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Anthropogenic dust emissions due to livestock trampling in a Mongolian temperate grassland

Erdenebayar Munkhtsetseg[1], Masato Shinoda[2], Masahide Ishizuka[3], Masao Mikami[4], Reiji Kimura[5], and George Nikolich[6]

[1]Meteorology, Hydrology and Permafrost Laboratory, National University of Mongolia, Ulaanbaatar, Mongolia
[2]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan
[3]Kagawa University, Takamatsu, Japan
[4]Meteorological Research Institute, Tsukuba, Japan
[5]Arid Land Research Center, Tottori University, Tottori, Japan
[6]Desert Research Institute, Nevada University, Las Vegas, USA

Correspondence to: Erdenebayar Munkhtsetseg (munkhtsetseg.e@seas.num.edu.mn)

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Abstract. Mongolian grasslands are a natural dust source region and they contribute to anthropogenic dust due to the long tradition of raising livestock there. Past decades of abrupt changes in a nomadic society necessitate a study on the effects of livestock trampling on dust emissions, so that research studies may help maintain a sustainable ecosystem and well-conditioned atmospheric environment. In this study, we conducted a mini wind tunnel experiment (using a PI-SWERL® device) to measure dust emissions fluxes from trampling (at three disturbance levels of livestock density, *N*) and zero trampling (natural as the background level) at test areas in a Mongolian temperate grassland. Moreover, we scaled anthropogenic dust emissions to natural dust emissions as a relative consequence of livestock trampling. We found a substantial increase in dust emissions due to livestock trampling. This effect of trampling on dust emissions was persistent throughout all wind friction velocities, u_* (varying from 0.44 to 0.82 $\mathrm{m\,s^{-1}}$). Significantly higher dust loading occurs after a certain disturbance level has been reached by the livestock trampling. Our results suggest that both friction velocity (u_*) and disturbance level of livestock density (N) have an enormous combinational effect on dust emissions from the trampling test surface. This means that the effect of livestock trampling on dust emissions can be seen or revealed when wind is strong. Our results also emphasize that better management for livestock allocation coupled with strategies to prevent anthropogenic dust loads are needed. However, there are many uncertainties and assumptions to be improved on in this study.

1 Introduction

Mongolian grasslands are a natural dust source region and they contribute to anthropogenic dust due to the long tradition of raising livestock there. The Mongolian ecosystem is generally sensitive to any external disturbance of the environment, natural or human, such as climate change or human activity (Peters, 2002; Pogue and Schnell, 2001). The projected increasing aridity warns that enhanced warming (climate change) coupled with rapidly increasing human activities will further exacerbate the risk of land degradation and desertification in the dry lands in the near future (Huang et al., 2016). Specifically, the major source regions of Asian dust have expanded from northwestern China to the Gobi desert in Inner Mongolia (Wang et al., 2008; Fu et al., 2008). Livestock population has increased substantially in the past decades (25 mL in 1990, 30 mL in 2000, 61 mL in 2016) and this increase is projected to persist into the future (Shabb et al., 2013). Natural grassland exposures to livestock trampling, overgrazing, and road vehicle traffic are some of the most prevalent modifiable risk factors for dust emissions in Mongolia. Animal husbandry will contribute to atmospheric dust loading through degraded and disturbed land by (i) grazing pressure and (ii) livestock trampling (trampling pressure).

The grazing pressure has been linked to an increased number of dust events through declined vegetation cover (Kurosaki et al., 2011) and altered areas of land cover types (Wang et al., 2008; Fu et al., 2008; Huang et al., 2016). Such a change in land cover data is mostly used to assess anthropogenic dust (Tegen et al., 2004; Huang et al., 2014). However, large uncertainties in the assessment of total anthropogenic dust still remain (Tegen et al., 2004; Ginoux et al., 2012; Huang et al., 2014). Thus, it is crucial to investigate the effects of livestock trampling on (anthropogenic) dust emissions.

Previous studies have shown associations between impacts of mechanical disturbance on soil particle bonds (Hoffmann et al., 2008; Steffens et al., 2008) and dust emissions strength (Neuman et al., 2009; Houser and Nickling, 2001; Baddock et al., 2011; Macpherson et al., 2008; Belnap and Gillette, 1997; Belnap et al., 2007). They revealed a common consequence of increased dust emissions. Very few studies have focused on the effects of natural disturbances such as livestock trampling for dust emissions, which produced limited data (Houser and Nickling, 2001; Baddock et al., 2011; Macpherson et al., 2008). Scarce and inconsistent data prevent scientists from parameterizing the disturbance effects on dust emissions and to scale their relative contribution to the atmospheric dust. The lack of consistency is attributable to the limited number of studies, the limited range and variable categorization of land disturbance and dust flux among studies, and possibly real differences between the effects of land disturbance on dust emissions from some land surface parameters.

Subsequently, we aimed to investigate the effects of livestock trampling on dust emissions rates and scale anthropogenic dust emissions to natural dust emissions as a relative consequence of livestock trampling. Therefore, we conducted a mini wind tunnel experiment (using a PI-SWERL® device) to measure dust emissions fluxes from trampling (at three disturbance levels of livestock density, *N*) and zero trampling (natural as the background level) at test areas in a Mongolian temperate grassland. It should be mentioned that our dust data represent the potential dust emissions as a restriction of wind tunnel measurements. The PI-SWERL® mini wind tunnel was successfully used on playa surfaces to produce potential erodibility estimates (Etyemezian et al., 2007) that were validated using conventional wind tunnel data (Sweeney et al., 2008). This PI-SWERL® device was also successfully used to investigate dust emissions on surfaces in the Mongolian temperate steppe grassland (Munkhtsetseg et al., 2016).

2 Study materials

2.1 A study site description

Mongolian grasslands occupy over 80 % of the total territory of the country. (equal to 113.1 million ha). According to FAO 2010, as much as one-third of total pastures is underutilized. Most unused land is far from administrative centers and many herders are increasingly loath to travel that far, especially when infrastructure is deficient. Every year new wells are operated, but a huge number of wells still remain out of operation, resulting in 10.7 million ha of pasture that cannot be used because of lack of water (Suttie et al., 2005). According to the spatial density of livestock in Mongolia (Saizen et al., 2010), the largest density of livestock is located on the Mongolian steppe grassland. The impact of grazing on plant diversity varies across environmental gradients of precipitation and soil fertility (Milchunas et al., 1988). In the desert steppe zone, species richness was lower in the drier years but did not vary with grazing pressure. In the steppe zone, species richness varied significantly with grazing pressure but did not vary between years. Species richness is not impacted by grazing gradient in desert steppe, but it is in the steppe (Cheng et al., 2011). Consequently, the Mongolian steppe has been impacted the most by grazing and trampling.

