

Response to Referee #1 :

We appreciate the Editor and Referee # 1 for their valuable and constructive comments for this manuscript, which greatly assist in improving the quality of the original manuscript. We have carefully checked and revised the whole manuscript according to the Referee #1's comments. Please find a point-by-point reply to the issues as follows. And we have also uploaded the file of 'acp-2017-94-revised.pdf'.

Comments raised by Referee # 1

This paper describes an experimental study on the effect of livestock trampling on dust emission using a mini wind tunnel. The subject is interesting from the anthropogenic dust point of view. However, the results presented in the paper seems not very reasonable (in my opinion) about the dust emission mechanism. Also, it does not provide sufficient information for estimating the impact of livestock trampling on the regional dust emission amount. From the dust emission mechanism point of view, there should be more detailed descriptions about the change in the physical condition of grassland surface by trampling. The ratio of the flux $F/F(\text{free})$ is considered in this analysis. However, the reason for taking the ratio is not explained. Physical meaning is not clear. (In addition, the data for $F(\text{free})$ contains big errors as can be seen in Appendix.) Also, the reason for describing the ratio by $1+f$ is not clear. It seems the function form to describe the experimental results is rather arbitrary. In Eq. (8), the major term that represents the effect of trampling is proportional to the 8th power of u^* . Is it reasonable? A physically reasonable function form should be used.

An important subject would be estimating the contribution of dust emission from trampled grassland. From this point of view, it would be better to discuss the dust emission flux in (trampled) grassland in comparison with that in arid and semi-arid regions.

Response: We greatly thank Anonymous Referee # 1 for quite helpful and constructive comments given to our manuscript (MS). We highly appreciate your contribution for the improvements of our manuscript with well-judged comments. We have revised our manuscript according to the suggestions and comments raised by the Referee # 1. We strongly believe that the Referee # 1 will satisfy with the revised version of the manuscript. The major revisions are included:

1. We agree to the Referee's point given on the livestock trampling function (f_L). The equation of the function was derivative by statistical fitting, not based on dust emission mechanism. We have revised our manuscript according to the Referee's point. The livestock trampling function (f_L) is no longer in the central focus of this MS. Instead, MS focuses on the dust emission at trampled grassland (F_N) in a comparison to dust emission from natural grassland (F_{REF}), as it suggested by the Referee # 1 in the concluding paragraph on the review letter.
2. We have used the ratio of F_N/F_{REF} to differentiate between the different dust strengths, and by it, we scaled factor of anthropogenic dust emission due to livestock trampling. We have included the explanation for scale factor in the 'Data analysis section'.

3. Since we have excluded f_L function, $1 + f_L$ term is no longer in the revised manuscript.

Point by point response

1. This paper describes an experimental study on the effect of livestock trampling on dust emission using a mini wind tunnel. The subject is interesting from the anthropogenic dust point of view.

Response: Thank you. This comment is very encouraging for us.

2. However, the results presented in the paper seems not very reasonable (in my opinion) about the dust emission mechanism. Also, it does not provide sufficient information for estimating the impact of livestock trampling on the regional dust emission amount.

Response: We appreciate Referee's concern. We considered the point, carefully. It is crucial to estimate the impact of livestock trampling on the regional dust emission amount. However, our limited dataset restricts us to provide sufficient information on a regional level. With this aim, we tried to develop the livestock trampling function as an applicable simple formula to estimate dust emissions from trampled Mongolian steppe (which occupy approx. 30% of its territory). The function is simple; depends on u_* and N . These kind of data can be downloadable on annual basis. Moreover, it will be easier to account the livestock number, than defining changes in soil physical conditions (Referee # 1 also mentioned, we should also check how soil physical condition changes). In practical application, a such derivation would be handful. However, the formula is fitted statistically; which fails to express its physical meaning. We completely agree to the Referee's point that the formula does not reflect dust emission physics. Therefore, we revised content of the MS into "scale factor" as a ratio of F_N to F_{REF} .

[Data analysis section: Page 12, Line 4-14]

And, we emphasized the necessity on larger dataset covering spatial variations and soil textures, as well as atmospheric conditions for a broad usage of the scale factor.

[Page 19, Line 19-20; Page 20, Line 23-24]

3. From the dust emission mechanism point of view, there should be more detailed descriptions about the change in the physical condition of grassland surface by trampling.

Response: Thank you very much for this comment. As the Referee mentioned, it would be a perfect illustration if we could link trampling effect on soil surface; and then connect it to the dust emission. This type of work is

needed for a better understanding and a well described anthropogenic dust emission mechanism. The referee is right to point it out, yet our research focus is the dust emission strength changes due to trampling. Our research is no longer focused on the dust mechanism.

It is true that the soil physical change by trampling is the study topic we should push forward. Importantly, in our study, the factual effect of trampling on dust emission is revealed; this foremost step will direct to the advanced study. We strongly believe that the Referee will agree to it. We have already included the brief descriptions of soil physics changes resulted from mechanical disturbance by livestock trampling. We believe this type of information is satisfactory in the content of our MS.

[Page 2, Line 30-31; Page 20, Line 2-5]

4. The ratio of the flux $F/F(\text{free})$ is considered in this analysis. However, the reason for taking the ratio is not explained. Physical meaning is not clear. (In addition, the data for $F(\text{free})$ contains big errors as can be seen in Appendix.)

Response: Thank you for pointing it out. Now, we have included the meaning of the ratio; and the reason. The ratio of F_N/F_{REF} is presented to differentiate between the different dust strengths. The ratio not only differentiates dust strengths but also it expresses / measures a scale factor of dust emission enhanced by trampling.

[Page 12, Line 7-13]

As for obtained data, we too were disappointed by the big errors (in Appendix). Later, we have been convinced that it is the correct. On the field, we had recognized heterogenous sediment surface by eye observation. The possible reason for heterogeneous sediment distribution was demonstrated by the other research findings. We separately added a detailed explanation on the relatively big standard deviations on measured dust emissions on mean dust emission sub section of 'Methods and Materials section'.

[Page 11, Line 9-20]

5. Also, the reason for describing the ratio by $1+f$ is not clear. It seems the function form to describe the experimental results is rather arbitrary.

Response: Right. We completely agree with the comment. Yes, the function is fitted, statistically. It will give some uncertainty for estimating impact of trampling effect on dust emissions; particularly for the areas beyond our study site. Therefore, we recommend that to test the same for more broad

illustration. This kind of result with updated data will be useful; and connecting and combining the results from other sites will surely give us a big picture.

Since, we focused on the scale factor of dust emission due to trampling (dust emission ratio from trampled to natural grassland) by removing fl function; at this time we have also excluded our $1 + f_L$ result from MS.

