens & Buck, 2009; von Holdt et al., 2019). The surface strength was measured with a torvane, an instrument that measures the torsional shear stress before failure in kPa, commonly used in wind erosion studies (Ellis et al., 2012; Gillette et al., 2001; Goossens, 2004; Goossens & Buck, 2009; Li et al., 2010; Sweeney & Mason, 2013; von Holdt et al., 2019). The torvane used in this study is custom-designed to capture the strength of just the topsoil surface and consists of eight blades with a penetration depth of three millimetres (Kuhn & Bryan, 2004). For each PI-SWERL run, 10 torvane measurements were performed next to the test surface and averaged.

For each pairwise PI-SWERL set, one sample each was collected for the measurement of soil moisture and soil texture. This aggregated sampling was executed in order to minimize the total number of soil samples, because a significant variability in soil texture and soil moisture was not expected within the distance of 1 m. The samples were taken from the top 1 cm to capture the characteristics of the surface exposed to the dust emission experiment. The soil samples were afterwards dried and analysed for their moisture content, grain size, and carbon content, using a Malvern Mastersizer 2000 and a Leco RC612, respectively. To disperse the sample before the grain size measurements, the samples were sonified at 60 J ml^{-1} in 12 s with no chemical dispersant. The moisture content was measured gravimetrically by drying the samples at 100 degrees Celsius. The effect of soil moisture on the emission of a surface has been described elsewhere (Cui et al., 2019b; Funk et al., 2008; Munkhtsetseg et al., 2016; von Holdt et al., 2019; Wang et al., 2015). The relative humidity and air temperature were recorded during the PI-SWERL measurements.

2.5. Statistical analyses

The statistical difference between crusted and LEM surfaces per field plot was determined using two-tailed t-tests, with an alpha value of 0.05 to determine statistical significance. A Boosted Regression Tree (BRT) machine learning analysis was used to determine the relative importance of and interactions between the measured soil surface properties and the emission flux from these surfaces as measured by the PI-SWERL (Elith et al., 2008). A BRT model was used by Von Holdt et al. (2019) to investigate the relationships between surface properties and emission flux measured with the PI-SWERL in the alluvial landscapes of Namibia. The BRT analysis provides the relative influence each input variable has on the dependent variable, which is in this case the emission flux measured by the PI-SWERL. The BRT models were run with the R package *gbm* was used (Ridgeway, 2007). A learning rate of 0.01, an interaction depth (or tree complexity) of 5, a bag fraction of 0.6, a cross fold of 10, and a maximum number of 1000 trees was used.

Per surface type, two different BRT analyses were performed. The BRT analyses presented in the text contains the main variables of interest, namely the surface shear strength, soil moisture, clay and silt content, and the content of Total Organic Carbon (TOC). For the crusted surfaces, also the OGS counts have been used which represents the count of abrading sand grains during a run. This can be regarded as an external factor for the emission flux in the case of undisturbed crusts. For the LEM surfaces, the OGS count is regarded as an indication of the disturbance or texture, rather than an external influence on emission. The clay and silt contents have been chosen as the only property to represent soil texture since there is a large covariance between these values and the sand content. Using all of these texture-related parameters would have reduced the strength of results received by this method. The second BRT analyses contain all the parameters that were measured, e.g., the surface shear strength, soil moisture, clay and silt content, TOC, Total Inorganic Carbon (TIC), and air humidity and air temperature. These analyses were performed to put the results of the first BRT in a wider context, at least qualitative, even if this is outside the immediate scope of the paper.