Our study was carried out in Bayan-Önjüül (sum center) located in the temperate Mongolian steppe (Fig. 1a; 47°02′38.5″ N, 105°56′55″ E). Nomads and settlements of this sum have raised a large number of livestock, and they rank at number 30 out of 329 sums for the largest number of livestock raised per sum (Saizen et al., 2010). In the last decade, the number of dust events associated with wind erodibility increased by 30 % in Bayan-Önjüül (Kurosaki et al., 2011). This is an area where dust emissions activity has been monitored on a long-term basis (Shinoda et al., 2010a) at a dust observation site (DOS) adjacent to the study site (Fig. 1a). According to long-term meteorological observations made at the monitoring station of the Institute of Meteorology and Hydrology of Mongolia located near the site, the prevailing wind direction is northwest. Mean annual precipitation is 163 mm, and mean temperature is 0.1°C for the period 1995 to 2005 (Shinoda et al., 2010b). Soil texture is dominated by sand (98.1 %, with only 1.3 % clay and 0.6 % silt; Table 1; Shinoda et al., 2010a).

2.2 Wind tunnel experiment

2.2.1 PI-SWERL® mini wind tunnel

The PI-SWERL® consists of a computer-controlled 24-volt DC motor attached on top of an open-bottomed cylindrical chamber 0.20 m high and 0.30 m in diameter (Fig. 1b). Inside the chamber there is a flat annular ring (width = 0.06 m) with an outer diameter of 0.25 m, which is positioned 0.05 m above the soil surface (Fig. 1b). As the annular ring re-

Table 1. Land surface and soil size characteristics in the study area.

	Pebble cover (%)	Soil texture fraction[1] (10 cm depth) (%)			Vegetation cover[2] (%)		Soil moisture[2] ($g\,g^{-1}$)	
	(< 30 mm)	Clay (< 0.002 mm)	Silt (0.002–0.02 mm)	Sand (0.02–2 mm)	In 2009	In 2010	In 2009	In 2010
Mean	2.4	1.3	0.6	98.1	2.4	2.3	0.0022	0.0024
SD	0.18	0.1	0.1	0.1	0.3	0.2	0.0001	0.00012

[1] Defined in Shinoda et al. (2010a).
[2] Presented in Munkhtsetseg et al. (2016).

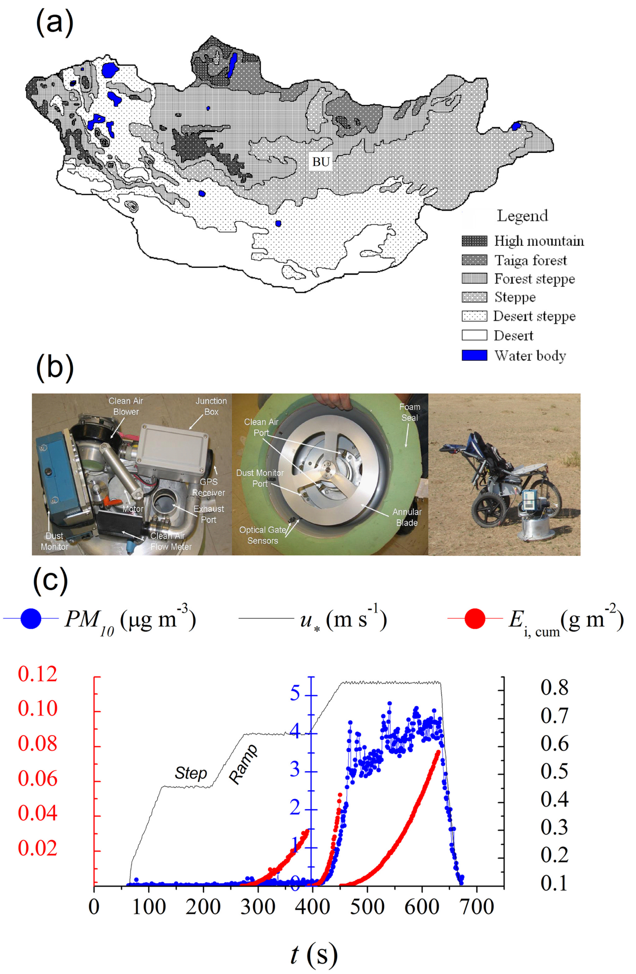

Figure 1. (a) BU (Bayan-Önjüül) denotes the location of the study site with respect to vegetation zones in Mongolia. **(b)** Pictorial illustrations of PI-SWERL®; top view on the left, bottom view in the middle, and in the field on the right side. **(c)** An example data trace of PM_{10} concentration and the cumulative dust emissions ($E_{i,\mathrm{cum}}$) associated with friction velocity (u_*) during the PI-SWERL® measurement period (t).

volves about its center axis, a velocity gradient forms between the flat bottom of the ring and the ground, creating a shear stress measured in newtons per square meter ($\mathrm{N\,m^{-2}}$) on the surface (Etyemezian et al., 2007). Dust and sand are mobilized by the shear stress generated by the rotating ring. Dust concentration (PM_{10}) within the chamber that encloses the annular ring is measured by a nephelometer-style instrument, the 8520 DustTrak (TSI, Inc., Shoreview, MN, USA). The PI-SWERL® tests measure the potential fugitive PM_{10} dust emissions from the surface at different friction velocity u_* ($\mathrm{m\,s^{-1}}$), corresponding to a wind speed of approximately 30 $\mathrm{m\,s^{-1}}$ at 2 m a.g.l. at the high end. In this experiment, the rotation per minute speed (in revolutions per minute) of the annular ring was converted to a corresponding ($\mathrm{m\,s^{-1}}$) friction velocity. The data measured using the PI-SWERL® instrument were analyzed using the miniature PI-SWERL® user's manual (version 4.2) (DUST-QUANT, 2009). Each PI-SWERL® experiment consisted of friction velocities varying from 0.16 to 0.82 $\mathrm{m\,s^{-1}}$. Depending on the different friction velocity, six levels are identified (i 1, 6) within each PI-SWERL® experiment. Four levels include two gradual increases in u_* of 0.54 and 0.73 $\mathrm{m\,s^{-1}}$ (ramp properties) separated by three constant u_* settings of 0.44, 0.64, and 0.82 $\mathrm{m\,s^{-1}}$ (step properties) dust emissions flux using (Fig. 2c). When performing the dust measurements by PI-SWERL®, we avoided duplicating measurements at the same location by shifting the position each time.

