FUGITIVE DUST EMISSIONS FROM OFF-ROAD VEHICLE MANEUVERS ON MILITARY TRAINING LANDS

J. C. Meeks, L. E. Wagner, R. G. Maghirang, J. Tatarko, N. Bloedow

ABSTRACT. *Off-road vehicle training can contribute to air quality degradation because of increased wind erosion as a result of soil disruption during high wind events. However, limited information exists regarding the impacts of off-road vehicle maneuvering on wind erosion potential of soils. This study was conducted to determine the effects of soil texture and intensity of training with off-road vehicles on fugitive dust emission potential due to wind erosion at military training installations. Multi-pass military vehicle trafficking experiments involving wheeled and tracked vehicles were conducted at three military training facilities (Fort Riley, Kansas; Fort Benning, Georgia; and Yakima Training Center, Washington) with different vegetative conditions and soil textures. The top 6 cm of soil was collected with minimum disturbance into trays and tested in a laboratory wind tunnel for dust emission potential. In wind tunnel testing, the amount of emitted dust was measured using a Grimm aerosol spectrometer. The dust emission potential due to wind erosion was significantly influenced by soil texture, vehicle type, and number of passes. For the light wheeled vehicle, total dust emissions (<20 μm) increased by 357% and 868% for 10 and 50 passes, respectively, from the undisturbed soil condition. For the tracked vehicle, an average increase in total dust emissions (<20μm) of 569% was observed between undisturbed soil and one pass, with no significant increase in emission potential beyond one pass. For the heavy wheeled vehicle, evaluated only at Yakima, emissions (<20 μm) increased by 2,108% and 5,276% for 10 and 20 passes, respectively, from the undisturbed soil condition. Soil texture also played an important role in dust emission potential. For all treatment effects with the light wheeled vehicle, there was a 1,396% increase in emissions (<20 μm) on loamy sand soil over silty clay loam soil.*

Keywords. *Air quality, Particulate matter, Soil, Wind erosion.*

The U.S. Department of Defense (DoD) manages and conducts training on over 12 million ha of land (DoD, 2013). This land is used for various purposes, including residential and commercial activities and intensive combat training operations. Many combat training activities require navigating large, heavy off-road vehicles across potentially sensitive and undisturbed off-road locations. These activities can create significant disturbance to the soil surface and adversely affect the local ecosystem. The most prevalent impacts include loss of vegetation, soil compaction, and soil loss due to erosion by water and wind (Althoff et al., 2010). Although some windborne dust events can be classified as exceptional events, soil transport by wind movement can contribute to monitored particulate matter (PM) values that exceed the National Ambient Air Quality Standards (NAAQS) (Ashbaugh et al., 2003). Suspended wind-eroded particulate matter (PM) emitted from military installations can be carried long distances from the training land and well beyond property boundaries.

Soil erosion by wind is a dynamic process that often results in loss of the fertile top layer of soil, which can reduce agricultural production as well as degrade local air quality (Skidmore and van Donk, 2003; Diaz-Nigenda et al., 2010). Intensive tillage and other agricultural practices on arid and semi-arid land can contribute to an increase in soil loss due to wind erosion. Many other factors, such as unpaved roads, confined animal operations, and intensive use as military training lands, may also contribute to dust emissions due to wind erosion (Gillies et al., 2005).

In addition to simulation and field studies, previous research on wind erosion has also used wind tunnels under field and laboratory conditions. Several studies (Van Pelt et al., 2010; Sweeney et al., 2008; Marticorena and Bergametti, 1997) have used *in situ* semi-portable wind tunnels that are set up directly in the field on the surface of interest. Other studies have used large laboratory wind tunnels to control both wind speed and soil surface conditions to some degree (Guoliang et al., 2003; Kohake et al., 2010). These

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The authors are **Jeremy C. Meeks,** Former Graduate Student, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas; **Larry E. Wagner, ASABE Member,** Agricultural Engineer, USDA-ARS Agricultural Systems Research Unit, Fort Collins, Colorado; **Ronaldo G. Maghirang, ASABE Member,** Professor, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas; **John Tatarko,** Soil Scientist, USDA-ARS Agricultural Systems Research Unit, Fort Collins, Colorado; **Nicholas Bloedow,** Graduate Research Assistant, Department of Statistics, Kansas State University, Manhattan, Kansas. **Corresponding author:** Larry Wagner, USDA-ARS Agricultural Systems Research Unit, 2150 Centre Ave., Bldg. D, Suite 200, Fort Collins, CO 80526; phone: 970-492-7382; e-mail: larry.wagner@ars.usda.gov.

studies have shown that wind tunnels can be used successfully to study the underlying principles of wind erosion while simulating the optimal conditions that contribute to initiating large wind erosion events.

Limited information exists regarding the impacts of military training activities on the wind erosion potential of soil. This research was conducted to determine the effects of off-road trafficking on fugitive dust emissions from military training lands. Specifically, the overall objective was to determine the effects of soil texture, vehicle type, and number of passes on dust emission potential using a laboratory wind tunnel.