3. Results and discussion

3.1. Surface conditions and PM_{10} emissions

The results from the PI-SWERL runs and shear strength measurements show that crusted surfaces have the lowest emissions in general, but show significant variance per field (Fig. 6 and Table 2). In contrast, loosened soils are the most emissive surfaces, among which the highest emissions are from loosened soil in maize fields. The sand deposits in the peanut field, which can be associated with wind erosion, had a much lower emission than the loosened soils. T-tests of the emission fluxes between surface types on each field plot, where statistical significance is defined as $p < 0.05$, show that the LEM surfaces, the loosened soils and the sand deposits, have a higher emission flux than crusted surfaces. Regarding shear strength, crusted surfaces have a much higher average cohesion, considering the average is between 11.1 and 14.1 kPa for crusted surfaces and between 4.5 kPa and 6.9 kPa for loose surfaces. This

Table 2
The results from the PI-SWERL measurements at a friction velocity of 0.56 m s^{-1} per field and surface type. For shear strength measurement per PI-SWERL run n = 10.

		Flux emission (mg s^{-1} m^{-2})		Shear strength (kPa)		Average OGS count (Hz)	
Type	Count	Mean	σ	Mean	σ	Mean	σ
Crust	133	0.48	0.35	13.4	3.6	104	79
Sand deposit	18	0.57	0.22	6.1	1.7	291	178
Loosened soil	28	2.34	1.47	4.6	1.6	348	256

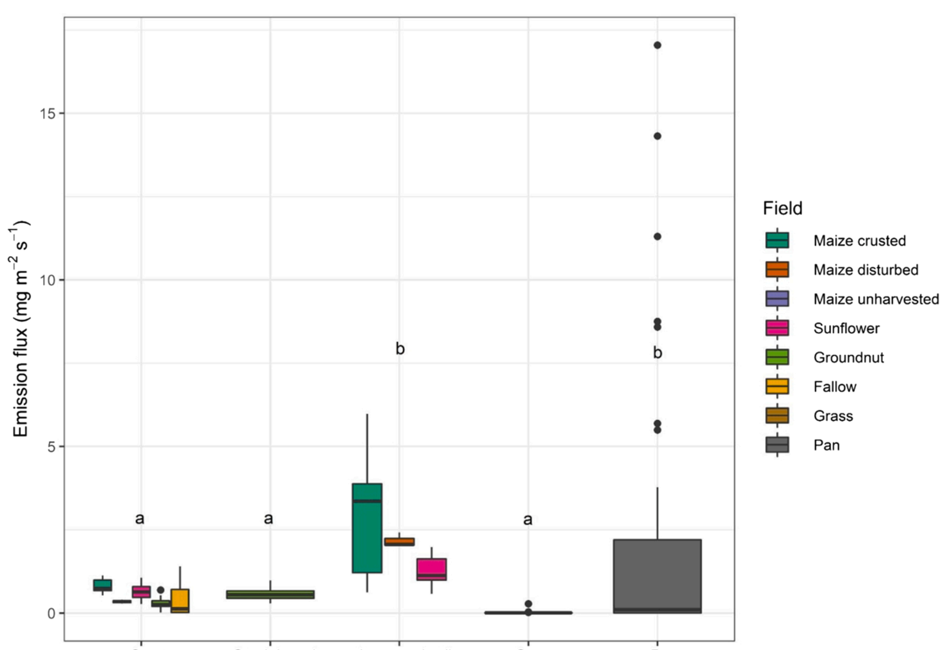

Fig. 6. The emission flux of each surface type per field as measured by the PI-SWERL at a friction velocity of 0.56 m s^{-1}. The dotted plots show the outliers that are more than 1.5 times higher than the difference between the 1st and 3rd quartile.

relationship is reversed for the average OGS count, which is significantly higher for the LEM surfaces (between 291 Hz and 452 Hz) than the crusted surfaces (between 56 and 111 Hz).

