An Anthropogenic Dust Emissions due to Livestock Trampling in a Mongolian Temperate Grassland

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Abstract. Mongolian Grasslands is one of the natural dust source regions and it contributes to anthropogenic dust due to its long tradition of raising livestock. Past decades of abrupt changes in a nomadic society necessitate a study on effects of livestock trampling on dust emissions, so that research studies may help maintain sustainable ecosystem and well-conditioned atmospheric environment. In this study, we conducted a mini-wind tunnel experiment (by PI-SWERL® device) to measure dust emission fluxes from trampling (at 3 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 an anthropogenic dust emission by natural dust emssion as a relative consequence of livestock trampling. We found the substantial increase in dust emissions due to the livestock trampling. This positive effect of trampling on dust emissions was persistent throughout all wind friction velocities, u_* (varying from 0.44 to 0.82 ms^{-1}). Significantly higher dust loading had occurred after a certain disturbance level has reached by the livestock trampling. Our result suggests that both friction velocity (u_*) and disturbance level of livestock density (N) has enormous combinational effect on dust emission from trampling test surface. It means that the effect of livestock trampling on dust emission can be seen or get into a play when wind is strong. It emphasizes that a better management for livestock allocation coupled with strategies to prevent anthropogenic dust loads is needed, however, there are many uncertainties and assumptions to be improved in this study.

Keywords: *surface disturbance; anthropogenic dust; PI-SWERL® mini wind tunnel; livestock density; Cobb-Douglas formula; friction velocity*

1 Introduction

Mongolian Grasslands is one of the natural dust source regions and it contributes to anthropogenic dust due to its long tradition of raising livestock. Mongolian ecosystem is generally sensitive to any external disturbance of the environment, natural or human, such as climate change or human activities (Peters, 2002; Pogue and Schnell, 2001). The projected increasing aridity warns that enhanced warming (climate change) coupled with rapidly increasing human activities will further exacarbate the risk of land degradation and desertification in the near future in the drylands (Huang et al., 2016). Specifically, the major source regions of Asian dust has expanded from northwestern China to the Gobi Desert in Inner Mongolia (Wang et al., 2008; Fu et al., 2008). Livestock population has been increased substantially in the past decades (25 ml. in 1990, 30 ml. in 2000, 61 ml. in 2016) and it 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 increased number of dust events through declined vegetation cover (Kurosaki et al., 2011) and altered areas in land cover types (Wang et al., 2008; Fu et al., 2008; Huang et al., 2015). A such 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 is still remained (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 emission 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 an increased dust emissions. Very few studies focused on natural disturbance effects 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 prevents scientists to parameterize the disturbance effects on dust emissions and to scale its 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 the dust emissions from some land-surface parameters.

Given above background, we aimed to investigate effects of livestock trampling on dust emission rate, and scale an anthropogenic dust emission by natural dust emssion as a relative consequence of livestock trampling. Therefore, we conducted a mini-wind tunnel experiment (by PI-SWERL® device) to measure dust emission fluxes from trampling (at 3 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 represents the potential dust emission, as a restriction of wind tunnel measurements. PI-SWERL® mini wind tunnel was successfully being used on playa surfaces to produce potential erodibility estimates (Etyemezian et al., 2007) that validated using conventional wind tunnel data Sweeney et al., 2008. This PI-SWERL® was also successfully used to investigate dust emission 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 its total territory (equal to 113.1 ml. hectare). According to FAO 2010, as much as one-third of total pastures is under utilized. 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 operates, but huge number of wells still remains out of operation, resulting 10.7 ml. hectare of pasture that cannot be used because of lack of water (Suttie et al., 2005). According to spatial density of livestock in Mongolia (Saizen et al., 2010), the largest number 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 the grazing and trampling.

Our study was carried out in Bayan-Unjuul (sum center) located in a 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 (Saizen et al., 2010). Last decade, number of dust events associated with wind erodibility has increased by 30% in Bayan-Onjuul (Kurosaki et al., 2011). This is an area where dust emission 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 Institute of Meteorology and Hydrology of Mongolia's (IMH) monitoring station 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 to the top of an open-bottomed cylindrical chamber 0.20 m high and 0.30 m in diameter (Figure 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 (Figure 1b). As the annular ring revolves about its center axis, a velocity gradient forms between the flat bottom of the ring and the ground creating a shear stress Nm^{-2} on the surface (Etyemezian et al., 2007). Dust and sand are mobilized by the shear stress generated by the