2.2.2 Experimental area setting

While grazing, livestock leave behind their trampling trace; therefore, we schemed a trampling route based on grazing routes (Fig. 2a). Many studies proved that livestock density (i.e., grazing pressure) is usually highest close to water sources or settlements and decreases with distance away from such localities (Andrew and Lange, 1986; Fernandez-Gimenez and Allen-Diaz, 2001; Landsberg et al., 2003; Sasaki et al., 2008; Cheng et al., 2011). According to Stumpp et al. (2005) the livestock spatial densities were higher in the first 300 m of the transects from the local centers. This finding of the heavy grazing with a radial gradient was also found at our study site (Cheng et al., 2011), which spots a trampling-active area. The trampling-active area (with 300 m transect) close to local centers is reasonable from the view point of livestock trampling routes as well. Three types of schematic diagram for livestock trampling routes could

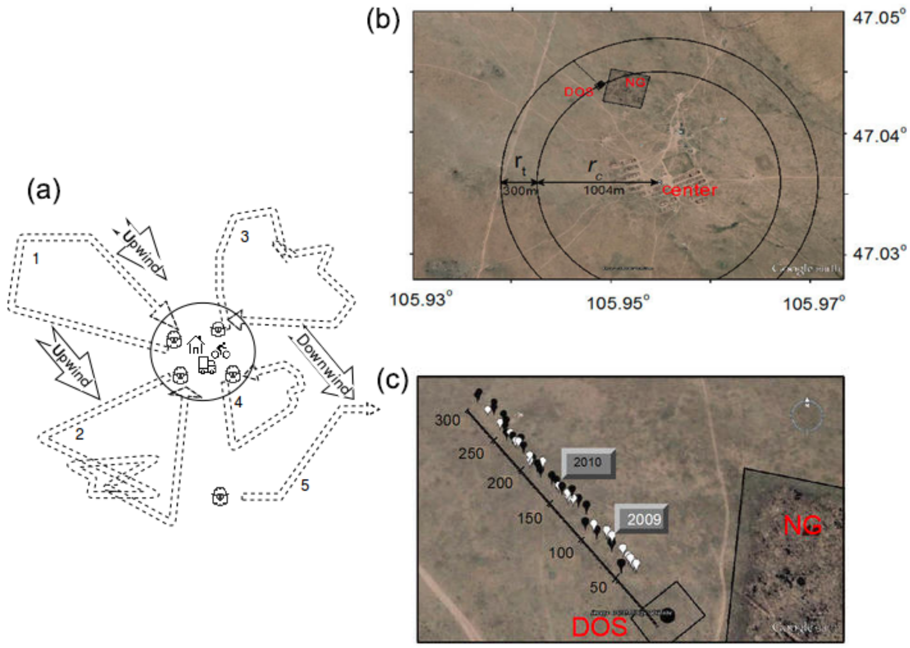

Figure 2. Experimental settings. **(a)** Schematic grazing or trampling routes are divided into three types regarding grazing routines. The grazing routines are irregular yet depend on climatic seasons (weather condition) and fodder sources. Therefore, it is assumed that Type I routes (marked by 1, 2, and 3) are usually used when weather conditions are good and rich fodder is available. The Type II route (marked by 4) is usually used during bad weather conditions, such as in spring and winter. The Type III route (marked by 5) is called *otor*. **(b)** Annulus area selected for this study. r_c is the distance from the sum center (center) to the inner circle for the selected annulus and r_t is the width of annulus area. **(c)** PI-SWERL® experimental test areas (transect lines; and dust observation site, DOS). White and dark balloons present dust sampling points along the transect in 2009 and 2010.

be illustrated based on published results (Suttie et al., 2005) on the seasonal and spatial variability in trampling density in reference to grazing habits in seasons and animal types (Fig. 2a). Type I, a long grazing route, draws summer and autumn pasture as usually grazed in common, with few problems of access or dispute. Type II, a short grazing route, draws the winter and spring camps, and grazing is the key to the herders' overall system; in a season when feed is very scarce, each must provide shelter as well as accessible forage throughout the season (Fig. 2a). Type III, a distanced grazing route, shows taking livestock to more distant fattening pastures (*otor*), which is an important part of well-organized herding and, if done with skill, can greatly improve the condition of stock before the long winter. Horses and cattle may be left to graze, except those being milked. Thus, measuring dust emissions in the area close to the local center will reflect on the trampling activity.

Our study aimed to measure dust emissions affected only by livestock trampling vs. no trampling. Therefore, we focused on performing the PI-SWERL® mini wind tunnel experiment under similar weather and surface aeolian conditions at the trampled and non-trampled areas. Performing the PI-SWERL® mini wind experiment for a short period of time will enable us to avoid weather changes. The experimental test area of livestock trampling was selected to be close to the no-trampling area, where both areas are subjected to similar surface aeolian conditions. Hence, the trampling-active area at our site was represented by the annulus area enclosed by inner and outer circles (Fig. 2b). The inner circle excludes a residential area where land is disturbed mainly by local people's daily activities, while the outer circle delimits trampling activity of 300 m from the local (outer) center. The residential area was defined with a radius starting from the BU sum center to the most distanced object. It is well known that sand and dust particles transported by wind likely deposit on the downwind lee when distracted by rough objects like vegetation, shelter areas, or buildings. This condition results in distinct fractions of sand and dust on land surface, which produce differential dust emissions. As mentioned above, the prevailing wind direction (northwest at our site) will differentiate potent emissions into upwind and downwind areas. In order to avoid or reduce a possible source of data uncertainty from the aeolian processes at the site, we narrowed our area of interest into the upwind area of the trampling active area. Further, regarding all possible requirements, the transect line shown in Fig. 2c was mandatory to run the PI-SWERL experiment.

2.2.3 Experimental conditions of land surface

Analogous conditions of vegetation and soil moisture. The vegetation and pebble survey was defined along the transect distanced at 50, 150, 200, and 300 m away from the DOS within a 1 m × 1 m plot (Table 1) (Munkhtsetseg et al., 2016). In the two springs of 2009 and 2010, vegetation conditions were similar. Vegetation cover was 2.4 and 2.3 % during the measurement periods in 2009 and 2010, respectively. These seasonal conditions resulted in sparse vegetation growth and caused large portions of the surface area to be free of vegetation. This open area enabled us to run the PI-SWERL® wind tunnel, which has a limitation in measuring dust emissions over a vegetated area where vegetation height is above 4 cm. Sparse vegetation growth during the measurement periods and the small size of PI-SWERL® (an effective area of 0.026 m^2) enabled us plenty of bare surfaces to conduct PI-SWERL® measurements. Therefore, our dust measurements using PI-SWERL® were not influenced by vegetation roughness. A recent study revealed that soil moisture has a clear seasonal variation in Mongolia, with the lowest value in the spring times (Nandintsetseg and Shinoda, 2015). Consequently, spring is recognized as a dust-favorable season due to its low seasonal precipitation (Shinoda et al., 2011). Averaged soil moisture values were 0.0022 and 0.0024 $g\,g^{-1}$ in 2009 and 2010, respectively. Soil moisture values showed a subtle change in the SD of soil moisture. Consequently, these SDs revealed insignificant changes in soil moisture among the transect lines for each year. As a temporal variation during the 2-year study period, the difference in averaged soil moisture values during these two springs was equal to 0.0002 $g\,g^{-1}$, which is an insignificant amount that can still alter the level of dust emissions (Fécan et al., 1998). These climatic conditions and abovementioned experimental settings clearly indicate that both soil moisture and vegetation conditions were not influential factors in altering dust emissions from bare, non-trampled, and systematically trampled surfaces in 2010 and the naturally trampled surfaces in 2009 and 2010.