The cropland surfaces have an average emission of 0.78 mg m^{-2} s^{-1} and are relatively high in comparison with other studies. Von Holdt et al. (2019) for example measured average emissions from LEM surfaces of 0.32 mg m^{-2} s^{-1} and for medium and high saltator crusts 0.086 mg m^{-2} s^{-1} and 0.34 mg m^{-2} s^{-1}, respectively. The arable land measured by Cui, Lu, Etyemezian, and et al (2019), Cui, Ku, Wiggs, and et al. (2019) also showed lower average emissions of 0.231 mg m^{-2} s^{-1}. By comparing dust emissions from agricultural fields to emissions from natural grassland or pan surfaces their relative importance can be seen, despite the fact that causes and processes, for example, drag absorption by plants, are different. Grassland surfaces show very little dust emission (0.03 mg m^{-2} s^{-1} on average), whereas pans can show very high emissions, which are statistically comparable to the ones from loosened soils. The variance of emissions from pans is very high however, and the median of the emission flux is as low as that of crusted surfaces. Additional data on the measurements on the pan and grassland surfaces are shown in the supplementary materials (Table S1), which again demonstrates the high variability of surface characteristics within the pans. Combining this with their small size in comparison to that of agricultural fields indicates that more observations on Free State pans are required for a full assessment of their contribution to dust emissions. In contrast, grasslands can be considered insignificant, when it comes to dust emission in this region.

3.2. Surface properties determining emissivity on all sites

The generated data set can be used to identify the most relevant soil surface properties for emissivity by performing BRT analyses. The first analysis comprised the entire data set and aimed at identifying the main controlling factors for emissivity. The results of this analysis are shown in Fig. 7, with the relative influence (in %) and the marginal effect of each factor. Hereby the marginal effect represents the influence of a variable on the emission flux without the influence from any of the other variables. These results show that shear strength has the greatest influence, with a relative influence of 74.7%. The marginal effect of shear strength shows the highest value below 5 kPa, where it has a value of 2.5, and the lowest value above 10 kPa, where it has a value of 0.5. This would mean that the shear strength alone increased the emission flux five-fold for our dataset when it is below 5 kPa compared to when it is above 15 kPa. Between these values, the marginal effect shows a steady decrease, which could represent an almost linear or exponential negative relationship between shear strength and emission flux when only these two values are considered. It is important to note however that the marginal effect is calculated with the BRT analysis and is not based on any functional relationship. The high relevance and the marginal effect of the shear strength explain the high emissions observed on the loosened soils because these surfaces had the lowest shear strength (Fig. 8). They also indicate that shear strength above 15 kPa is most effective in reducing emissions, which matches with the low emission from the crusted surfaces.

The BRT analysis furthermore shows a small positive influence of the TOC content, with the most significant increase in marginal effect being between 0.1 and 0.3%. This means that above a TOC of 0.3%, the influence of a change in TOC on emission is neglectable. The moisture content has a low effect, which was expected since the measured moisture content (0.25% mean, 0.17% STDV, 0.81% maximum) was below the level where moisture is described to have an effect, which is above 1% (Cui et al., 2019b; Funk et al., 2008; Munkhtsetseg et al., 2016; von Holdt et al., 2019). This would of course only be relevant for our PI-SWERL measurements, since moisture could still be a relevant factor for the temporal variability of wind erosion, as described by Wiggs and Holmes (2011). Surprisingly, the clay and silt content can be considered insignificant for the emission, when differences in surface type are not considered. Similar results can be found in the BRT analysis including the complete variable set (Supplementary). This analysis also shows a high importance of humidity and temperature, which is an influence also described by Etyemezian et al. (2019) and McKenna Neuman (2004). Since daily weather conditions and access to sampling sites limited the ability to carry out PI-SWERL tests systematically at constant relative air humidity and soil temperature, more research should be done to the influence of these variables. Also in this analysis, the shear strength remains the variable with the highest relative influence.

3.3. Surface properties determining emissions on individual surface types

The large relative influence of shear strength when considering all

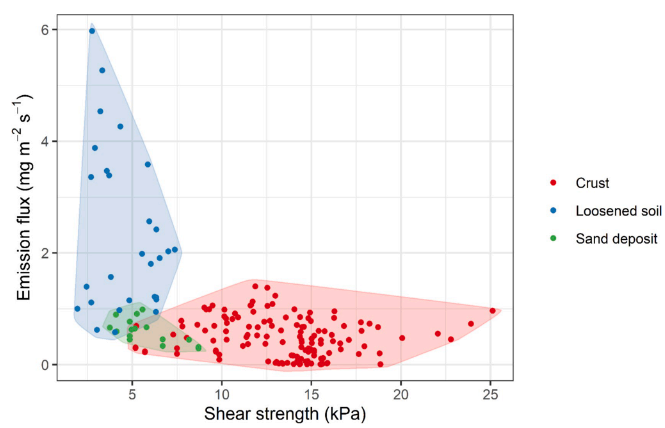

Fig. 8. The average shear strength of the agricultural surfaces versus the emission flux at a friction velocity of 0.56 m s^{-1}.