[Page 10, Line 13-19; Page 17]

6. In Eq. (8), the major term that represents the effect of trampling is proportional to the 8th power of u^* . Is it reasonable? A physically reasonable function form should be used.

Response: Yes, somehow. We are not certain; this result should be confirmed by other results. One of the confirmations was the recent finding by Zhang et al. 2016; showed that the dust emission dependent on $u^{*4} - u^{*10}$ varied by the renewal process. This renewal process (disturbance) is kind of artificial disturbance. Our result lies in the range, which was discussed in the MS. However, as the Reviewer mentioned we should aim for the physically based formula. Again, now we focused on the contribution of the dust from the trampled grassland by removing fl function; therefore the related changes excluded such a discussion.

[Page 19, Line 12-14]

7. An important subject would be estimating the contribution of dust emission from trampled grassland. From this point of view, it would be better to discuss the dust emission flux in (trampled) grassland in comparison with that in arid and semi-arid regions.

Response: Thank you very much. This comment gave us a clear directional insight how to revise our manuscript. We totally agree to the Referee's concluding comment. In the revised manuscript, a comparison between dust emissions from trampled surface and non-trampled surface is the main research point. In the previous version of the manuscript, the major point was cluttered by the livestock trampling function. We have revised our manuscript according to the Referee's comments.

Response to Referee #2 :

We appreciate the Editor and Referee # 2 for their valuable and constructive comments for this manuscript, which greatly assist in improving the quality of the original manuscript. We have carefully checked and revised the whole manuscript according to the Referee #2's comments. Please find a point-by-point reply to the issues as follows. And we have also uploaded the revised manuscript file of 'acp-2017-94-revised.pdf'.

Comments raised by Referee # 2

This paper examines the effect of livestock trampling on the potential for dust emissions from Mongolian Steppe grass landscape. The basic approach is to use wind tunnel measurements (PI-SWERL) to measure windblown emissions on background (untrampled) surfaces and subsequently trampled surfaces. Two types of measurements are conducted. The first is in a controlled pen where livestock grazing was not allowed for some time. This area was apparently used to obtain background (undisturbed/ untrampled) levels of dust emissions. The area was then grazed by livestock (estimated density of 250 head per hectare) and re-measured for emissions. In separate tests, a transect of wind tunnel measurements was conducted in 2009 and again in 2010 through an area of actual livestock grazing with estimated densities of 201 and 241 head per hectare. The results are analyzed for dust emissions increases due to livestock grazing at different values of friction velocity.

Overall, this information is very valuable to the understanding of wind erosion, especially in the Mongolian Steppe. These kind of data are lacking from the literature and can be very helpful for estimating anthropogenic impacts on the dust problems within Asia.

I have two major concerns with the manuscript. The first is that it can be rather difficult to follow the discussion because the presentation is not always clear. I found myself having to guess the meaning of a lot of sentences and infer information where I would have liked to know for sure that the authors were conveying a specific point. The second is that while the data collected are quite valuable, the variation in conditions is rather limited and it is not clear that the extensive development of functional relationships is warranted or justified. These include somewhat limited temperature, relative humidity, and antecedent soil moisture information. They also include a limited range of livestock trampling which span from 201 to 250 head per hectare and are based on necessarily coarse estimates since it is difficult to know precisely how many sheep trampled over what area during what period of time.

In my view, both of these concerns can be addressed by substantially shortening the manuscript and sticking strictly to the main findings. Organizationally, I suggest greatly shortening the introductory and background information to the minimum necessary to convey the importance of livestock grazing to Asian dust. Technically, I recommend that rather than fitting a function of u_* and N , it would be better to simply provide an enhancement factor of emission due to livestock trampling at different values of u_* and stating that the information applies to N 250 head per hectare. The exact representation is up to the authors, but one option would be a curve that has u_* on the x-axis and enhanced emissions on the y-axis (F_N/F_{REF} in the notation of the manuscript, similar to what is now depicted in Figure 5a and b). This would also help show that there is apparently a u_* below which there appears to

be little difference in emissions between trampled and untrampled steppe soil. Perhaps the discussion can then focus on the limited nature of the study and where additional information would be most helpful in future work.

Response: We completely agree to the Referee's comments given on our manuscript (MS); and by it, we have substantially improved quality of our MS. We strongly believe that the Referee # 2 will satisfy with the revised version of the manuscript. We greatly appreciate your contribution for the improvements of our manuscript giving us well-instructed comments. The major revisions are included:

1. The livestock trampling function (f_L) is excluded from our MS. Our revised MS focuses on the scale factor of dust emission due to trampling as the Referee # 2 suggested.
2. We have shortened 'Introduction section'. We have added a tabular chart of a scale factor for a better illustration, and revised texts in 'Discussion section' for a clarity.
3. Since we have stucked to the main results, the related and associated parts (title, abstract, result, discussion) are justified and corrected as well.

Point by point response

1. This paper examines the effect of livestock trampling on the potential for dust emissions from Mongolian Steppe grass landscape. The basic approach is to use wind tunnel measurements (PI-SWERL) to measure windblown emissions on background (untrampled) surfaces and subsequently trampled surfaces. Two types of measurements are conducted. The first is in a controlled pen where livestock grazing was not allowed for some time. This area was apparently used to obtain background (undisturbed/untrampled) levels of dust emissions. The area was then grazed by livestock (estimated density of 250 head per hectare) and re-measured for emissions. In separate tests, a transect of wind tunnel measurements was conducted in 2009 and again in 2010 through an area of actual livestock grazing with estimated densities of 201 and 241 head per hectare. The results are analyzed for dust emissions increases due to livestock grazing at different values of friction velocity.

Overall, this information is very valuable to the understanding of wind erosion, especially in the Mongolian Steppe. These kind of data are lacking from the literature and can be very helpful for estimating anthropogenic impacts on the dust problems within Asia.

Response: Thank you very much for your careful reading of our manuscript. We greatly appreciate your positive comment and given a value on our work.

2. I have two major concerns with the manuscript. *The first* is that it can be rather difficult to follow the discussion because the presentation is not always clear. I found myself having to guess the meaning of a lot of sentences and infer information where

I would have liked to know for sure that the authors were conveying a specific point. *The second* is that while the data collected are quite valuable, the variation in conditions is rather limited and it is not clear that the extensive development of functional relationships is warranted or justified. These include somewhat limited temperature, relative humidity, and antecedent soil moisture information. They also include a limited range of livestock trampling which span from 201 to 250 head per hectare and are based on necessarily coarse estimates since it is difficult to know precisely how many sheep trampled over what area during what period of time.