Livestock trampling density. The total number of livestock at *bag* (smallest administrative level in Mongolia) scale for the Bayan-Önjüül subdistrict were counted as 52 378 and 43 709 for 2009 and 2010, respectively (National Statistical Office of Mongolia reports, 2009, 2010). We calculated livestock densities in the annulus area (Fig. 2b) for a given year, as presented in Eq. (1):

$$N = \frac{10^4\,\mathrm{num}}{\pi(r_\mathrm{c} + r_\mathrm{t})^2 - \pi r_\mathrm{c}^2}, \tag{1}$$

in which N is livestock density in head per hectare per year and per hectare (head $ha^{-1}\,yr^{-1}$, and refer to head ha^{-1}), num is total livestock in a head, r_c (= 1004) is the radius distance from the center to the transect start line in meters, r_t (= 300) is the transect line in meters, and 10^4 is a unit conversion of square meter to hectare (Fig. 2c). Total livestock in a head is the total number of five types of animals, sheep, goats, camels, cattle, and horses, which are traditionally herded by the nomads. The calculated livestock densities were 241 and 201 head ha^{-1} along transect lines in 2009 and 2010, respectively.

As for trampling inside the DOS fenced area, a calculation of livestock density followed a basic procedure. The total fenced area of DOS was 50 m × 35 m. Inside the DOS fence, sheep movement was constrained to a subarea of 8 m ×35 m to ensure that allocated meteorological equipment would not be damaged. Livestock density inside the DOS was therefore calculated as the spatial distribution of the total number of sheep in the enclosed area of 8 m ×35 m, and it was estimated as 250 head ha^{-1}.

We assumed that all types of livestock (small and large ruminants) have the same effect on land surface trampling, irrespective of the size or distribution of the footprints. In addition, we made no distinction between the weights of the different livestock species. However, the potential variability due to the difference in weights warrants further investigation. Xu (2014) tested the quantity of dust emitted from vehicles and found that it varied with the weight of the vehicles.

2.2.4 Field experiment

Figure 3 presents experimental details, including experimental plots, measurement replications, and associated livestock density (N). Inside the DOS, where the non-trampling area is ($N = 0$), we collected seven replicative dust measurements on 16 May 2010. On the same day, we collected four replicative dust measurements after 5 h of grazing of seven sheep (N_{250}), those herded inside the DOS (Fig. 3a). We collected 21 replicative dust measurements along the naturally trampled transect line (shown in Fig. 2c), with an N of 241 head ha^{-1} (N_{241}) on 15 May 2009. In the following winter, livestock density at our study site was reduced due to the moderate *dzud* (Mongolian word indicating harsh winter conditions that contribute to livestock mortality) (Natsagdorj and Dulamsuren, 2001; Begzsuren et al., 2004). We collected 25 replicative dust measurement along the naturally trampled transect line, with an N of 201 head ha^{-1} (N_{201}) on 15 May 2010 (Fig. 3b).

All dust emissions data were obtained using the PI-SWERL® mini mind tunnel. For producing replicative data, we avoided running the PI-SWERL experiment at the same spot by shifting to another area. Additionally, we tried to perform all PI-SWERL® measurements on the same day to obtain unbiased data on weather changes from day to day. Since April 2008, the DOS was fenced to keep out livestock; there was no livestock trampling for a 2-year period. These measured dust fluxes, on bare surfaces inside the DOS (fenced to keep livestock out), were considered as a reference dust measurement for non-trampled surfaces (F_{REF}).

Moreover, livestock trampling intensities for all three types of measurements were subject to an annual timescale.

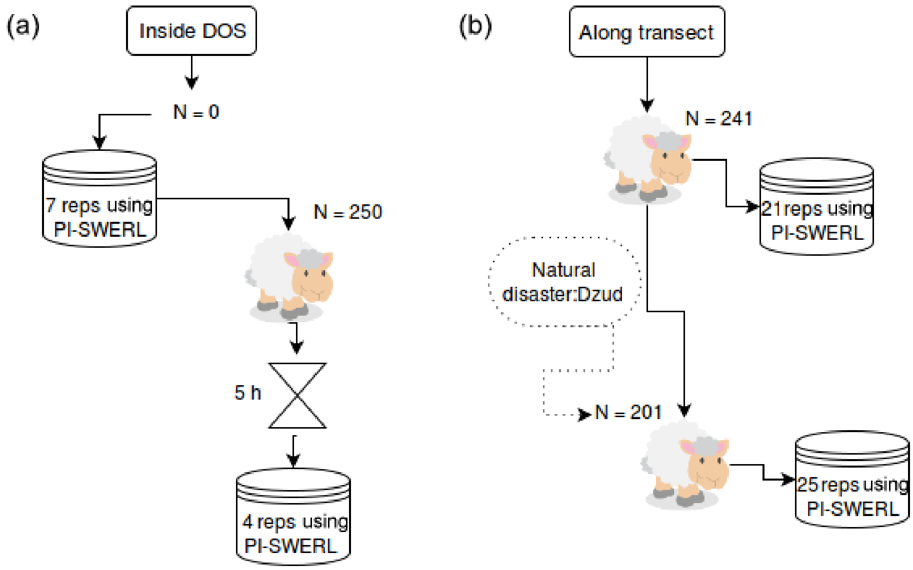

Figure 3. A schematic flowchart of the PI-SWERL® experimental test **(a)** for zero trampling and trampling of N_{250} inside the DOS and **(b)** for trampling of N_{201} and N_{241} along transect areas. PI-SWERL® experimental replications for each dataset are marked as reps.