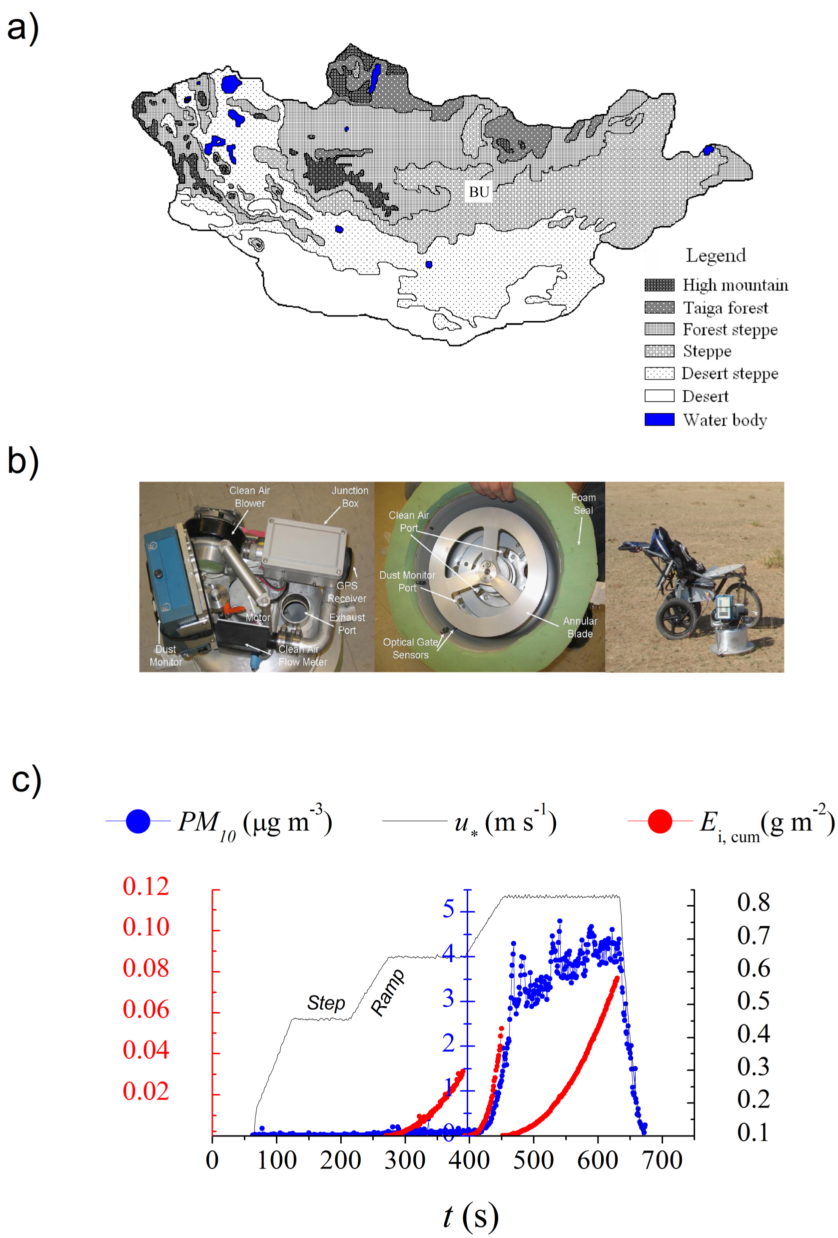


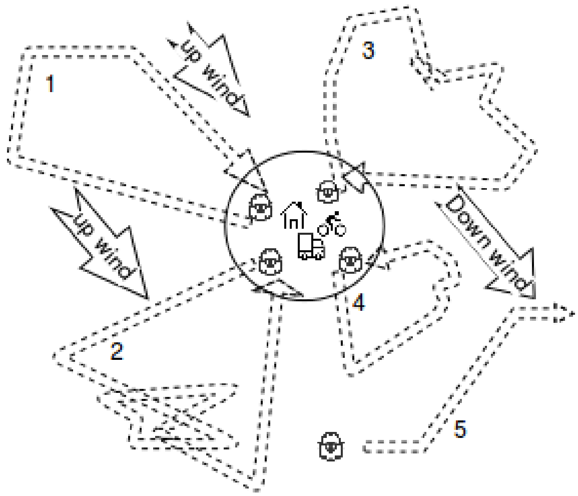
Figure 1. (a) BU (Bayan-Unjuul) denotes the location of the study site in with respect with to vegetation zones in Mongolia; (b) Pictorial illustrations of PI-SWERL® , top view at on the left, bottom view in the middle, and in the field situation at on the right sides; (c) An example data trace of PM_{10}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

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). The PI-SWERL® tests measure the potential fugitive PM10 dust emissions from the surface at different friction velocity u_* (ms^{-1}) corresponding at the high end to a wind speed of approximately 30 ms^{-1} at 2 m above ground level (AGL). In this experiment, the rotation per minutespeed RPM (in rpm) of the annular ring was converted correlated to with a corresponding (in ms^{-1}) friction velocity. The measured data by 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 vary from 0.16 to 0.82 ms^{-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_* 0.54, 0.73 ms^{-1} (ramp properties) separated by three constant u_* settings of 0.44, 0.64, and 0.82 ms^{-1} (step properties) dust emission flux was used (Fig. 2c). When performing the dust measurements by PI-SWERL® , we avoided duplicating measurements on the same location by shifting its position each time.

2.2.2 Experimental area setting

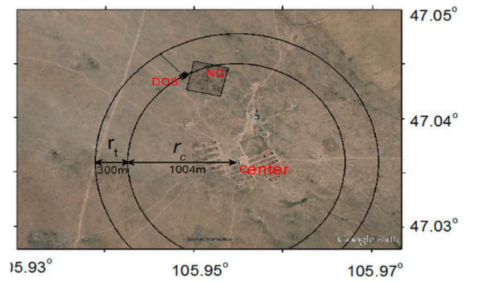
While grazing, livestock leaves behind its trampling trace; therefore, we schemed a trampling route based on grazing route (Fig.2a). Many studies proved that livestock density (i.e.,grazing pressure) is usually highest close to water sources or settlements and decreases with distance away from such localities (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 pictoral livestock trampling routes could be illustrated based on published result (Suttie et al., 2005) on a seasonal and spatial variability of 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 is 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 are the key to the herders overall system; (at a season when feed is very scarce) each must provide shelter as well as accessible forage through that difficult season (Fig.2a). Type III, a distanced grazing route, draws taking livestock to more distant fattening pastures (*otor*) 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. So, measuring dust emissions at the area close to the local center will reflect on the trampling activity.