Response: We totally agree to the two major points raised by the Referee # 2.

- Firstly, we have revised 'Discussion section' according to the Referee's point by adding a tabular chart for scale factor (Fig.7) and editing text.

[Page 19, Figure 7; Page 17]

- Secondly, our data was obtained in the limited condition. Yes, the further study is needed to investigate and develop a such functional relationship as Referee # 2 mentioned. Livestock trampling time span is on annual. We have clarified it in the manuscript.

[Page 8, Line 15]

3. In my view, both of these concerns can be addressed by substantially shortening the manuscript and sticking strictly to the main findings.

Organizationally, I suggest greatly shortening the introductory and background information to the minimum necessary to convey the importance of livestock grazing to Asian dust.

Technically, I recommend that rather than fitting a function of u_* and N , it would be better to simply provide an enhancement factor of emission due to livestock trampling at different values of u_* and stating that the information applies to N 250 head per hectare. The exact representation is up to the authors, but one option would be a curve that has u_* on the x-axis and enhanced emissions on the y-axis (F_N/F_{REF} in the notation of the manuscript, similar to what is now depicted in Figure 5a and b). This would also help show that there is apparently a u_* below which there appears to be little difference in emissions between trampled and untrampled steppe soil.

Response: We highly appreciate comments raised by Referee # 2. We have revised our manuscript according to the Referee's point.

- We have shortened 'Introduction section' as recommended by Referee # 2.

[Page 2-3]

- The livestock trampling function (fL) is no longer in the central focus of this MS. Instead, MS focuses on the (enhancement) scale factor of emission due to livestock trampling as the Referee # 2 suggested. We have separated Figure 5a and b into two figures (Figure 5 and Figure 6) to present the u_* -magnified and N -elevated scale factor. For a better presentation (and more clarified 'Discussion section'), we have added a tabular chart of scale factor in Figure 7.

[Page 15, Figure 5; Page 17, Figure 6; Page 19, Figure 7]

4. Perhaps the discussion can then focus on the limited nature of the study and where additional information would be most helpful in future work.

Response: Thank you for pointing it out. We obtained dust data on the limited nature; so that our result represents the limited condition. Yes, we agree to the comment. It is important to mention our study limitations and mention additional information those are needed to be explored for future research work. We have discussed the limited nature of the study and future work.

[Page 19, Line 17-24; Page 20, Line 1-6; 12]

~~A~~ **An Anthropogenic Dust Emissions due to Livestock Trampling Function for Potential Emission Rate of Wind-blown Dust 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. ~~Decades~~ 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. ~~For sealing the effect strength of trampling, therefore~~ 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 emission 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. ~~Furthermore, we successfully developed a livestock trampling function dependant on u_* and N . In the livestock trampling function, almost 4 times greater of determinant power for u_* than of for N was determined ($f_L(N, u_*) \sim N^{1.1} u_*^4$). It points~~ It means that the effect ~~strength of trampling get magnified with an increase in u_* , and, therefore dust will emit much as stronger wind prevails at the trampled surfaces. This finding indicates that the effect of trampling of livestock trampling on dust emission~~ can be seen or get into a play in emission 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. ~~The applicability of our result is feasible with a care to other areas beyond the study location.~~

20 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 exacerbate 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). ~~In water and nutrient limited environments, increased grazing is expected to increase plant mortality and ultimately decrease species richness (Huston and Huston, 1994; Proulx and Mazumder, 1998). The effect of grazing on land degradation that manifested with the declined plant species composition, low productivity and poor soil fertility (Steffens et al., 2008; Li et al., 2009) is well established, and evidence that these outcomes are more severe in areas close to urban settlements and water resources (e.g., Mandakh et al., 2007; Wang et al., 2013; Hilker et al., 2014; Fujita et al., 2013; Bat-Oyun et al., 2013). This~~

The grazing pressure has been linked to increased number of dust events through elevated erodibility of land surface 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). Most studies assessed anthropogenic dust based on A such change in land cover data (Tegen et al., 2004; Huang et al., 2014). So that dust loads from grazing pressure has been included in the 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, semi/directly, however, there still remain large uncertainties 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.

~~It has been long stated that dust models require land surface parameterizations to improve their prediction performances (Shao, 2000; Marticorena and Bergametti, 1995; Uno et al., 2006; Lee et al., 2013). Under scoring effect of animal trappings on the dust emission might be hindered research community to predicting dust precisely, particularly for intensive grazed dust sources. Although we have known for some time that livestock trampling is also important factor in anthropogenic dust, our knowledge of the magnitude of the relation, both for total dust loads and for dust loads from anthropogenic activities, and the land disturbance of trampling pressure in terms of total atmospheric dust from grasslands is limited.~~ 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. ~~However, areas of interest in such studies have been selected consistently to be the playa, where surface stability is considered to be a critical~~

control in dust emission dynamics of dry lakes. Aside from physical crusts of playas, disturbance has also been investigated for the erodibility of biologically crusted desert soils with field wind tunnels (e.g., Belnap and Gillette, 1997; Belnap et al., 2007). In such experiments, the simulation of disturbance often involves an artificial agent, and although both are effective in disrupting consolidated surfaces and offering straightforward replication, quantifying the effect of a natural process of disturbance should also be of significant interest for understanding wind erosion. 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 ~~reveal effect of~~ investigate effects of livestock trampling on dust emission ~~processes, in a quantitative manner. For scaling the effect strength of trampling, therefore~~ rate, and scale an anthropogenic dust emission by natural dust emission as a relative consequence of livestock trampling. Therefore, we conducted a mini-wind tunnel experiment ~~(by PI-SWERL[®] device)~~ (by PI-SWERL[®] device) to measure dust emission fluxes from trampling ~~and zero trampling test areas. For achieving study aim, we purposed (1) to investigate effect of livestock trampling on dust emissions (2) to develop a livestock trampling function for emission rate, and (3) to examine the reliability of the trampling function and its applicability for assessing anthropogenic dust. Successfully introduced livestock trampling function will be useful to quantify an emission rate from trampling areas; and further, it might provide an insight into the possible assessment of anthropogenic dust for grazing areas (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).

25 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 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.