Materials and Methods

Field Sites

Testing was conducted at three DoD military training sites: Fort Riley, Kansas; Fort Benning, Georgia; and Yakima Training Center, Washington. These three sites represent a diversity of vegetative conditions, soil textures, and off-road training activities. Two off-road military training vehicles were used at each site, representing a range of relatively lightweight to very heavy fully armored military off-road vehicles. Military training facilities cover a wide variety of locations within the U.S. Each experimental site was selected to provide a variety of soil textures as well as represent wind erosion susceptible soils at military installations in different climates, but not necessarily represent a majority of the soils at all U.S. military training facilities.

Fort Riley (39° 18′ 0″ N; 96° 55′ 18″ W) was the first installation chosen for testing, which was completed in October and November 2010. This installation is located in the Flint Hills region of north central Kansas in Geary and Riley counties and covers 407 km^2, with 287 km^2 used for maneuver training (EPA, 2010). Fort Riley receives annual precipitation of 889 mm and has an annual mean temperature of 12.6°C. Testing at Fort Riley was conducted on silty clay loam (SiCL) and silt loam (SiL) soil textures (table 1). An M1A1 Abrams heavily armored tracked vehicle (61,500 kg) and a light armored M1025A2 high-mobility multipurpose wheeled vehicle (3,100 kg), commonly called a Humvee (HMMWV), were used for testing. Figure 1 shows the two vehicles during testing at the Fort Riley site. The vegetation at the Fort Riley site was a mixed tallgrass prairie dominated by big bluestem (*Andropogin gerardii*) and Indian grass (*Sorghastrum nutans*) species. Testing on both soils was done on 18-22 October 2010 with the M1A1 and on 8-12 November 2010 with the HMMWV.

Figure 1. (top) Heavy tracked model M1A1 and (bottom) light armored HMMWV model M1025A2 vehicles.

The second installation was Fort Benning, Georgia (32° 24′ 14″ N; 84° 45′ 21″ W), with testing conducted on 21-24 July 2012. Fort Benning is located on 765 km^2 in west central Georgia. This site is located in the humid Southeastern region of the U.S., which has relatively high precipitation and is affected by tropical maritime events, including frequent thunderstorms and inland-moving hurricanes (NCDC, 2011). Fort Benning has average annual precipitation of 1245 mm and a mean annual temperature of 18.3°C. Testing at Fort Benning was done at Rowan Hill on a loamy sand (LS) soil texture (table 1). The two vehicles used were a HMMWV up-armored vehicle (model M1151A1) with a curb weight of approximately 3,800 kg

Table 1. Measured soil properties for the original surface at the experimental sites.

Site	Soil Texture	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})	Organic Matter (g kg^{-1})	IWC[a] (kg kg^{-1})	IBD[a] (g cm^{-3})
Fort Riley	Silt loam (SiL)	102	707	190	40	0.16 T[b] 0.17 W	1.27
	Silty clay loam (SiCL)	79	641	280	41	0.18 T 0.21 W	1.22
Fort Benning (Rowan Hill)	Loamy sand (LS)	877	95	28	9	0.02	1.47
Yakima Training Center	Loam (L)	513	438	50	21	0.01	1.30

[a] IWC = initial water content and IBD = initial bulk density (5 cm depth) taken prior to trafficking at each site.

[b] T denotes the tracked vehicle experiment (Oct. 2010) and W denotes the wheeled vehicle experiment (Nov. 2010) at Fort Riley.

Table 2. Vehicle specifications and locations used in experiments on specified dates.

Vehicle	Traction Type	Weight (kg)	Track/Tire Width (cm)	Speed (km h^{-1})	Fort Riley	Fort Benning	Yakima
M1025A2 HMMWV	Wheeled	3,100	4.72	25-30	Nov. 2010	-	Aug. 2012
M1A1 Abrams tank	Tracked	61,500	9.45	8	Oct. 2010	July 2012	-
M1151A1 Up-armored HMMWV	Wheeled	3,800	4.72	25-30	-	July 2012	-
M925A1 Five-ton fire truck	Wheeled	15,000	5.90	12	-	-	Aug. 2012

and an M1A1 heavily armored tracked vehicle weighing approximately 61,500 kg. Fort Benning is within the longleaf pine ecosystem, and the site was dominated by loblolly pine (*Pinus taeda*), longleaf pine (*Pinus palustris*), and white oak (*Quercus alba*), with areas of herbaceous groundcover including grasses dominated by thin paspalum (*Paspalum setacum*) and southern crabgrass (*Digitaria ciliaris*) and forbs dominated by orangegrass (*Hypericum gentianoides*) and pine barren tricklefoil (*Desmonium strictum*).

Yakima Training Center, Washington (46° 41′ 36″ N; 120° 26′ 15″ W), was the third site, with testing conducted on 11-14 August 2012. This site is situated on 1323 km^2 of shrub-steppe land in south central Washington. This site is located in the Yakima Valley region with a mean annual temperature of 12.7°C and is dry, with average annual precipitation of 207 mm (NCDC, 2011). Testing at Yakima Training Center was conducted on a loam (L) soil texture (table 1). A tracked vehicle was not available for use; therefore, a fully loaded, tandem dual rear axle, six-wheel drive M925A1 water tanker fire truck weighing 15,000 kg was used in addition to a light armored HMMWV (model M1025A2). Vegetation at the Yakima Training Center site was characterized by a shrub-steppe vegetation dominated by perennial bunchgrasses such as bluebunch wheatgrass (*Pseudoroegneria spicata*) and Sandberg bluegrass (*Poa secunda*).