Our study aimed to measure dust emission affected only by livestock trampling versus no-trampling. Therefore, we focused to do PI-SWERL® mini wind tunnel experiment under similar weather and surface aeolian conditions at the trampled and no-trampled areas. Performing PI-SWERL® mini wind experiment for a short period of time will enable us to avoid weather changes. 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 condition. Hence, at foremost, trampling active area at our site was presented by annulus area enclosed by inner and outer circles (Fig.2b). Inner circle excludes a residential area where land is disturbed mainly by local

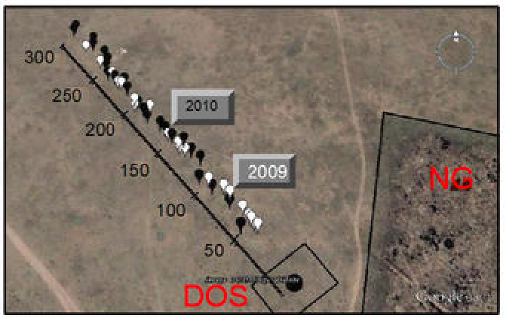


2a.png

(a) A schematic drawing of grazing route around administrative center (or well). Livestock will graze on daily routine depending on weather and fodder source. Type I route (marked by 1, 2, and 3) usually happens good weather condition with rich fodder; Type II route (marked by 4) happens during bad weather condition, like spring and winter; Type III route (marked by 5) is called *otor*.



(b) Annulus area selected for this study. r_c is the distance from sum center (*Center*) to the inner circle for the selected annulus are 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 presents dust sampling points along the transect in 2009 and 2010.

Figure 2. Experimental settings

people's daily activities, while 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 to deposits on downwind lee, when distracted by rough objects like vegetation, shelter areas or buildings. This condition results a distinct fractions of sand and dust on land surface, which will produce a differenial dust emissions. As mentioned above, the prevailing wind direction (*NW* at our site) will differentiate potent emission into upwind and downwind areas. In order to avoid or reduce a possible source of data uncertainty by of 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 Figure 2c was mandatory to run 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 $1\ \mathrm{m} \times 1\ \mathrm{m}$ plot (Table 1) (Munkhtsetseg et al., 2016). In the two springs of 2009 and 2010, vegetation conditions were similar. Vegetation covers were 2.4 and 2.3 percentages during the measurement periods in 2009 and 2010, respectively. These seasonal conditions resulted in sparse vegetation growth and exposed large portions of the surface area to be free of vegetation. This open area enabled us to run PI-SWERL® wind tunnel which has a limitation in- measuring dust emissions over a vegetated area where vegetation height is above 4cm. Sparse vegetation growth during the measurement periods and a 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 by PI-SWERL® were not influenced by vegetation roughness. 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, the 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 gg^{-1} in 2009 and 2010, respectively. Soil moisture values

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] (gg^{-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] is defined in Shinoda et al. (2010a); [2] is presented in Munkhtsetseg et al. (2016)

showed a subtle change in standard deviations of soil moisture. Consequently, these standard deviations revealed insignificant changes in soil moisture among the transect lines for each year. As a temporal variation between the 2-year study period, the difference in averaged soil moisture values on these two springs was equal to 0.0002 gg^{-1}, which is insignificant amount that can alter amount of dust emissions (Fécan et al., 1998). These climatic conditions and above mentioned 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 numbers of livestock at bag-scale for Bayan-Onjuul subdistrict were counted as 52378 and 43709 for 2009 and 2010, respectively (National statistical Organization reports, 2009; 2010). We calculated livestock densities in the annulus area (Fig. 2b) for a given year, as presented in Eq.(1):

$$N = \frac{10^4 num}{\pi(r_c + r_t)^2 - \pi r_c^2} \qquad (1)$$

where N is livestock density in head per hectare and per a year ($\mathrm{Headha^{-1}yr^{-1}}$, and refer to $\mathrm{Headha^{-1}}$); *num* is total livestock in a head; r_c (=1004) is the radius distance from the center to the transect start-line in meter; r_t (=300) is the transect line in meter; 10^4 is a unit conversion of square meter to hectare (Fig. 2c). Total livestock in a head is the total number of 5 animals: sheep, goat, camel, cattle, and horse that are traditionally herded by the nomads. The calculated livestock densities were 241 and 201 $\mathrm{Headha^{-1}}$ along transect lines in 2009 and 2010, respectively.

As for trampling inside DOS fenced area, a calculation of livestock density was followed a basic procedure. A total fenced area of DOS was 50 m x 35 m. Inside DOS fence, sheep movement was constrained into a subarea of 8 m x 35 m to ensure that allocated meteorological equipments would not be damaged. Livestock density inside DOS, therefore, calculated as a spatial distribution total sheep to the enclosed area of 8 m x 35 m, and it estimated as 250 $\mathrm{Headha^{-1}}$.