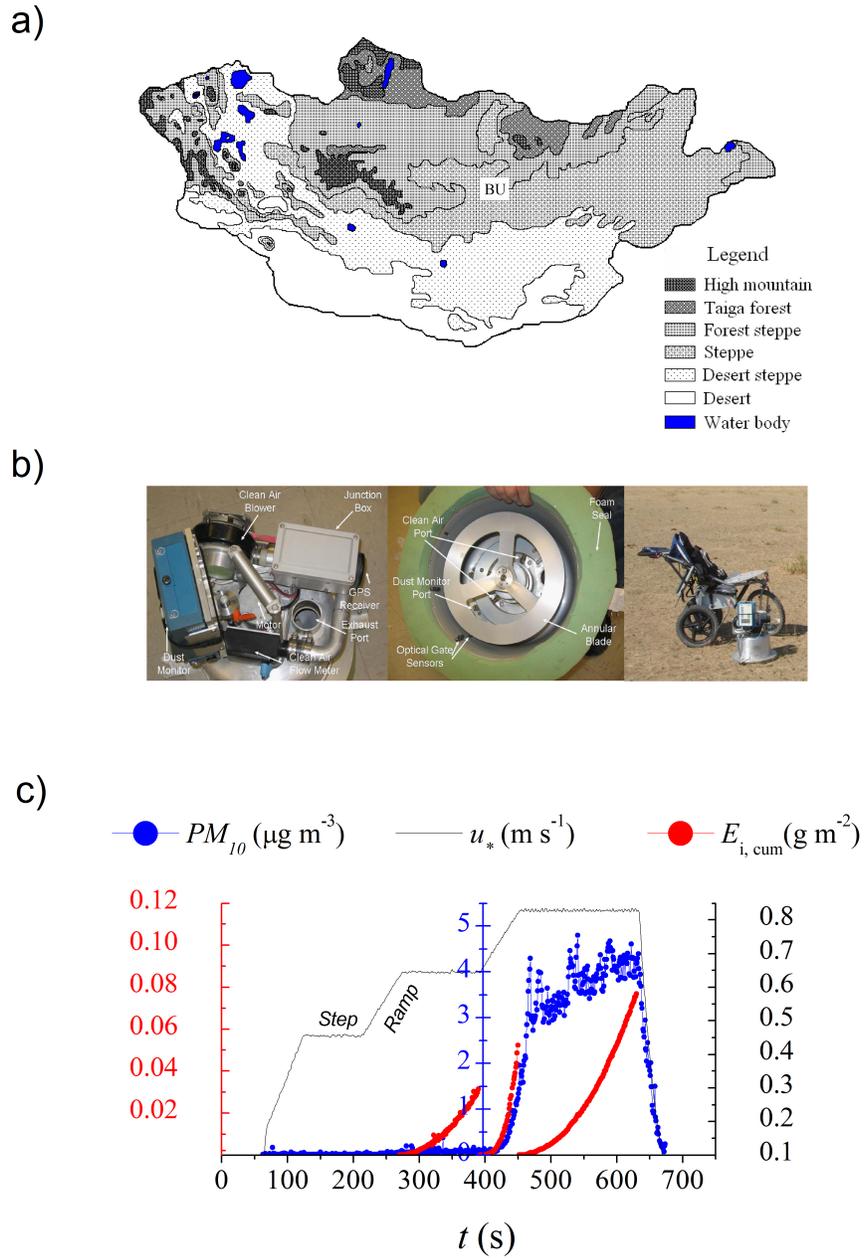
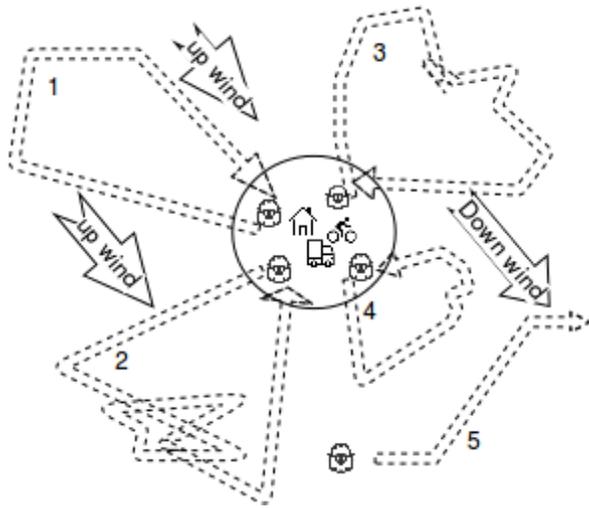


Figure 1. (a) BU (Bayan-Unjuul) denotes the location of the study site in with respect with to vegetation zones in Mongolia; (b) Pictorial illustrations of PI-SWERL[®], top view at on the left, bottom view in the middle, and in the field situation at on the right sides; (c) An example data trace of PM_{10}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

2.2.2 Experimental area setting

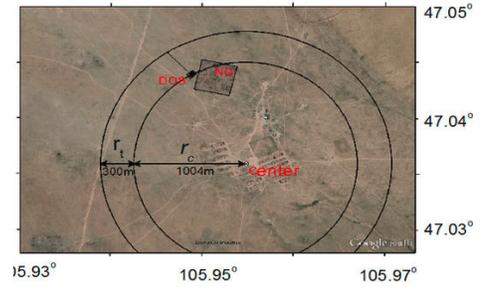
While grazing, livestock leaves behind its trampling trace; therefore, we schemed a trampling route based on grazing route (Fig.2a). Many studies proved that livestock density (i.e., grazing pressure) is usually highest close to water sources or settlements and decreases with distance away from such 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 pictorial 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 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 differential 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.

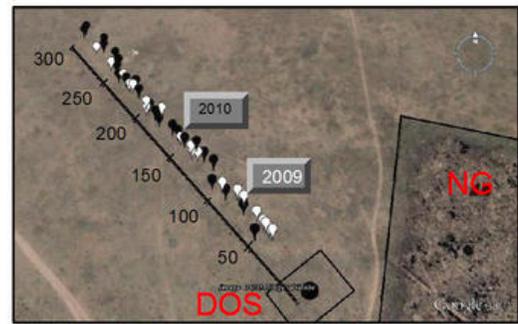


2a.png

(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

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 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 m²) 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 Shin-

oda, 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.

10 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):

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

15 where N is livestock density in head per hectare (and per a year ($Headha^{-1}yr^{-1}$, and refer to $Headha^{-1}$); 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 $Headha^{-1}$ along transect lines in 2009 and 2010, respectively.

20 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 $Headha^{-1}$.