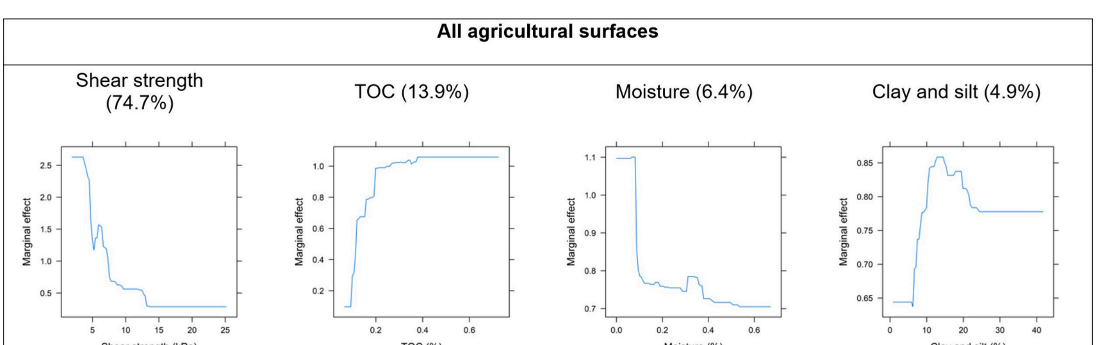

Fig. 7. The results from the BRT analyses on the whole data set, showing the relative influence on the emission flux in percentage for each variable, and the marginal effect of this variable.

surface types may mask some unexplained variability for individual surfaces (Fig. 8). The crusts and loosened soils show no significant relationship between shear strength and emission flux ($R^2 = 0.08$ and 0.02 for the crusts and loosened soils, respectively) and the sand deposits show a negative trend with a R^2 of 0.48. The loosened soils have a very large range in emission (between 0.5 mg s^{-1} m^{-2} and 6 mg s^{-1} m^{-2}) that is not explained by a difference in shear strength. For example, a low emission has been measured on the sand deposits, regardless of their low shear strength. To determine the factors that are most important for the difference in emissivity of these surfaces, additional boosted regression tree models have been performed. This was done on the separate data of the crusted surfaces and on the LEM surfaces, which are the loosened soils and sand deposits. This separation will enable the identification of soil properties influencing the emissions from crusted and non-crusted surfaces.

3.3.1. Emissivity controls on crusted surfaces

For the BRT analysis of the crusted surfaces, the OGS count has been added to the data set. This was done because saltating grains and abrasion have been described as relevant external factors for emissions from crusted surfaces (Houser & Nickling, 2001; Klose et al., 2019; McKenna Neuman et al., 1996; McKenna Neuman & Maxwell, 1999; Rice et al., 1999; Rice et al., 1996; Rice & McEwan, 2001; Zobeck et al., 2003). The results show that the OGS count is indeed the most prominent factor for crusted surfaces with a relative influence of 68.2% (Fig. 9). The marginal effect of the OGS shows that the saltation count influences the emissivity greatly up to approximately 150 Hz. OGS count and the emission flux display a significant power relationship (Fig. 10) which demonstrates that saltating sand is indeed an important trigger for the emission of dust from crusted surfaces on Free State cropland. Considering that the abraders that trigger emission from crusts might originate from nearby disturbed or loosened soil surfaces, indicates that indirectly, the non-crusted surfaces could thus increase the emission on crusted surfaces. Consequently, the importance of minimizing the disturbance of crusts to limit the emissivity is also dependent on the interaction of crusted patches with adjacent surfaces.