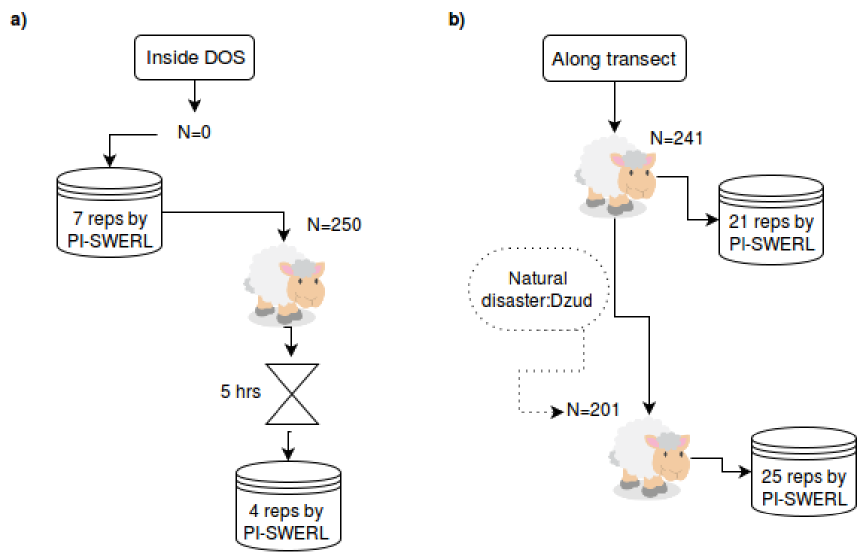
We assumed that all types of livestock (small and large rumnitants) has the same effect on land surface trampling, irrespective of the size or distribution of the footprints. In addition, we made no distinction between the weights of the different livestock species. However, the potential variability 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 is no-trampling area (N=0), we collected 7 replicative dust data on 16 May, 2010. At the same day, we collected 4 replicative dust data after 5 hours of grazing of 7 sheep (N_{250}), those herded into inside the DOS (Figure 3a). We collected 21 replicative dust data along the naturally trampled transect line (shown Fig. 2c) with N of 241 $\mathrm{Headha^{-1}}$ (N_{241})on 15 May 2009. On following winter, livestock denity at our study site was reduced due to the moderate dzud (Mongolian word indicating harsh winter conditions contributes to livestock mortality) (Natsagdorj and Dulamsuren, 2001; Begzsuren et al., 2004). We collected 25 replicative dust data along the naturally trampled transect line with N of 201 $\mathrm{Headha^{-1}}$ (N_{201}) on 15 May, 2010 (Fig. 3b).

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

Moreover, livestock trampling intensities for all 3 types of measurements was likely subject to on annual basis. Because, dust emissions at the naturally trampled transect were measured on annual basis (at the springs 2009 and 2010). As for dust for N=250 $\mathrm{Headha^{-1}}$, 5 hour of grazing is also annual if we considere that average walking speed for livestock is 314 $\mathrm{mh^{-1}}$ (equal to approximately within 11.5 s time-period covers a 1 m path) (Plachter and Hampicke, 2010). Assuming that the livestock pass 4 times (from sum center to grazing area and vise versa) along the transect lines of the ring area in a day, this will resulted in a yield of 1460 times passages per a year. On annual basis, livestock walk over and over a 1 meter path for a



3.png

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

time period of 4.6 h (11.5 s $\times$ 1460 times=16790 s). This finding can be used to estimate an average time period of livestock trampling in the fence. Due to limited space, the livestock inside the fence was in a near static movement by not walking the path. This condition enabled us to assume that each sheep stands in the static state covering around 1 m path with respect to their body size. Thereafter livestock trampling continued for a half day ($\approx$ 5 h) on bare surfaces inside DOS, after which systematic trampled dust emissions measurements were conducted by 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. It results an unevenly distributed sediment within a local site by producing limited or unlimited sediment supply surface (Kimura and Shinoda, 2010; Yoshihara et al., 2010). A such microscale sediment heterogeneity was captured in our dust data resulting larger deviations even for the same density of livestock (Appendix 1 and 2). To present dust emission on a local scale, the averaged values of measured dust emissions for a given livestock density is prefered. Because, it was demonstrated that livestock affects grassland heterogeneity on a local scale, while marmots contribute to a 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 groups (N of 0, 201, 241 and 250 $\mathrm{Head ha^{-1}}$). Data from each group for each friction velocity were treated separately.

We tested datasets normality with 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 samples from 4 to 2000 (Razali et al., 2011). One-way analysis of variance (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 Headha^{-1}) from zero trampled surface.

We employed OriginPro 8.1 Academic software (Northampton, MA 01060 USA) for calculating statistics and determining the coefficients by the least square optimization method with Levenberg-Marquardt algorithm (Moré, 1978).he Levenberg-Marquardt (LM) 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.

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

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

A scale factor is a number which scales, or multiplies, some quantity of natural dust emission (F_{REF}) to get anthropogenic dust emission (F_N, influenced by livestock trampling). In this study, the scale factor (without unit) was calculated as a 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 emission (F_{REF}) from anthropogenic dust emission (F_N), and 2) to scale an effectual factor of livestock trampling on dust emission.

If $F_N/F_{REF} \simeq 1$, will indicate no effect of livestock trampling on dust emission. If $F_N/F_{REF} < 1$, means suppressing effect of livestock trampling on dust emission, and if $F_N/F_{REF} > 1$, will point an increasing or enhancement effect of livestock trampling on dust emission.