We assumed that all types of livestock (small and large ruminants) 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

5 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 Headha^{-1} (N_{241}) on 15 May 2009. On following winter, livestock density 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 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 replicative 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

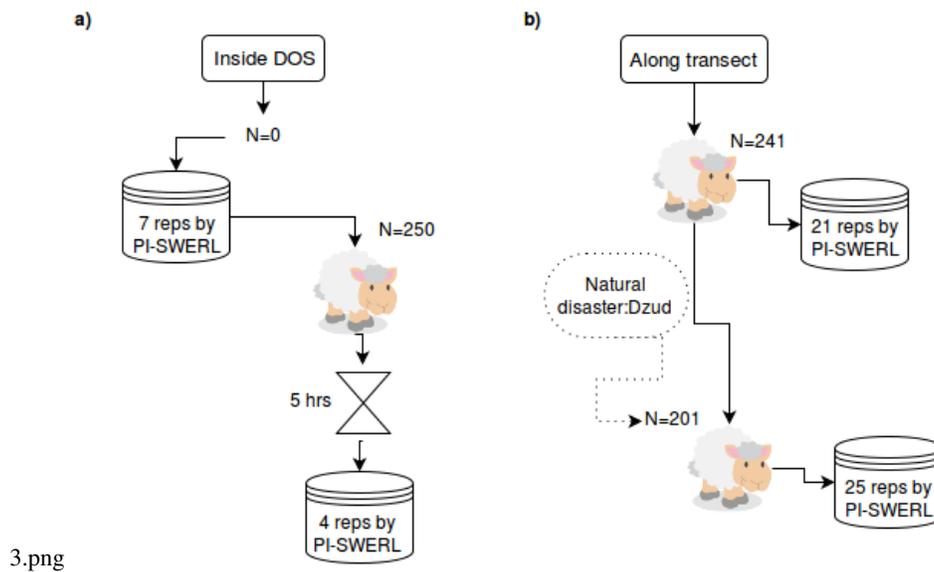


Figure 3. A schematic flowchart of PI-SWERL[®] experimental test a) for zero and trampling of N_{250} inside *DOS*; and b) for trampling of N_{201} and N_{241} along transect areas. PI-SWERL[®] experimental replications for each dataset is marked as *reps*.

emissions at the naturally trampled transect were measured on annual basis (at the springs 2009 and 2010). As for dust for $N=250 \text{ Headha}^{-1}$, 5 hour of grazing is also annual if we consider that average walking speed for livestock is 314 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 vice 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 time period of 4.6 h ($11.5 \text{ s} \times 1460 \text{ times}=16790 \text{ s}$). 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 ($\approx 5 \text{ h}$) on bare surfaces inside DOS, after which systematic trampled dust emissions measurements were conducted by the PI-SWERL[®] instrument.

3 Study methods Data analysis

3.1 Anthropogenic dust induced by trampling Mean values of livestock dust emissions

In this study, anthropogenic dust emission flux, F_N , is considered two main assumptions. These two main assumptions are: 1) dust amount will be larger at the livestock trampling test areas than at the zero trampling surfaces ($F_N \geq F_{REF}$); 2) increased dust amount will be subject to a trampling function, $f_L(N, u_*)$. Therefore, our dust flux formula was expressed as shown in Eq.:

$$F_N = F_{REF}(1 + f_L(N, u_*))$$

where F_N and F_{REF} are dust emissions from test areas of trampling and zero-trampling, respectively. In equation, F_{REF} is included for a quantity term only, whereas $f_L(N, u_*)$ is referred to a physical term for defining F_N .

3.2 A formula of livestock trampling function for 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). It suggests that a formula of livestock trampling function $f_L(N, u_*)$ should be derived by livestock density (effect of trampling) and u_* (wind blown dust). Moreover, $f_L(N, u_*)$ should be a dust product (of N and u_*) to reflect the physical term of F_N . Thus, we employed the Cobb-Douglas function for defining our livestock trampling formula. The Cobb-Douglas function is widely used in economics to show the relationship between input factors and the level of total production, Y , as presented in Eq.:

$$Y = AL^\beta K^\alpha$$

where, A is total factor productivity, L is labor input, K is capital input; α and β are the measures the responsiveness of output to a change in levels of either L or K used in production, Y . If $\alpha + \beta = 1$, the production function has constant returns to

scale, meaning that doubling the usage of capital K and labor L will also double output Y . If $\alpha + \beta < 1$, returns to scale are decreasing, and if $\alpha + \beta > 1$, returns to scale are increasing. In last decades, this function has been widely used in environmental studies, such as, to show the relationship between human population as a capital input and pollutant emissions as a labor inputs, to output activities to economic growth etc (Labini, 1995; Dong et al., 2013; Cheng et al., 2015). Similarly to this, we employed Cobb-Douglas function to define a formula of $f_L(N, u_*)$ as a product of N and u_* considering trampling increases the weak-bonded dust particles by a labor of livestock density, (as L , labor), and these dust particles are carried away by wind, u_* (as K , capital). If we replace our inputs in eq., the formula of $f_L(N, u_*)$ will be defined as eq.:

$$f_L(N, u_*) = AN^\beta u_*^\alpha$$

where, N is livestock density. 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 (N) and u_* is friction velocity (u_*).

4 Data analysis

It was demonstrated that microscale disturbance by marmots creates spatially heterogeneous grasslands at a fine scale (Yoshihara et al., 2010; 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 preferred. Because, 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). Thus, in this study, we used the means of dust emission for investigating effect of trampling 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 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 Head ha^{-1}) from zero trampled surface. The determined coefficients for A , β and α are equal to 0.06853, 1.1 and 4 (Fig. 3c). We used

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) to determine the coefficients of A , β and α . The 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. We employed

OriginPro 8.1 Academic software (Northampton, MA 01060 USA) for calculating statistics and determining the coefficients by the least square optimization method.

3.1 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 $F_N/F_{REF} \approx 1$, 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 ($10.5 \mu\text{gm}^{-2}\text{s}^{-1}$). This was elevated to $15.7 \mu\text{gm}^{-2}\text{s}^{-1}$ at u_* of 0.54 ms^{-1} , and then backed to background level $10.1 \mu\text{gm}^{-2}\text{s}^{-1}$ at 0.64 ms^{-1} . A noticeably increased emission rates of 39 and $37.3 \mu\text{gm}^{-2}\text{s}^{-1}$ 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} trappings, 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 25th and 75th 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