The BRT shows a small influence, almost binary relationship of the shear strength, with a threshold around 15 kPa. This shear strength value has also been identified by Goossens (2004) to be a threshold for the resistance to dust emissions from a crusted surface. However, the small relative influence of the crust strength (12%) indicates that such a high crust strength is not a prerequisite for a crust to prevent dust emission. Furthermore, the texture and chemistry of the soil appear to be almost insignificant for the emission from crusts. This points towards the universal protection soil crusts offer in relation to the presence of abraders.

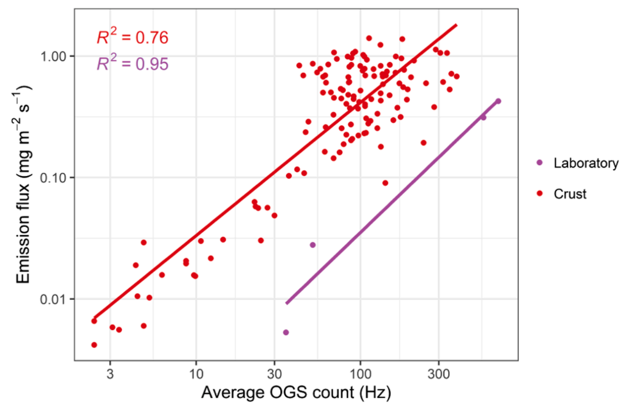

Fig. 10. The OGS count versus the emission of the field crusts and the average emission from laboratory crusts from Vos et al. (2020). Note the logarithmic scale of the OGS plot.

3.3.2. Emissivity controls on LEM surfaces

Fig. 11 shows the result of the BRT analysis for the LEM surfaces, which consist of the loosened soils and sand deposits. The most important factor is the clay and silt content with a relative influence of 44%. This influence of clay and silt is confirmed when plotting the clay and silt content versus the emission flux (Fig. 12). The emission from purely LEM soils is increased by the presence of clay and silt, as described by Wang et al. (2015), Madden et al. (2010) and Sweeney and Mason (2013). This shows that the most emissive surfaces can be found on LEM surfaces with a higher clay and silt content (up to 20%). The sand deposits were notable due to their low emission, despite their very low cohesive strength. The low content of clay and silt in the sand deposits would be the result of a depletion of these particle sizes in the surfaces by previous wind erosion events. The high degree of sorting also explains the very low shear strengths of the sand deposits. This can also be seen when comparing the clay and silt from the sand deposits (1.3% and 4.2% clay and silt, respectively) to the crusts on the same test plot or field (2.7% and 9.2% clay and silt, respectively). The relevance of fines for dust emissions also illustrates that sandy surfaces, which are highly vulnerable to wind erosion, are not necessarily emitting large quantities of dust, because they could have been depleted of it.

3.4. Laboratory and field comparison

The third objective of this study was to compare the results from the field measurements to the measurements carried out in the laboratory by Vos et al. (2020). In their study rainfall simulations with 15 mm of rainfall were used to create physical crusts on small soil plots. Emissions