4 Results

4.1 Livestock trampling effects on dust emission

The mean rate of PM_{10} emission from the test surface areas for each friction velocity of PI-SWERL® experiment reveals greater detail concerning the behaviour of dust emission and the effect of trampling (Fig. 4)(Appendix 1). The dust emission from the undisturbed, zero trampling surface at friction velocity u_* of 0.44 ms^{-1} was low (10.5 $\mu g m^{-2} s^{-1}$). This was elevated to 15.7 $\mu g m^{-2} s^{-1}$ at u_* of 0.54 ms^{-1}, and then backed to background level 10.1 $\mu g m^{-2} s^{-1}$ at 0.64 ms^{-1}. A noticeably increased emission rates of 39 and 37.3 $\mu g m^{-2} s^{-1}$ are seen at the u_* of 0.73 and 0.82 ms^{-1} respectively, however, their difference was negligible. These dust emission behaviors in a change with u_*, which are in a sequential order for each PI-SWERL experiment, suggest that our sandy soil of temperate grassland is somewhat similar to a supply-limited surface with successive emission (Macpherson et al., 2008). In contrast, dust emission from trampling test areas presents that the disturbed, trampling surface is an unlimited-supply dust surface concerning its apparent increased emission rate with an increase in u_* (Fig. 4), except the case of 0.64ms^{-1} subtle declined to 0.64ms^{-1}.

At friction velocity of 0.44 ms^{-1}, although dust emission was almost doubled between zero trampling and N_{250} trampling, this difference was not statistically significant (Fig. 4b). Additionally to this, trampling effect is visible when considering an increase in mean dust fluxes with all trampling densities of 201, 241 and 250 head ha^{-1} (Fig. 4b). However, a such increase is invalid if include dust flux at zero trampling in comparisons with those N_{201} and N_{241} tramplings, but their differences are very small. We used Shapiro-Wilk test (with a significance of $\alpha = 0.05$) and standard deviation to assess whether the variables had a normal distribution and equilibrium or diverse variances in the statistical populations, respectively. Dust flux for zero trampling surface shows statistically significant with the normality. Contrastingly, the insignificant normalities is demonstrated with the trampled area datasets (Fig. 4a) along with larger standard deviations (Fig. 4b), those are resulted by scattered data points from their sample populations (see Fig. 4a; data points with box chart of 25^{th} and 75^{th} percentiles). Higher diversity of dust fluxes presents morphological disparity and sedimentological diversification presence in livestock trampled test areas.

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

At high friction velocities of 0.73 and 0.82 ms^{-1}, trampling effect is strongly pronounced. It can be seen in enlarged emission rates at all trampling area from that zero trampling; specifically, 5-10 times for u_* of 0.73 ms^{-1}, and 10-20 times for u_* of 0.82 ms^{-1}. Consequently, emission rates at N_{201} and N_{250} significantly differ from that zero trampling, which is supported statitically by their significant normalities (Fig. 4b, denoted by *). Moreover, an increase in mean dust fluxes with increase in N for all trampling densities (including non-trampling) also perceives the effect of trampling.

Overall, the effect of trampling on dust emissions was persistent throughout all friction velocities. Significantly higher dust loading was occurred after a disturbance level has reached by the trampling N_{250}. But, the disturbance level was lowered with an increase in wind force, u_*. It indicates the effect of trampling can be seen or get into a play in dust emission when wind gets stronger.

4.2 A scale factor of dust emission due to livestock trampling

The calculated scale factor for each N at different u_* values are shown in Figure 5. The scale factors for N_{250} varied from 2.5 to 20 (Fig. 5, $F_{N_{250}}/F_{REF}$). Similarly, the scale factors ranged between 0.8-16 and 0.5-10 for N_{241} and N_{201}, respectively. Very few of the scale factors were below 1, those were occured at low u_* values for livestock trampling with N_{201} and N_{241}