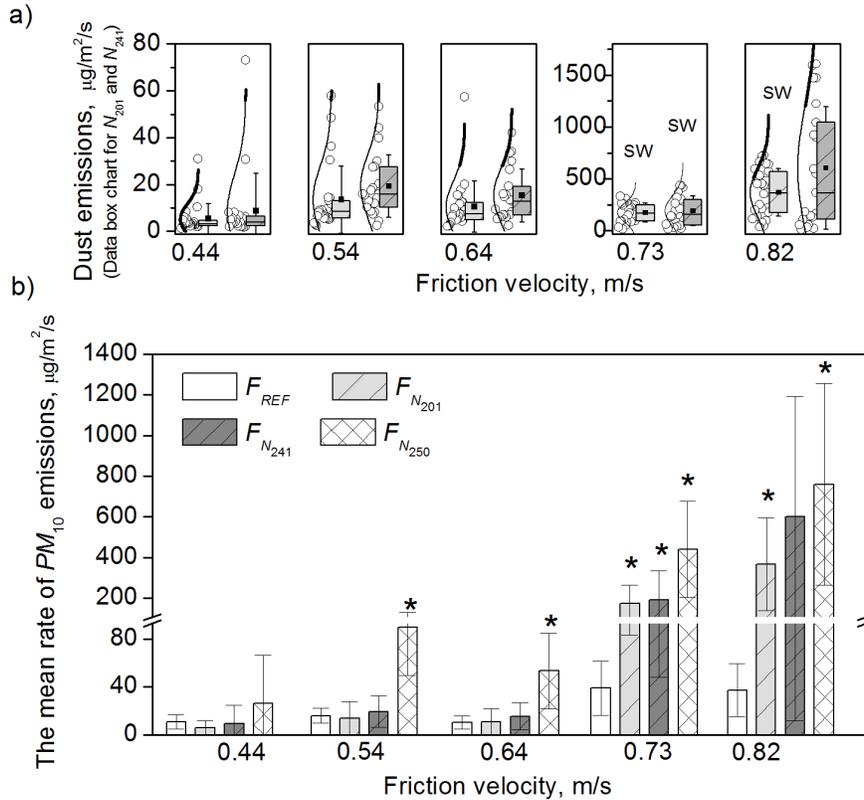


Figure 4. a) Measured dust fluxes from the trampled surfaces with N of 201 and 241 Headha⁻¹. Open circles (\circ) and curved lines (\cup) denote collected dust data and normal distributions. Center dots (\bullet) and dashes ($-$) in the boxes denote means and medians of dust emissions. Opening and closing of the boxes presents 25 and 75th 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 *.

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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}

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presents significant normalities, and this significance 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 statistically 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 **emission as strong as dust storm happens** dust emission when wind gets stronger.

4.2 A scale factor of dust emission due to livestock trampling function for dust emissions

The mean ratio of F_N and F_{REF} demonstrates the effect of trampling in dust emission as a relative rate scaling by F_{REF} for each u_* . Because every mean ratio is calculated under the same shear force (u_*), it would remove the effect of u_* in the relative rate. For a given trampling density, therefore, we expected a constancy in the relative rate among all calculated scale factor for each N at different u_* . But in reality, the mean ratio varies at the same trampling density (Fig. 5a; As for an example, $F_{N_{250}}/F_{REF}$ ranged values are shown in Figure 5. The scale factors for N_{250} varied from 2.5 to 20). This indicates that the effect of trampling can be dissimilar throughout u_* . Very interestingly, we found that the variabilities in the mean ratio is subject to changes in u_* demonstrating positive relationships for all trampling test areas (Fig. 5a). Thus the effect strength of trampling is likely to be determined by u_* . Some of the mean ratios are less than 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, particularly at low friction velocities those were occurred at low u_* values for livestock trampling with N_{201} and N_{241} Headha⁻¹, which also supports our idea on importance of high u_* for revealing the effect of trampling. Beside of u_* , trampling density (N) also contributes the mean ratio variabilities to increase. It can be seen in the elevated mean ratios, those are increased from 10 (at N_{201}) to 16 and 20 (at N_{241} and N_{250} , respectively), demonstrated for u_* of 0.82 (Fig. 5b). However, the differences between $F_{N_{201}}/F_{REF}$ and $F_{N_{241}}/F_{REF}$ become smaller as the value in u_* of 0.82 shifts to moderate and low values (Fig. 5b). This is consistent with the finding in section 5.1, that significantly higher dust loading occurs after a disturbance level has reached by the trampling N_{250} . But measuring the effect of trampling, in an interactive term of u_* and N is somewhat challenging). 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

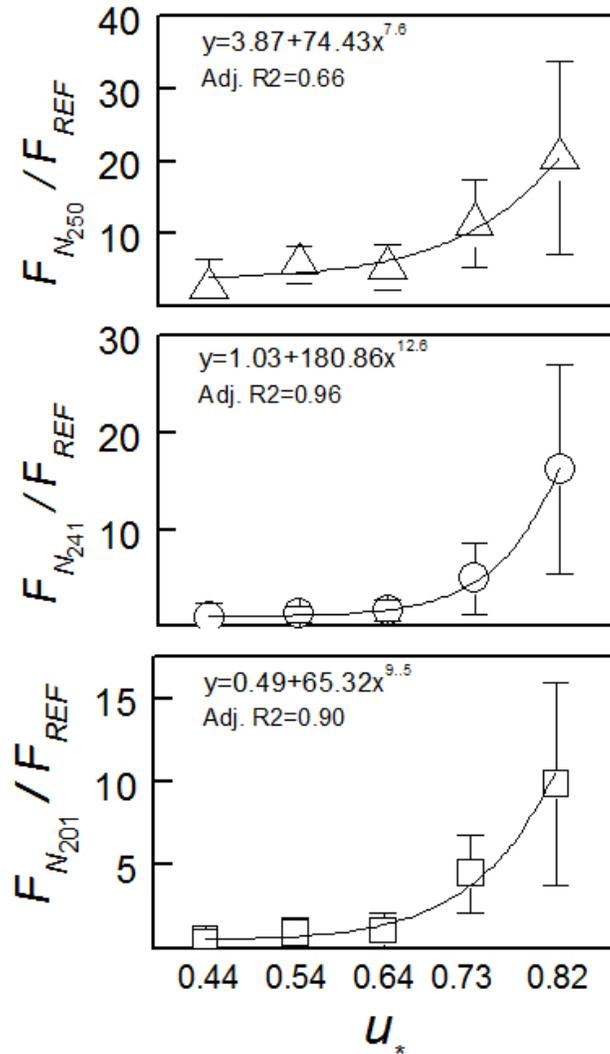


Figure 5. Dust emission ratio dependencies on friction velocity and livestock density. Open triangles (Δ), circles (\circ), and squares (\square) denote dust emission values from the trampled surfaces with livestock densities of 250, 241, 201 Headha⁻¹, respectively. a) Relationships between the mean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

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.

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Moreover, an increase in the trampling density (N) also results an increase in the scale factors (Fig. 4.3). The scale factors

for N_{250} were higher than those scale factors for N_{201} , N_{241} at all u_* values as depicted in Figure 4.3. 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 4.3. It demonstrates that scale factors of 10, 16 and 20 were corresponding to N_{201} , N_{241} and N_{250} , respectively (Fig. 4.3). 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. 4.3). The scale factor is proportional to $u_*^{8.39}$ (Fig. 4.3) 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.