Thus, dust emissions at the naturally trampled transect were measured on an annual basis (in spring in 2009 and 2010). As for dust for $N = 250$ head ha^{-1}, 5 h of grazing is also annual if we consider that the average walking speed for livestock is 314 m h^{-1} (equal to approximately 1 m per 11.5 s) (Plachter and Hampicke, 2010). Assuming that the livestock pass four times (from sum center to the grazing area and vice versa) along the transect lines of the ring area in a day, this will result in a yield of 1460 passages per year. On an annual basis, livestock walk over and over a 1 m path in a time period of 4.6 h (11.5 s × 1460 times = 16 790 s). This finding can be used to estimate an average time period of livestock trampling within the fence. Due to limited space, the livestock inside the fence were nearly static. This condition enabled us to assume that each sheep stands covering around 1 m path with respect to their body size. Thereafter, livestock trampling continued for a half day (≈ 5 h) on bare surfaces inside the DOS, after which systematic trampled dust emissions measurements were conducted using the PI-SWERL® instrument.

3 Data analysis

3.1 Mean values of dust emissions

Generally, transported sediments are sheltered and trapped by surface roughness elements, including surface relief, vegetation, and marmot mounts, etc. This results in an unevenly distributed sediment within a local site by producing limited or unlimited sediment supply surface (Kimura and Shinoda, 2010; Yoshihara et al., 2010). Such a microscale sediment heterogeneity was captured in our dust data, resulting in larger deviations even for the same density of livestock (Supplement 1 and 2). To present dust emissions on a local scale, the averaged values of measured dust emissions for a given livestock density are preferred. Therefore, it was demonstrated that livestock affect grassland heterogeneity on a local scale, while marmots contribute to small-scale surface heterogeneity (Yoshihara et al., 2010; Liu and Wang, 2014).

We calculated the mean values of dust emissions by averaging measured dust fluxes for each livestock density group (N of 0, 201, 241, and 250 head ha^{-1}). Data from each group for each friction velocity were treated separately.

We tested dataset normality with the Shapiro–Wilk test. The Shapiro–Wilk test is widely used to define the normality when the sample number is below 50. It is believed that it works well with sample numbers of 4 to 2000 (Razali and Wah, 2011). ANOVA was used to determine if there is a difference in the mean dust emissions of livestock-trampled surfaces (with livestock densities of 201, 241, and 250 head ha^{-1}) from a non-trampled surface.

We employed OriginPro 8.1 academic software (Northampton, MA 01060, USA) for calculating statistics and determining the coefficients using the least square optimization method with the Levenberg–Marquardt algorithm (Moré, 1978). The Levenberg–Marquardt algorithm is an iterative technique that locates the minimum of a function that is expressed as the sum of squares of nonlinear functions (Marquardt, 1963; Lampton, 1997). It has become a standard technique for nonlinear least squares problems and widely adopted in a broad spectrum of disciplines.

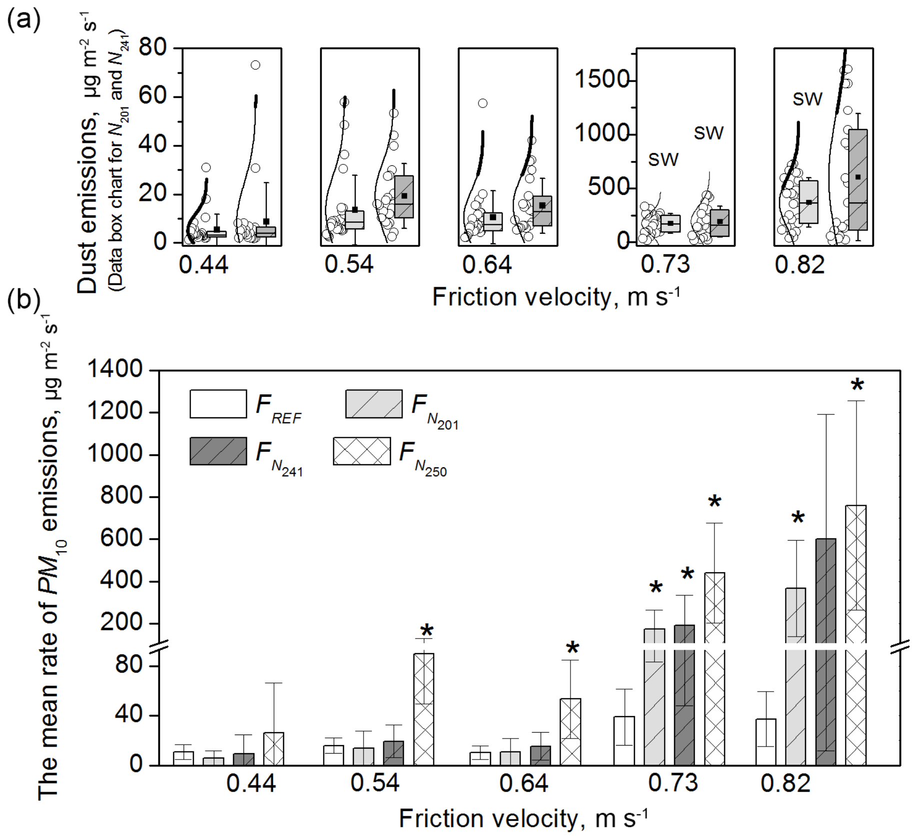

Figure 4. (a) Measured dust fluxes from the trampled surfaces with N values of 201 and 241 head ha^{-1}. Open circles (∘) and curved lines (≀) denote collected dust data and normal distributions, respectively. Center dots (·) and dashes (−) in the boxes denote the means and medians of dust emissions, respectively. The openings and closings of the boxes present the 25 and 75th percentiles for each dataset. SW denotes statistically significant datasets with the Shapiro–Wilk normality test. **(b)** Mean dust emissions fluxes with SDs on correspondent friction velocities. The significant differences (p value with a significance level of 0.05) for mean dust emissions of the trampled surfaces from the F_{REF} on each friction velocity are denoted by $*$.

3.2 A scale factor to reveal the effect of livestock trampling on dust emissions

On a physical basis, livestock trampling weakens soil particle bonds to result in dust being released by wind and blown (u_*) into the atmosphere (Baddock et al., 2011; Macpherson et al., 2008). Surface disturbance does not directly cause dust emissions but it does recover surface-available dust (Zhang et al., 2016) and supply sediment to emit.

A scale factor is a number that scales, or multiplies, some quantity of natural dust emissions (F_{REF}) to get anthropogenic dust emissions (F_N, influenced by livestock trampling). In this study, the scale factor (without unit) was calculated as the ratio between F_N and F_{REF}, as F_N/F_{REF}. The scale factor will be useful in the areas (1) to differentiate natural dust emissions (F_{REF}) from anthropogenic dust emissions (F_N) and (2) to scale an effectual factor of livestock trampling on dust emissions.