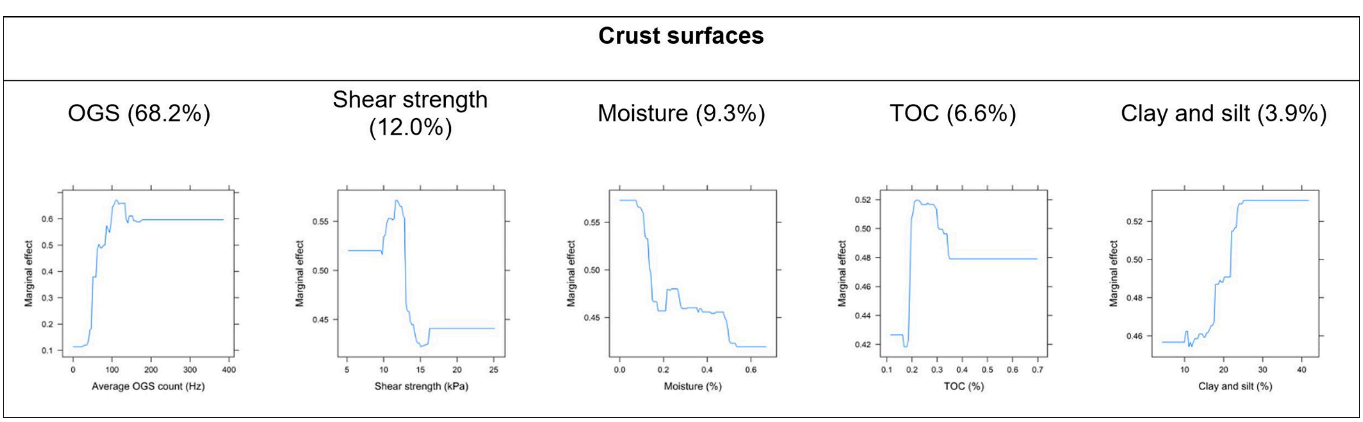

Fig. 9. The results from the BRT analyses on the crust data, showing the relative influence on the emission flux in percentage for each variable, and the marginal effect of this variable.

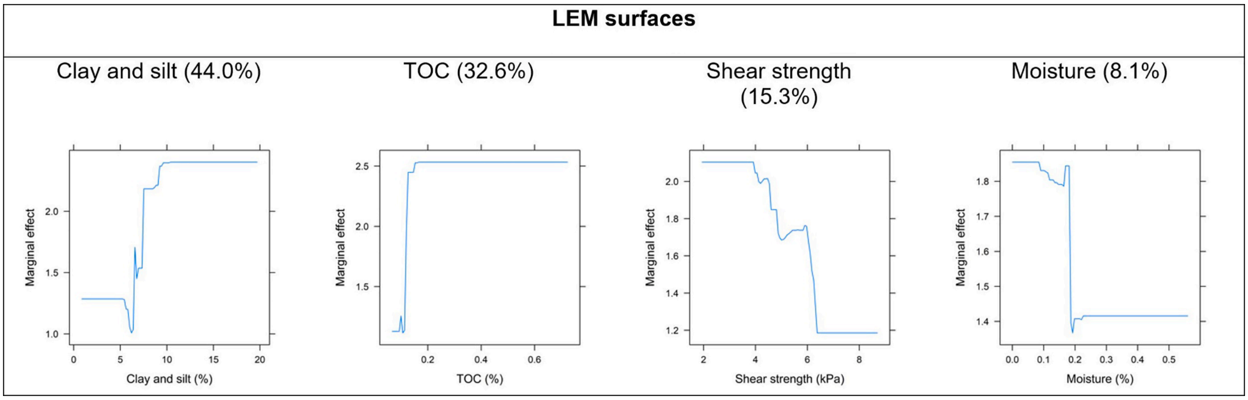

Fig. 11. The results from the BRT analyses on the LEM data set (including the sand deposits and loosened soil), showing the relative influence on the emission flux in percentage for each variable, and the marginal effect of this variable.

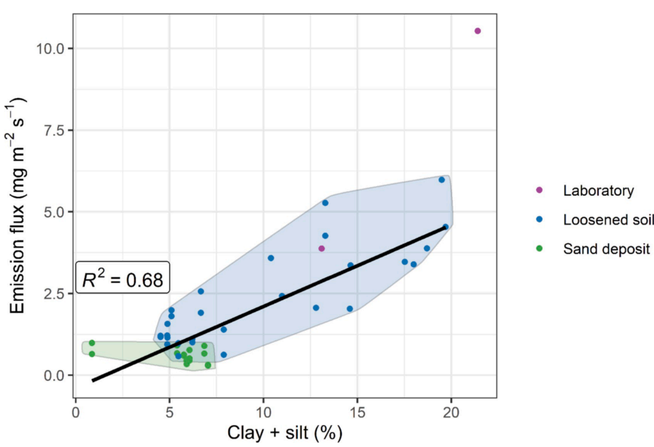

Fig. 12. The clay and silt content versus the emission flux at a friction velocity of 0.56 m s^{-1}, including the average laboratory data from Vos et al. (2020).