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 ($10.5 \mu\text{gm}^{-2}\text{s}^{-1}$). It was elevated to $15.7 \mu\text{gm}^{-2}\text{s}^{-1}$ at u_* of 0.54 ms^{-1} , and then backed to background level $10.1 \mu\text{gm}^{-2}\text{s}^{-1}$ at 0.64 ms^{-1} . A noticeably increased emission rates of 39 and $37.3 \mu\text{gm}^{-2}\text{s}^{-1}$ 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 ms^{-1} a subtle decline to 0.54 ms^{-1} . This shift in natural soil, from supply 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 $760 \mu\text{gm}^{-2}\text{s}^{-1}$, 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

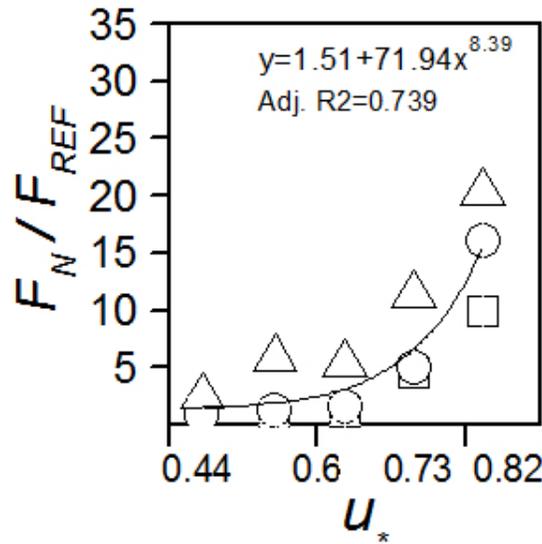


Figure 6. A statistically fitted relationship between dust emission ratios and u_* for all livestock trampled surfaces; e) A relationship between dust emission ratio and Cobb-Douglas production function of N and u_* ; d) A plot of F_N / F_{REF} versus $1 + f_L(N, u_*)$. n denotes sample number, ν is degree of freedom, χ^2 / ν is the reduced chi square, $RMSE$ is root mean square error, $Adj. R^2$ is adjusted r^2 , residual sum of squares.

Anthropogenic dust emission formula is defined in (Section 3.1). If we divide both side of Equation by F_{REF} , it will yield an Equation. This equation suggests that the livestock trampling function, $f_L(N, u_*)$, can be obtained by the mean emission ratio, F_N / F_{REF} , presented in Figure 5b.

$$\frac{F_N}{F_{REF}} = 1 + f_L(N, u_*)$$

$$f_L(N, u_*) = 0.06853N^{1.1}u_*^4, \quad \text{for } 240 < N \leq 250 \text{ and } 0.44 \leq u_* \leq 0.82$$

The determined α , α and β for $f_L(N, u_*)$ illustrated in Figure 5c, and the defined $f_L(N, u_*)$ presented in Eq. Both of $\alpha > 1$ and $\beta > 1$ indicates the increasing scale for each component return. This means that 15% of increase will return 16.6% in N and 74.9% in u_* of increased $f_L(N, u_*)$ output. Consequently, effect of trampling will be magnified by an increase in both N and u_* . The magnitude strength is greater with a change in u_* than in N . We examined a performance of the defined $f_L(N, u_*)$, Eq., plotting against F_N / F_{REF} in Figure 5c.

It validates the well-parameterization for $f_L(N, u_*)$, illustrating a reasonable error ($RMSE = 2.96$), a good fit ($Adj. r^2 = 0.87$) and a significant value ($p < 0.05$; by reduced χ^2 test) between the term of $1 + f_L(N, u_*)$ and F_N / F_{REF} (Fig. 5d). This ensures that livestock trampling function is applicable to assess the effect of trampling; however, a valid range is limited (Eq.).

4.3 An application of $f_L(N, u_*)$ for assessing dust emission flux

Applying the results tackled in Section 5.2, anthropogenic dust can be assessed by Equation, however the valid range for N is much narrow.

This limits the usage of the Eq. to assess F_N in a broad range of areas (for Mongolia), where livestock density varies spatially (Saizen et al., 2010).

$$F_N = F_{REF}(1 + f_L(N, u_*)), \quad \text{for } 200 \leq N \leq 250 \text{ and } 0.44 \leq u_* \leq 0.82$$

To extend applicability of the eq., we merged the valid range of $200 \leq N \leq 250$ down to $0 \leq N \leq 250$, concerning that equation yields $F_N = F_{REF}$, when $N = 0$. This will also provide an opportunity to assess natural dust within the equation. Thus, we generalized eq. into

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 demonstrated 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 25th and 75th 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, the 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 Effect strength A scale factor of dust emission by livestock trampling

Very interestingly, we found that the variabilities in the mean ratio of F_N and F_{REF} scale factor of F_N/F_{REF} is subject to changes in u_* demonstrating positive relationships for all trampling test areas (Fig. 5a). As for an example, $F_{N_{250}}/F_{REF}$ ranged from 2.5 to 20 for u_* values increased from 0.44 to 0.82 (5). It points that the effect strength of scale factor of dust emission by trampling get magnified with an increase in u_* . This means that anthropogenic dust emits much as stronger wind prevails at the trampled surfaces wind blows stronger, like revealing 'hidden effect' of trampling. Some of the mean ratios The suppressing effect of livestock trampling on dust emission was found at low u_* with demonstration of the scale factors below 1, particularly at low friction velocities for livestock trampling with N_{201} and N_{241} (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 trampling livestock trampling on dust emission is a coincidence with the dust emissivity pattern of unlimited supply surfaces, discussed in Section 6.1. Our finding may hint the possible reason of huge amount of dust loading happenings when it originates from Mongolia (Laurent et al., 2006) 5.1.

Beside of u_* , trampling density (N) also contribute the mean ratio variabilities to increase. It can be seen in the elevated mean ratios, those are increased from 10 (at N_{201}) to 16 and 20 (at N_{241} and N_{250} respectively), demonstrated for u_* of 0.82 (Fig. 5b). It is likely that increased N results an elevated dust emission. However, the differences between $F_{N_{201}}/F_{REF}$ and $F_{N_{241}}/F_{REF}$ become smaller as the value in u_* of 0.82 shifts to moderate and low than those for N_{241} and N_{201} at all u_* values (Fig. 5b 4.3). Relatedly, greater dust loading was manifested at the trampling density of N_{250} , and not, for N_{241} and N_{250} (Fig. 4b, denoted by *). This indicates significantly higher dust loading emission occurs after a disturbance level has reached to N_{250} . Similar 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 emission (comparably to F_{REF}) was lowered

with an increase in wind force, u_* (Fig. 4b). ~~This suggests~~ Our research findings indicate that both u_* and N has enormous combinational ~~effect on dust emission from trampling test surface~~ influence on anthropogenic dust emission due to livestock trampling effect, and eventually, determines the effect strength of ~~trampling. But to measuring livestock trampling on dust emission. But, summarizing~~ the effect of trampling, in an interactive (combinational) term of u_* and N livestock trampling on dust emission is somewhat challenging.