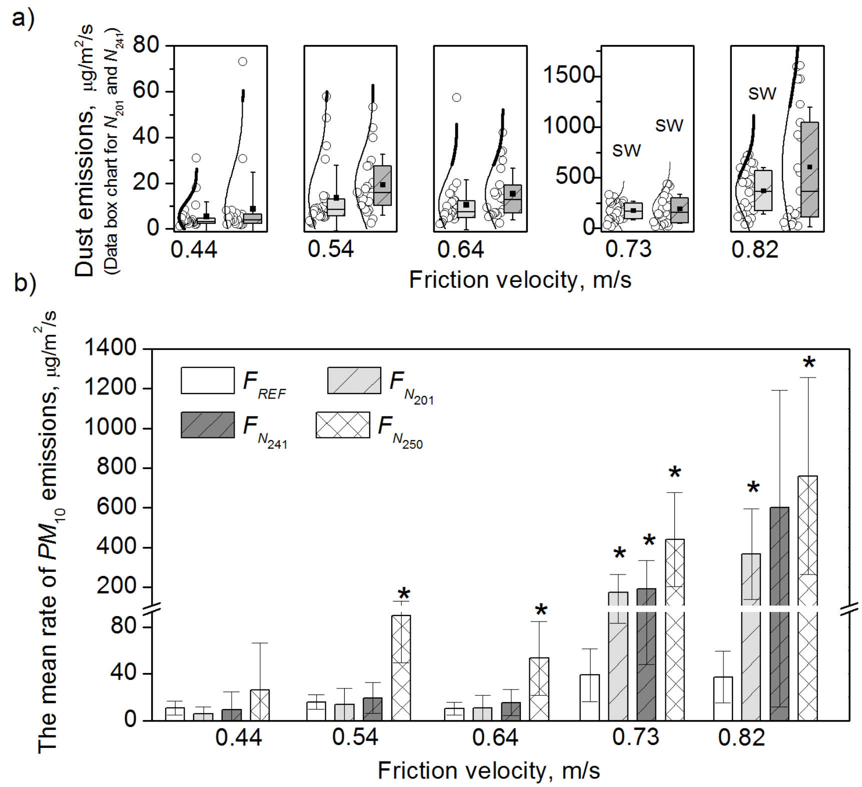


Figure 4. a) Measured dust fluxes from the trampled surfaces with N of 201 and 241 Headha^{-1}. Open circles (○) and curved lines (≀) denote collected dust data and normal distributions. Center dots (.) and dashes (–) in the boxes denote means and medians of dust emissions. Opening and closing of the boxes presents 25 and 75^{th} percentiles for each dataset. *SW* denote statistical significant datasets with Shapiro-Wilk normality test. b) Mean dust emission fluxes with standard deviations on correspondent friction velocities. The significant differences (*p* value with the significant level of 0.05) for mean dust emissions of the trampled surfaces from the F_{REF} on each friction velocity is denoted by $*$.

Headha^{-1} (Fig. 5, $F_{N_{201}}/F_{REF}$ and $F_{N_{241}}/F_{REF}$). Consequently, 80% of the scale factors were greater than 1 revealing that livestock trampling had been likely enfolded an enhancement effect on dust emissions.

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

Moreover, an increase in the trampling density (N) also results an increase in the scale factors (Fig. 6). The scale factors for

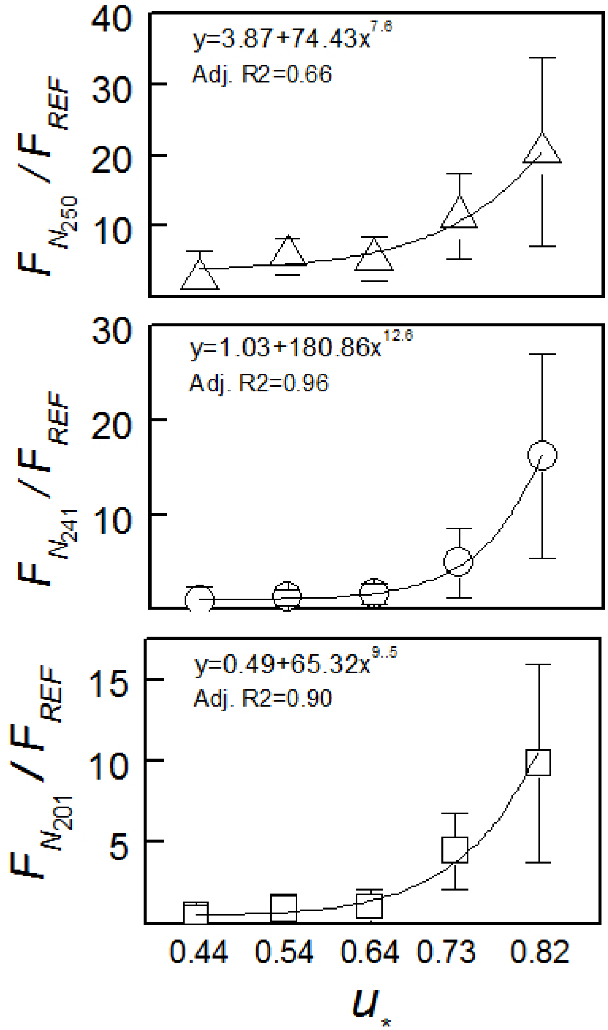


Figure 5. Dust emission ratio dependencies on friction velocity and livestock density. Open triangles (△), circles (○), and squares (□) denote dust emission values from the trampled surfaces with livestock densities of 250, 241, 201 Headha^{-1}, respectively. a) Relationships between the mean emission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

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

These results suggest that both u_* and N has enormous combinational effect on dust emission from trampling test surface, and eventually, determines the effect strength of trampling.

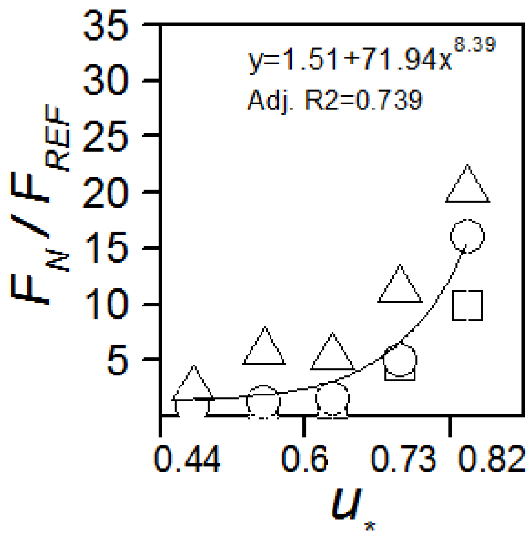


Figure 6. A statistically fitted relationship between dust emission ratios and u_* for all livestock trampled surfaces; *n* denotes sample number, *v* is degree of freedom, χ/v is the reduced chi square, *RMSE* is root mean square error, Adj.R^2 is adjusted r^2, residual sum of squares.