from these crusted surfaces were then compared to emissions from non-crusted, loosened soil by using the PI-SWERL. The results showed that the emission from crusted Arenosols and Luvisols are 0.14 and 0.26%, respectively, of that of a loose surface. When introducing sand particles acting as abraders on the crusts, which simulates a likely scenario in the field, emissions observed in the laboratory were still only 10% of those observed on loose soil in the laboratory. The soils used in the laboratory study had a texture and shear strength similar to those in the field (Table 3). Comparing this data with the PI-SWERL measurements carried out for this study, the effect of crusts on dust emission appears smaller on actual cropland. This can be attributed to both, a higher emission from the field crusts and a lower emission from the loose surfaces in the field.

When looking at the influence of saltators on the emission of crusts (Fig. 10), laboratory and field crusts show a similar power relationship. However, at a similar OGS count, emissions in the lab were a magnitude smaller. This could be explained by loose fines that settled on these field surfaces after wind events, and that get suspended again easily. These fines would be absent from the laboratory crusts. We furthermore speculate that this difference could also be caused by a difference in the composition of the abraders in the field and laboratory measurements. Grainsize measurements on the loose particles collected on field crusts showed an average of 5% clay and silt, whereas the abraders in the lab were sonified to rid them of fines, before being used as abraders. This means that in the lab, no additional emission of fines from the abraders took place which is in contrast to field measurements. Lastly, the crusts in the field could have been exposed to degradation which could have increased the emission from these crusts and the sensitivity to abraders. This degradation could have been caused by freeze-thawing processes and previous abrasion (Liu et al., 2017; Wang et al., 2014). While field and laboratory results generally indicate a similar effect of crusts on dust emissivity, the differences between them also highlight the risk of an overassessment of the relevance of crusts when looking at laboratory results alone.

When it comes to the loose surfaces and their relationship to texture, there is an overlap between the field and laboratory surfaces (Fig. 12). The laboratory and field surfaces show approximately a similar relationship between texture and emission flux. The laboratory Arenosol plots in the same region as the field measurements, whereas the laboratory Luvisol has a higher clay and silt content and therefore a higher emission. The disturbance on the unharvested maize field, which held the Luvisol soil, left a much more aggregated surface with a higher roughness, which is why there was no measurement on a loose Luvisol soil. The sieving of soils before laboratory measurements could disturb a soil to a degree that might not always occur in the field, which should be taken into account for laboratory measurements.

4. Conclusion

The objectives of this study were to (1) determine the extent to which physical soil crusts reduce dust emissions from croplands, to (2) determine which factors influence the emissivity from loose and crusted surfaces, and to (3) compare emissions from laboratory surfaces to field surfaces. The dust emissions of the croplands appear much higher than of bare grassland soils, which is the largest surface area in the Free State. While the pan showed a dust flux statistically similar to that of the loose soil, more information on their emissivity is required. However, pan emissions would probably not match those of the cropland due to their

Table 3
The average shear strength and soil texture of the laboratory crusts from Vos et al. (2020).

	Emission (mg s^{-1} m^{-2})			Clay (%)	Silt (%)	Sand (%)	Crust shear strength (kPa)
	Crust	Crust with abrader	Loose				
Arenosol	0.00053	0.311	3.872	2.7	10.4	86.9	17.4
Luvisol	0.0278	0.425	10.534	6.3	15.1	78.4	21.5