If $F_N/F_{\mathrm{REF}} \simeq 1$, no effect of livestock trampling on dust emissions is indicated. If $F_N/F_{\mathrm{REF}} < 1$, the effect of livestock trampling on dust emissions is suppressed, and if $F_N/F_{\mathrm{REF}} > 1$, an increasing or enhancement effect of livestock trampling on dust emissions is indicated.

4 Results

4.1 Livestock trampling effects on dust emissions

The mean rate of PM_{10} emissions from the test surface areas for each friction velocity of the PI-SWERL® experiment reveals greater detail concerning the behavior of dust emissions and the effect of trampling (Fig. 4) (Supplement 1). The dust emissions from the undisturbed, zero trampling surface at friction velocity u_* of 0.44 m s^{-1} was low (10.5 μg m^{-2} s^{-1}). This was elevated to 15.7 μg m^{-2} s^{-1} at u_* of 0.54 m s^{-1} and then reduced to background level 10.1 μg m^{-2} s^{-1} at 0.64 m s^{-1}. Noticeably increased emissions rates of 39 and 37.3 μg m^{-2} s^{-1} are seen at the u_* of 0.73 and 0.82 m s^{-1}, respectively. However, their difference was negligible. These dust emissions behaviors with a change in u_*, which are

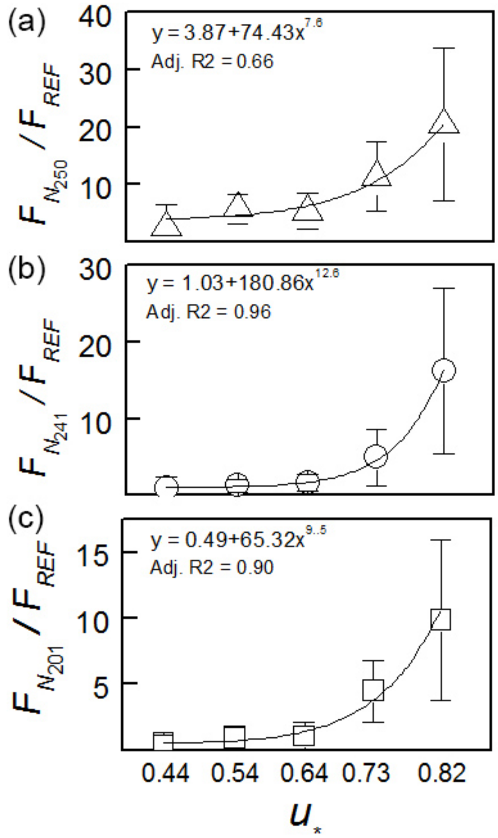

Figure 5. Dust emissions ratio dependency on friction velocity and livestock density. Open triangles (△), circles (○), and squares (□) denote dust emissions values from the trampled surfaces with livestock densities of 250, 241, and 201 head ha^{-1}, respectively. **(a)** Relationships between the mean emissions ratio (F_N/F_{REF}) and u_* for N values of 201, 241, and 250 head ha^{-1}.

in sequential order for each PI-SWERL experiment, suggest that the sandy soil of temperate grassland is somewhat similar to a supply-limited surface with successive emissions (Macpherson et al., 2008). In contrast, dust emissions from trampling test areas shows that the disturbed, trampling surface is an unlimited-supply dust surface, concerning its apparent increased emissions rate with an increase in u_* (Fig. 4), except for the case of 0.64 m s^{-1} subtly declining to 0.64 m s^{-1}.

At friction velocity of 0.44 m s^{-1}, although dust emissions were almost doubled between zero trampling and N_{250} trampling, this difference was not statistically significant (Fig. 4b). In addition, trampling effects are visible when considering an increase in mean dust fluxes with all trampling densities of 201, 241, and 250 head ha^{-1} (Fig. 4b). However, such an increase is invalid if including the dust flux at zero trampling in comparison with the N_{201} and N_{241} tramplings, but their differences are very small. We used the Shapiro–Wilk test (with a significance of $\alpha = 0.05$) and SD to assess whether the variables had a normal distribution and equilibrium or diverse variances in the statistical populations. Dust flux for the zero trampling surface is statistically significant with the normality. In contrast, the insignificant normalities are demonstrated with the trampled area datasets (Fig. 4a) along with larger SDs (Fig. 4b), which result from scattered data points from their sample populations (see Fig. 4a; data points with box chart of 25th and 75th percentiles). A higher diversity of dust fluxes presents morphological disparity and sedimentological diversification in livestock-trampled test areas.

At moderate friction velocities of 0.54 and 0.64 m s^{-1}, emissions rates at N_{250} trampling area were almost 5 times larger than those of non-trampling, and their differences were statistically significant (One-way ANOVA test; p value with 0.05) (Fig. 4b, denoted by $*$). The trampling effect, which was visible for u_* of 0.44 m s^{-1}, is apparent when observing increases in mean dust fluxes with all trampling densities for u_* of 0.54 m s^{-1} and for a u_* of 0.64 m s^{-1} includes even non-trampling (Fig. 4b). The insignificant normalities of emissions rates with trampling densities of N_{201} and N_{241} (Fig. 4a) along with larger SDs (Fig. 4b) are demonstrated, as it was also seen for a u_* of 0.44 m s^{-1}. Emissions rates with trampling densities of zero and N_{250} present significant normalities, and this significance supports the difference of dust fluxes between zero trampling and N_{250} trampling (Fig. 4b, denoted by $*$). Dust emissions produced at 0.54 m s^{-1} were smaller than those at 0.64 m s^{-1}, reflecting surface emissions characteristics similar to the undisturbed surface, and these types are discussed by Macpherson et al., 2008.

At high friction velocities of 0.73 and 0.82 m s^{-1}, trampling effects are strongly pronounced. This can be seen in enlarged emissions rates, specifically, 5–10 times for a u_* value of 0.73 m s^{-1} and 10–20 times for a u_* value of 0.82 m s^{-1}, in all trampling areas in comparison to those in no-trampling areas. Consequently, emissions rates at N_{201} and N_{250} significantly differ from those at zero trampling, which is supported statistically by their significant normalities (Fig. 4b, denoted by *). Moreover, an increase in mean dust fluxes with an increase in N for all trampling densities (including non-trampling) also shows the effects of trampling.

Overall, the effect of trampling on dust emissions was persistent throughout all friction velocities. Significantly higher dust loading occurred after a disturbance level was reached by the trampling N_{250}. However, the disturbance level decreased with an increase in wind force, u_*. This indicates that the effect of trampling can be seen or initiated in dust emissions when wind becomes stronger.