5 Discussion

5.1 The effect of trampling on dust emission

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

The dust emission from the undisturbed, zero trampling surface at friction velocity u_* of 0.44 ms^{-1} was low (10.5 $\mu g m^{-2} s^{-1}$). It was elevated to 15.7 $\mu g m^{-2} s^{-1}$ at u_* of 0.54 ms^{-1}, and then backed to background level 10.1 $\mu g m^{-2} s^{-1}$ at 0.64 ms^{-1}. A noticeably increased emission rates of 39 and 37.3 $\mu g m^{-2} s^{-1}$ are seen at the u_* of 0.73 and 0.82 ms^{-1} respectively, however, their difference was negligible. These dust emission changeable behaviors in a change with u_*, those are in a sequential order of shear stress for each PI-SWERL experiment, suggest that our sandy soil of temperate grassland is somewhat similar to a supply-limited surface with successive emission (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, that the disturbed, trampling surface behaves as an unlimited-supply dust surface, concerning its consistent increase in emission rate with an increase in u_* (Fig. 4), except the case of $0.64\mathrm{ms}^{-1}$ a subtle decline to $0.54\mathrm{ms}^{-1}$. This shift in natural soil, from suply limitedness to unlimited supply surface, could be explained by the weakening of inter particle 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 to this explanation, we observed increased dust emission from the trampling test areas in comparison to those from zero trampling, despite similar ranges in shear velocity. Their differences was statistically significant (One-way ANOVA test; p value with 0.05) (Fig. 4b, denoted by $*$) at most of u_*, particularly for N_{250} trampling. Observed emission rate at N_{250} trampling were 26.1 and 760 $\mu g m^{-2} s^{-1}$, those value are approximately 2 and 20 times greater than those zero trampling, measured at u_* of 0.44 to 0.82 ms^{-1}. Supportingly with these facts, we could conclude that emission 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) has been taken place on Mongolian temperate grassland, where is endured traditional animal husbandry for centuries. However, we are not able to give further insight at this point for increased dust contribution either from directly the availability of readily suspendable sediment or indirectly the process relationship between abrasive saltation by disturbance and dust emission, those are discussed in detail by (Macpherson et al., 2008; Baddock et al., 2011; Zhang et al., 2016).

It was demonstated that wind erosion and deposition processes forms uneven spatial distribution of dust supplements as driven by microclimatic, sedimentological, geochemical, surface patchiness and biological conditions (Gill, 1996). Likewise, we noticed larger standard deviations (Fig. 4b), those are resulted by scattered data points from their sample populations (see Fig. 4a; data points with box chart of 25^{th} and 75^{th} percentiles). Higher diversity of dust fluxes presents morphological disparity and sedimentological diversification presence in test areas. It may caused by as a result of the aeolian processes, tha dust emissions are highly variable with space and between distinct landforms, even within individual landforms (Gill, 1996; Reynolds et al., 2007). Another reason it may related to that dust flux does not come to a similar saturation from a field site (Gillette and Passi, 1988). One of possible microscale disturbance by marmots creates spatially heterogeneous grasslands at a fine scale (Yoshihara et al., 2010). Moreover, it was emphasized that the livestock modified spatial heterogeneity at the landscape scale, whereas marmots modified spatial heterogeneity at the local scale (Yoshihara et al., 2010).

5.2 A scale factor of dust emission by livestock trampling

We found that the variabilities 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). It points that the scale factor of dust emission by trampling get magnified with an increase in u_*. This means that anthropogenic dust emits much as wind blows stronger, like revealing 'hidden effect' of trampling. The suppressing effect of livestock trampling on dust emission was found at low u_* with demonstration of the scale factors below 1 (Fig. 5). These low scale factors, in turn, supports the idea that (hidden) enhancement effect of trampling on dust emission requires high u_* to be revealed out. This u_*-magnified effect of livestock trampling on dust emission is a coincidence with the dust emissivity pattern of unlimited supply surfaces, discussed in Section 5.1.

Additionally, an increased trampling density elevated the scale factors. Larger scale factors was observed for N_{250} than those for N_{241} and N_{201} at all u_* values (Fig.6). Relatedly, 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 significantly higher dust emission occurs after a disturbance level has reached to N_{250}. A similar result of increased dust occurence with the disturbance level for cattle passes was presented (Baddock et al., 2011). Surprisingly, we observed that the disturbance level for the significant dust emission (comparably to F_{REF}) was lowered with an increase in wind force, u_* (Fig. 4b). Our research findings indicate that both u_* and N has enormous combinational influence on anthropogenic dust emission due to livestock trampling effect, and eventually, determines the effect strength of livestock trampling on dust emission. But, summarizing the effect of livestock trampling on dust emission is somewhat challenging.

Figure 7 illustrates a tabular chart of a scale factor for the different values in N and u_*. It is apparent that the scale factor is gradiently increased with an increase both in u_* and N. As displayed in Figure 7, the fixed u_* versus the fixed range of N delimits an application range of the tabular chart. Moreover, primary conditions of land surface (dry soil and low vegetation) that 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 emission due to livestock trampling when natural dust emission is known. Therefore, implication of the chart should be considered the valid range for livestock density, friction velocity, and land surface conditions.

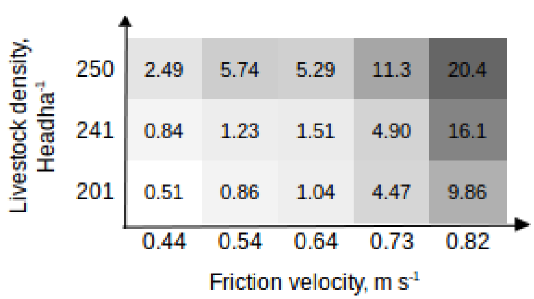


Figure 7. A table chart of scale factor (F_N/F_{REF}) with different u_* and N of 201, 241 and 250 Headha^{-1} per year. A color gradient from light to dark gray corresponds to an increase in the scale factor.