small cumulative size. The cohesion of a surface, expressed as shear strength, appears to be the main factor influencing dust emissions on croplands. This influence can be seen in the lower emissions of the cohesive crusts, in comparison to the less cohesive loosened soils and sand deposits. Considering that crusts can build up quickly, even during the dry season (Vos et al., 2020), physical soil crusts could be the main factor limiting dust emissions from bare fields with low roughness and cover. This is in strong contrast to the conventional assumption that the clay and silt content of sandy soils are too low to form strong crusts (Rajot et al., 2003; Rice et al., 1999). The dust emissions from crusts themselves are controlled by the presence of abraders, which can originate from adjacent non-crusted surfaces. This shows that besides the higher emission from loose surfaces in the first place, these loose surfaces can have an additional increasing effect on emissions from crusted surfaces. In the case of the fallow field, we speculate that the unlimited supply of abraders originates from bordering disturbed fields and that without these abraders, emissions from the fallow field would be much lower. Consequently, the emissions from the fallow field could be limited even further by keeping mobile sand to a minimum, e.g. by increasing sand traps such as fences or vegetation, maintaining a residue cover or crusts, and stabilizing sand on margins with vegetation.

The influence of texture on dust emissions appears to be ambiguous in our study since it is not identified as highly relevant when analysing the whole data set. However, it does appear to be a major influence for emissions from loose surfaces, where the presence of clay and silt increases the emission. This relationship does not take into account that higher contents of clay and silt could also potentially result in the development of clods and thus higher surface roughness. An increase in clay and silt could then increase the threshold friction velocities and reduce dust emissions. However, due to the very low content of clay and silt in the soils investigated in the Free State, this context was not within the scope of this study. The influence of texture also explains the unexpected low dust emissions from the sand deposits where depletion of fines had caused soil degradation by wind erosion. This also suggests that the fields that show the most signs of wind erosion, such as moving or ripple marks, might not be the fields that actually emit the most dust in their current state due to this degradation.

Our results are in line with the laboratory measurements from Vos et al. (2020) that showed a large difference in emissions between crusted and loose surfaces. For crusted surfaces, the field measurements showed that the majority of the crusts are subjected to abraders which leads to higher emissions. When taking the influence of abraders into account, field crusts still have a greater emission than in the laboratory, which could be the result of degradation of the surface and loose fines on top of the surface. For loose surfaces, the laboratory results are comparable to loose surfaces with similar clay and silt content. Laboratory studies on the emission from crusted surfaces should take the underestimation of emission from crusted surfaces into account.

Our data showed interesting implications for assessing or modelling dust emissions from sandy, rain-fed croplands in semi-arid to arid regions. The importance of cohesion and the presence of crusted surfaces in minimizing dust emissions should be taken into account when predictions of dust emissions are made for cropland areas. Especially during dry years, when the growth of crops is limited, protecting crusts could be used as an important land management technique to limit dust emissions from fallow fields with no protection from stubble. Hereby, the presence and input from neighbouring fields of saltating particles should be minimized. Furthermore, the importance of soil texture for the loose surface is noticeable, indicating that the emissions of surfaces with more clay and silt are only higher when it is disturbed by loosened soils. These contradictory influences should be considered for predictions on the emissivity of sandy, agricultural surfaces.

For future work, the focus should be on assessing a wider range of surfaces present on these agricultural lands. This includes the disturbed surfaces with a certain roughness or clod content. These surfaces were present on agricultural fields, but these surfaces are too rough to be measured with the PI-SWERL. Furthermore, the influence of larger roughness elements in these croplands, such as stubble or ploughing ridges, should be determined since windbreaks at the margins of fields are not practised in the region as a measure against wind erosion. This could then give insight under which conditions the roughness and cover are not sufficient to protect a surface, and therefore the formation of crusts and the limitation of saltators could be the primary solution of protection against dust emission.

CRediT authorship contribution statement

Heleen C. Vos: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Wolfgang Fister:** Methodology, Validation, Investigation, Writing - review & editing, Funding acquisition. **Johanna R. Von Holdt:** Methodology, Software, Validation, Writing - review & editing. **Frank D. Eckard:** Conceptualization, Validation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Anthony R. Palmer:** Conceptualization, Writing - review & editing, Project administration, Funding acquisition. **Nikolaus J. Kuhn:** Conceptualization, Validation, Investigation, Writing - review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeolia.2021.100747.

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