4.2 A scale factor of dust emissions due to livestock trampling

The calculated scale factor for each N value at different u_* values is shown in Fig. 5. The scale factors for N_{250} varied from 2.5 to 20 (Fig. 5, $F_{N_{250}}/F_{\mathrm{REF}}$). Similarly, the scale factors ranged between 0.8–16 and 0.5–10 for N_{241} and N_{201},

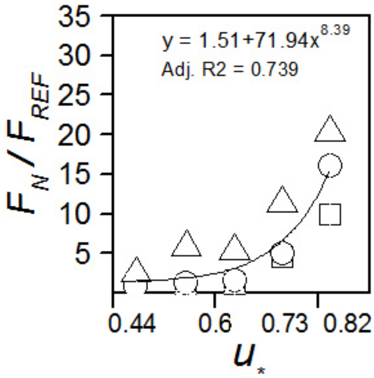

Figure 6. A statistically fitted relationship between dust emissions ratios and u_* for all livestock-trampled surfaces; n denotes sample number; v is degree of freedom; χ/v is the reduced chi square; RMSE is root mean square error; Adj.R^2 is adjusted r^2, residual sum of squares.

respectively. Very few of the scale factors were below 1. Those that were occurred at low u_* values for livestock trampling with N_{201} and N_{241} head ha^{-1} (Fig. 5, $F_{N_{201}}/F_{\mathrm{REF}}$ and $F_{N_{241}}/F_{\mathrm{REF}}$). Consequently, 80 % of the scale factors were greater than 1, revealing that livestock trampling had been likely enhanced dust emissions.

In addition, we can observe the significant positive relationships between the scale factor and u_* values for all trampling densities illustrated in Fig. 5. The scale factors for N_{250} increased from 2.5 to 20 in response to an increase in u_* from 0.44 to 0.82 m s^{-1} (Fig. 5, $F_{N_{250}}/F_{\mathrm{REF}}$). The similar u_*-dependant positive relationships were manifested in the scale factors for N_{241} and N_{201} as well (Fig. 5, $F_{N_{201}}/F_{\mathrm{REF}}$ and $F_{N_{241}}/F_{\mathrm{REF}}$). This positive feedback of u_* on the scale factors strongly indicates that an increased u_* value elevates the enhancement effect of livestock trampling on dust emissions. Consequently, the livestock-trampled grassland areas emit a larger amount of dust in a comparison to natural grasslands, particularly during strong storms.

Moreover, an increase in the trampling density (N) also results in an increase in the scale factors (Fig. 6). The scale factors for N_{250} were higher than the scale factors for N_{201} and N_{241} at all u_* values as depicted in Fig. 6. This increase in the scale factors in response to an increased N value is more apparent for a high u_* of 0.82 m s^{-1} in Fig. 6. It demonstrates that scale factors of 10, 16, and 20 correspond to N_{201}, N_{241}, and N_{250}, respectively (Fig. 6). However, the differences in the scale factors between $F_{N_{201}}/F_{\mathrm{REF}}$ and $F_{N_{241}}/F_{\mathrm{REF}}$ were negligible at moderate and low u_* values (Fig. 6). The scale factor is proportional to $u_*^{8.39}$ (Fig. 6) for all variables, whereas its rate varies over orders for $u_*^{7.6} - u_*^{12.6}$ at a given N (Fig. 5).

These results suggest that both u_* and N have enormous effects on dust emissions from trampling tests and eventually determine the strength of the effect of trampling.

5 Discussion

5.1 The effect of trampling on dust emissions

We found a substantial effect of trampling on dust emissions. The mean rate of PM_{10} emissions from the test surface areas for each friction velocity of the PI-SWERL® experiment reveals greater detail concerning the behavior of dust emissions and the effect of trampling (Fig. 4).

The dust emissions from the undisturbed zero-trampling surface at friction velocity u_* of 0.44 m s^{-1} was low (10.5 µg m^{-2} s^{-1}). It increased to 15.7 µg m^{-2} s^{-1} at a u_* of 0.54 m s^{-1} and then decreased to the background level 10.1 µg m^{-2} s^{-1} at 0.64 m s^{-1}. Noticeably increased emissions rates of 39 and 37.3 µg m^{-2} s^{-1} are seen at u_* values of 0.73 and 0.82 m s^{-1}, respectively. However, their difference was negligible. These dust emissions changeable behaviors with a change in u_* are in a sequential order of shear stress for each PI-SWERL experiment and suggest that the sandy soil of temperate grassland is somewhat similar to a supply-limited surface with successive emissions (Macpherson et al., 2008). This is consistent with the hypothesis for supply-limited surfaces that the quantity of dust ejected into the atmosphere is controlled by the capacity of the surface to release fine particles (Nickling and Gillies, 1993).

In contrast to the undisturbed surface, the disturbed trampling surface behaves as an unlimited-supply dust surface, with a consistent increase in emissions rate with an increase in u_* (Fig. 4), except for the case of a u_* value of 0.64 m s^{-1}, which shows a subtle decline to 0.54 m s^{-1}. This shift in natural soil, from supply limitedness to an unlimited supply surface, could be explained by the weakening of interparticle bonds as a consequence of trampling (Belnap et al., 2007; Baddock et al., 2011; Macpherson et al., 2008). In some crusted desert soils with higher sand contents, disturbance can lead to increased sand availability and the occurrence of effective abrasion (e.g., Belnap and Gillette, 1997). In conjunction, we observed increased dust emissions from the trampling test areas in comparison to those from zero trampling, despite similar ranges in shear velocity. Their differences were statistically significant (One-way ANOVA test; p value of 0.05) (Fig. 4b, denoted by $*$) at most u_* values, particularly for N_{250} trampling. The observed emissions rates at N_{250} trampling were 26.1 and 760 µg m^{-2} s^{-1}, which are approximately 2 and 20 times greater than those for zero trampling, measured at a u_* of 0.44 to 0.82 m s^{-1}. Further supporting these facts, we could conclude that emissions rates from the trampling test areas were much greater than the zero trampling surface because of the larger supplies of loose surface dust. It indicates the substantial effect of trampling (for dust loads) that has taken place on Mongolian temperate grassland, where traditional animal husbandry has endured for centuries. However, we are not able to gain further insight for increased dust contribution either directly from the availability of readily suspendible sediment or indirectly from the process relationship between abrasive saltation by disturbance and dust emissions at this point. Those are discussed in detail by Macpherson et al. (2008), Baddock et al. (2011), and Zhange et al. (2016).