~~In the livestock trampling function, almost 4 times greater of determinant power for u_* than of for~~ Figure 7 illustrates a tabular chart of a scale factor for the different values in N was presented. It points that the effect strength of trampling get magnified and u_* . It is apparent that the scale factor is gradiently increased with an increase both in u_* , and , therefore dust will emit much as stronger wind prevails at the trampled surfaces. This finding indicates that the effect of trampling can be seen or get into a play in emission when wind is strong.

5.3 The applicability of $f_L(N, u_*)$ function for assessing anthropogenic dust

We confirmed that eq. has a feasible potential to assess dust emission fluxes, properly. Based on our eq. (considering $F = F_{REF} + F_N$), anthropogenic dust is proportional to u_*^8 . This is in a good agreement with dust fluxes proportional to u_*^6 for natural soil with abrasion and u_*^{10} for fully unlimited supply soil (Zhang et al., 2016). Importantly, it implies that anthropogenic dust flux induced by trampling at a temperate grassland has a emission potent in between those have at natural soil with abrasion and fully unlimited supply. However, the threshold friction velocity should be included further for a better prediction performance, precisely (Gillette and Passi, 1988; Belnap and Gillette, 1997). ~~Moreover 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.~~

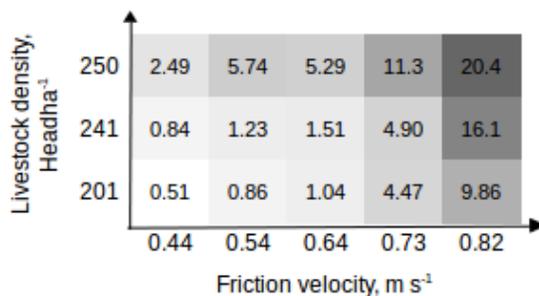


Figure 7. A table chart of scale factor (F_N/F_{REF}) with different u_* and N of 201, 241 and 250 Head ha^{-1} per year. A color gradient from light to dark gray corresponds to an increase in the scale factor.

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 environmental-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 surface patchiness. Therefore, the direct use of our trampling function for assessing anthropogenic dust is limited to the temperate grassland. Implication should be given attention to the valid range for livestock density and friction velocity, u_* . 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. The applicability of our dust flux formula to other areas beyond the study location could be accomplished with PI-SWERL tests over a wider geographic area. As we mentioned, potential dust emission data obtained by PI-SWERL, so that formula F , with eq., will also provide a possible evaluation of potential anthropogenic dust. We calculated N as a total livestock number, which needs to be resolved in the near future. We In this study, we assumed that all types of livestock (small and large ruminants) 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. (Xu, 2014) tested the quantity of dust emitted from vehicles and found that it varied with the weight of the vehicles. 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

In this study, we aimed to reveal effect of We studied effects of livestock trampling on dust emission processes, in a quantitative manner. For achieving study aim, we investigated effect of livestock trampling on dust emissions, developed a livestock trampling function for emission rate, and finally discussed the reliability of the trampling function and its applicability for assessing anthropogenic dust. Based on our results, we drawn major conclusions as :-

Finally, we 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_{*c} 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. The applicability of our result is

5 ~~feasible with a care to other areas beyond the study location.~~

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

u_* , ms^{-1}	Measured dust emissions, $\mu\text{gm}^2\text{s}^{-1}$									
	F_{REF}					F_{N250}				
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

u_* , ms^{-1}	Measured dust emissions, $\mu\text{gm}^2\text{s}^{-1}$									
	$F_{N_{201}}$					$F_{N_{241}}$				
	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

A3 Appendix A3

It is necessary to provide the uncertainty of dust flux formula, δF , (since Eq. is derived based on the mean values F_N for N). We estimated uncertainties of the calculated dust flux for each u_* , thus the uncertainty will be converted to Eq. by substituting Eq. 3; and, considering u_* as a constant for a given friction velocity:-

$$5 \quad \delta F = |cu_*^4| \delta(1 + f_L(N, u_*)) \xrightarrow{\text{substitution of } F_N/F_{REF}} \text{ will yield } \delta F = |cu_*^4| \delta(F/F_{REF}).$$

If we apply uncertainty analysis for multiplication (Taylor, 1997) into Eq., we will obtain Eq.??,-

$$\delta F = |cu_*^4| \frac{F}{F_{REF}} \sqrt{\left(\frac{\delta F}{F}\right)^2 + \left(\frac{\delta F_{REF}}{F_{REF}}\right)^2}$$

where δF and δF_{REF} are uncertainties of F and F_{REF} , respectively. Hereafter, we estimated δF and δF_{REF} using the basic statistical methodology for calculating uncertainty as a standard error of the mean value ((Taylor, 1997; Coleman and Steele, 2009)).

10 It has been proven by Taylor (1997) that the standard error of the mean value for a certain population is defined as that a standard deviation of a given population (SD) is divided by the square root of its population number (\sqrt{n}). Thus, we calculated the uncertainty in the means of F as $\delta F = \frac{SD}{\sqrt{n}}$. As for a small dataset (Taylor (1997); Coleman and Steele (2009)),

we calculated uncertainty in the means of F_{REF} as $\delta F_{REF} = \frac{F_{REF,max} - F_{REF,min}}{2\sqrt{n}}$ using the maximum ($F_{REF,max}$) and minimum ($F_{REF,min}$) values among the dataset for the non-trampled surfaces. For defining δF_{REF} , first we solved

15 $\sqrt{\left(\frac{\delta F}{F}\right)^2 + \left(\frac{\delta F_{REF}}{F_{REF}}\right)^2}$ as 0.41, 0.31, 0.37, 0.32, and 0.37 for each u_* of 0.44, 0.54, 0.64, 0.73, and 0.82. For general use,

we adopted the mean of the solved $\sqrt{\left(\frac{\delta F}{F}\right)^2 + \left(\frac{\delta F_{REF}}{F_{REF}}\right)^2}$ values, thus δF is defined as in Eq.??-

$$\delta F = 0.36F$$

We can interpret the uncertainty of dust flux is 0.36 times as much as the calculated dust flux (Eq. 3S).-

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