Future work is needed to discover the scale factor (or anthropogenic dust due to trampling) relationships on unlimited, natural variations of soil moisture, and crust strengths. Because 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 in soil physical properties gets augmented when the soil is moist at the time of trampling (Warren et al., 1986). Consequently, it would be a way better to develop the scale factor as a functionally 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 include 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 livestock different types. The assessment should be on annual basis, but can be modified to the required time period if grazing route is known. In this study, we assumed that all types of livestock (small and large rumnitants) has 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 emission. The applicability of the tabular chart of the scale factor to the other grasslands areas beyond the study location could be accomplished with PI-SWERL tests over a wider geographic area.

6 Conclusions

We studied effects of livestock trampling on dust emission strength conducting PI-SWERL® experiment in a temperate grassland of Mongolia. A significant increase in dust emission was manifested with an elevated trampling density and an increased friction velocity. The scale factor demonstrated that 1) dust emission is greatly enhanced due to livestock trampling; 2) the enhancement rate in the dust emission 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 get into a play in dust emission 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 is needed, however, there are many uncertainties and assumptions to be improved in this study.

7 Data availability

The underlying data can be found in the Appendix.

Appendix A: Appendix A

A1 Appendix A1

Table 2. Land surface and soil size characteristics in the study area

	Measured dust emissions, $\mu g m^2 s^{-1}$									
			F_{REF}					$F_{N_{250}}$		
u_*, ms^{-1}	0.44	0.54	0.64	0.73	0.82	0.44	0.54	0.64	0.73	0.82
	7.75	14.87	9.95	17.14	13.71	86.76	73.70	32.08	141.49	110.21
	7.58	16.11	9.60	25.77	32.44	5.92	125.49	87.57	677.31	928.18
	17.08	16.47	20.31	58.69	83.07	4.41	40.24	21.06	370.49	709.59
	6.88	16.62	9.22	28.64	23.24	7.18	120.81	72.79	571.93	1292.03
	12.21	15.00	7.32	39.68	32.53					
	19.59	26.07	11.60	79.69	37.85					
	2.07	4.51	2.54	23.12	38.46					
Mean	10.5	15.7	10.1	39.0	37.3	26.1	90.1	53.4	440.3	760.0
SD	6.2	6.3	5.4	22.6	22.0	40.5	40.6	31.9	236.4	495.3

A2 Appendix A2

Table 3. Land surface and soil size characteristics in the study area

	Measured dust emissions, $\mu g m^2 s^{-1}$									
			$F_{N_{201}}$					$F_{N_{241}}$		
u_*, ms^{-1}	0.44	0.54	0.64	0.73	0.82	0.44	0.54	0.64	0.73	0.82
	2.07	9.10	9.36	268.38	569.14	1.89	4.37	8.50	412.38	1469.22
	2.4	5.45	4.51	247.47	477.52	6.34	15.92	12.9	124.73	165.94
	1.97	5.06	4.19	215.55	433.93	72.99	14.31	7.07	24.52	23.24
	2.71	5.67	5.85	97.96	641.01	1.82	2.51	2.49	50.45	131.55
	2.97	9.64	7.49	229.35	648.04	5.67	20.25	13.4	153.83	143.61
	4.09	11.62	10.44	222.24	452.61	1.99	8.14	6.04	42.57	55.1
	2.94	5.68	6.42	146.43	223.69	1.97	7.37	7.06	191.46	899.14
	3.21	14.28	12.41	160.77	365.88	4.01	29.91	19.13	246.65	551.89
	2.75	6.13	5.15	217.09	533.54	6.83	11.98	7.16	26.54	31.83
	2.73	5.61	4.85	85.18	177.24	2.26	8.52	6.12	137.08	596.04
	2.37	8.57	12.44	276.89	450.74	3.31	18.58	33.96	300.54	923.68
	3.41	9.2	7.78	170.03	728.82	5.25	17.48	15.43	213.66	1042.76
	3.81	8.02	17.81	308.82	712.61	4.08	27.73	29.94	432.75	1472.39
	3.76	8.9	11.64	259.24	597.8	8.05	44.2	42.09	433.13	1592.87
	31.04	48.44	15.28	244.37	354.01	30.71	53.14	26.27	143.26	180.92
	5.52	13.13	9.85	145.49	210.6	3.56	12.87	6.02	47.52	107.3
	8.4	14.43	15.37	261.1	661.45	5.7	10.29	5.31	16.61	10.14
	18.14	36.23	20	79.97	93.23	3.62	39.83	33.47	369.67	365.11
	3.56	8.09	7.07	48.61	46.17	4.98	15.48	9.29	62.39	56.63
	6.06	30.54	57.19	330.62	253.18	1.98	15.89	14.71	319.52	1221.66
	10.36	57.89	6.34	109.65	81.43	8.08	27.42	15.96	262.56	1604.88
	4.69	6.57	3.77	18.18	36.43					
	2.15	2.52	2.71	90.26	136.25					
	1.58	2.94	2.34	90.37	197.62					
	1.2	3.64	2.12	33.32	115.36					
Mean	5.4	13.5	10.5	174.3	367.9	8.8	19.3	15.3	191	602.2
SD	6.4	14.3	10.9	91	228.4	15.9	13.4	11.3	143.2	590.6

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