It was demonstrated that wind erosion and deposition processes form uneven spatial distribution of dust supplements as driven by microclimatic, sedimentological, geochemical, and biological conditions and surface patchiness (Gill, 1996). Likewise, we noticed larger SDs (Fig. 4b), which result from scattered data points from sample populations (see Fig. 4a; data points with the box chart of 25th and 75th percentiles). The higher diversity of dust fluxes presents morphological disparity and sedimentological diversification in test areas. That dust emissions are highly variable with space and between distinct landforms, even within individual landforms, may be caused as a result of aeolian processes (Gill, 1996; Reynolds et al., 2007). It may also be related to dust fluxes not coming from a similar saturation from a field site (Gillette and Passi, 1988). Possible microscale disturbances by marmots create spatially heterogeneous grasslands on a fine scale (Yoshihara et al., 2010). Moreover, it was emphasized that the livestock modified spatial heterogeneity on the landscape scale, whereas marmots modified spatial heterogeneity on the local scale (Yoshihara et al., 2010).

5.2 A scale factor of dust emissions from livestock trampling

We found that the variability in the scale factor of F_N/F_{REF} is subject to changes in u_*, demonstrating positive relationships for all trampling test areas (Fig. 5). This shows that the scale factor of dust emissions from trampling is magnified with an increase in u_*. This means that anthropogenic dust is emitted more as wind blows more strongly, revealing a "hidden effect" of trampling. The suppressing effect of livestock trampling on dust emissions was found at low u_* values, with a demonstration of the scale factors below 1 (Fig. 5). These low-scale factors, in turn, support the idea that the (hidden) enhancement effect of trampling on dust emissions requires high u_* values to be revealed. This u_*-magnified effect of livestock trampling on dust emissions coincides with the dust emissivity pattern of unlimited supply surfaces, discussed in Sect. 5.1.

Additionally, an increased trampling density elevated the scale factors. Larger scale factors were observed for N_{250} than for N_{241} and N_{201} at all u_* values (Fig. 6). In relation, greater dust loading was manifested at the trampling density of N_{250} and not for N_{241} and N_{201} (Fig. 4b, denoted by $*$). This indicates that significantly higher dust emissions occur after a disturbance level has reached N_{250}. A similar result of increased dust occurrence with the disturbance level for cattle passes was presented (Baddock et al., 2011). Surprisingly, we observed that the disturbance level for the significant dust emissions (comparably to F_{REF}) was lowered with an increase in wind force, u_* (Fig. 4b). Our research findings indicate that both u_* and N have enormous combinational influence on anthropogenic dust emissions due to the effect of livestock trampling and eventually determine the effect strength of livestock trampling on dust emissions. However, summarizing the effect of livestock trampling on dust emissions is somewhat challenging.

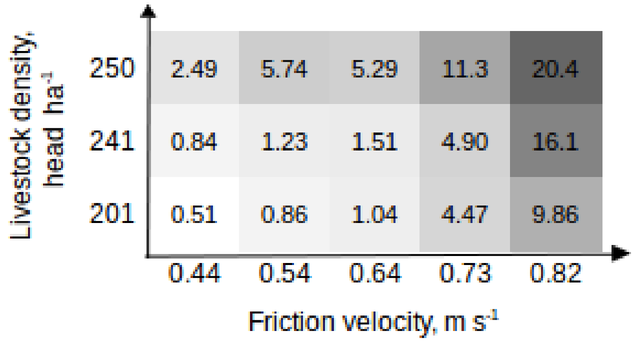

Figure 7. A table chart of the scale factor (F_N/F_{REF}) with different u_* and N values of 201, 241, and 250 head ha^{-1} yr^{-1}. A color gradient from light to dark gray corresponds to an increase in the scale factor.

Figure 7 illustrates a tabular chart of scale factors for the different values of N and u_*. It is apparent that the scale factor increases with an increase in both u_* and N. As displayed in Fig. 7, the fixed u_* vs. the fixed range of N delimits an application range of the tabular chart. Moreover, primary conditions of land surface (dry soil and low vegetation) should be met for a direct use of the scale factor. Spatially, an application of the tabular chart of the scale factor (Fig. 7) is limited to the temperate grassland, which occupies over 30 % of the total territory of the country. Furthermore, this type of chart will be quite useful for assessing anthropogenic dust emissions due to livestock trampling when natural dust emissions are known. Therefore, implication of the chart should be considered the valid range for livestock density, friction velocity, and land surface conditions.

Future work is needed to discover the scale factor (or anthropogenic dust due to trampling) relationships with unlimited natural variations in soil moisture and crust strength. It is well known that livestock trampling deteriorates soil physical parameters (infiltration rate, bulk density, water release curve) (Tollner et al., 1990; Greenwood and McKenzie, 2001) and destroys surface soil structure or crust (Zhang et al., 2006; Liu and Wang, 2014). Damage to soil physical properties is augmented when the soil is moist at the time of trampling (Warren et al., 1986). Consequently, it would be better to develop the scale factor as a function related to not only u_* and N but also dependant on soil moisture and crust. However, dust emissions cannot be perfectly estimated (Shao, 2001; Uno et al., 2006) using only livestock density information due to the influence of many other surface variables (Shinoda et al., 2011) such as soil aggregation (Ishizuka et al., 2012), soil moisture (Fécan et al., 1998;

Ishizuka et al., 2009), vegetation roughness (Kimura and Shinoda, 2010; Nandintsetseg and Shinoda, 2015), and atmospheric forcings, including air temperature, relative humidity, and wind speed (Park and In, 2003; Park et al., 2010).

We calculated N as a total livestock number, which needs to be considered for different livestock types. The assessment should be on an annual basis but can be modified to the required time period if the grazing route is known. In this study, we assumed that all types of livestock (small and large ruminants) have the same effect on land surface trampling, irrespective of the size or distribution of the footprints. In addition, we made no distinction between the weights of the different livestock species. However, the potential variability due to the difference in livestock weights warrants further investigation.

It should be noted that the scale factor provides a possible evaluation of potential anthropogenic dust emissions. The applicability of the tabular chart of the scale factor to the other grassland areas beyond the study location could be accomplished with PI-SWERL tests over a wider geographic area.

6 Conclusions

We studied the effects of livestock trampling on dust emissions strength by conducting PI-SWERL® experiments in temperate grassland of Mongolia. A significant increase in dust emissions was manifested with an elevated trampling density and an increased friction velocity. The scale factor demonstrated that (1) dust emissions is greatly enhanced due to livestock trampling and (2) the enhancement rate in the dust emissions is magnified by an increase in u_* and elevated subtly by an increase in N. Overall, our results indicated that the effect of trampling can be seen or initiated in dust emissions as friction velocity increases. We recommend that a better management for livestock allocation coupled with strategies to prevent dust loads, such as reducing wind speed with a shelter or vegetation planting, are needed. However, there are many uncertainties and assumptions to be improved on in this study.

Data availability. The underlying data can be found in the Supplement.

The Supplement related to this article is available online at https://doi.org/10.5194/acp-17-11389-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

Special issue statement. This article is part of the special issue "Anthropogenic dust and its climate impact". It is not associated with a conference.

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