Initial (untrafficked) soil samples were taken to a 5 cm depth. Bulk density and water content (Retta et al., 2013) were measured to provide a general characterization of the soils and are reported in table 1. Clay contents of the <2 mm soil were measured by pipette method, sand fraction by wet sieving, and silt by difference according to the method of Gee and Dani (2002). Organic matter was measured at the Kansas State University Soil Testing Laboratory using the Modified Walkley-Black method (Swift, 1996). Percent vegetation cover was determined by the line intercept method (Sloneker and Moldenhauer, 1977).

At each of the installations, sites were selected with as little prior disturbance as possible. The sites may have been used for training activities in the past, but all locations had been undisturbed by vehicles for an extended period of time, e.g., several years, with plentiful natural vegetation regrowth for the site's climatic conditions. At the Fort Riley site, the vegetation was so dense that it required mowing and removal prior to sampling. Note that the two models of HMMWV are referred to as "light wheeled vehicle" and were considered the same for analysis, as the differences in weight were minor compared with the other much heavier vehicles. Additionally, the M1A1 Abrams tank is referred to as "tracked vehicle," whereas the M925A1 water tanker fire truck is referred to as "heavy wheeled vehicle." Table 2 summarizes the vehicle properties.

To accommodate the type of turns that military vehicles normally make during training maneuvers, a figure-8 pattern (fig. 2) on 80 m × 40 m plots was followed, similar to those employed by Althoff and Thien (2005). The inside turning radius of the vehicles within the figure-8 plots was approximately 10 m. In most training maneuvers, a point on the ground may experience many passes, or high traffic intensity, by one or more vehicles. High traffic intensity also leads to increased damage and the potential for more dust emissions.

The number of trafficking passes was established for each vehicle based on test runs representing minimum, medium, and severe relative levels of disturbance (i.e., trafficking intensity levels) that would also likely provide measurable differences among the trafficking intensity levels (Retta et al., 2013). The number of vehicle passes was kept the same for each vehicle type at all experimental sites. For the M1A1, the three trafficking intensity levels consisted of one pass, followed by four additional passes (five cumulative passes), and then followed by five final passes (10 cumulative passes). For the HMMWV, the trafficking intensity levels consisted of 10, 25, and 50 cumulative passes. The M925A1 trafficking levels consisted of double the M1A1 passes, for cumulative totals of 2, 10, and 20 passes. The M1A1 was driven at a typical off-road maneuvering speed of 8 km h^{-1}, the HMMWV at approximately 25 to 30 km h^{-1}, and the M925A1 at approximately 12 km h^{-1}. However, the speed was adjusted at the discretion of the driver, with a primary consideration of staying within the same vehicle tracks for every pass.

The figure-8 patterns were staked out for each treatment and replication at each installation (fig. 2). Three replications were conducted for each vehicle/soil treatment combination at each site. Three levels of trafficking intensity

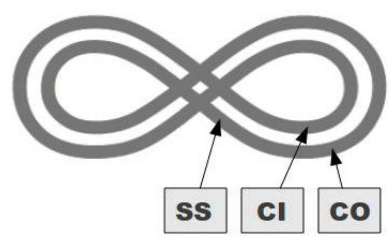

Figure 2. Figure-8 plot showing tray sample locations: SS = straight section, CI = curve inside, and CO = curve outside.

(i.e., number of passes) were conducted on each replicated figure-8, with samples taken after the completion of each trafficking intensity level as well as before any trafficking to determine initial conditions.

Wind tunnel tray samples were collected on the outside and inside curved sections (CO and CI) as well as from a straight section (SS). Figure 2 illustrates those sample locations within the figure-8 plots. All sampling locations per treatment are listed in the sampling matrix in table 3, which indicates the location within the figure-8 (i.e., CO, CI, and SS) at which samples were collected and the number of passes for each vehicle at each site. Due to resource constraints, a balanced experiment was not conducted on the Fort Riley site with the HMMWV.

Wind Tunnel Testing

The top 6 cm of the soil surface was carefully removed from a 122 cm × 20 cm area for each sample location. Samples were removed with a flat-bottom shovel and placed into trays (fig. 3) to minimize disturbance. These trays allowed consistent samples to be collected and also aided in ease of transportation, storage, and testing. The trays were retrieved from the field and stored on closely spaced shelving in a trailer for transport from the field site to the laboratory in Manhattan, Kansas, to minimize disturbance during transportation. It was noticed that some settling and shifting occurred during transport of some soil trays; however, the disturbance was minimal and did not significantly alter the tray configuration. All samples were allowed to completely air-dry in a greenhouse for at least one month prior to wind tunnel testing.

A vertically integrated, slot-style sampler (fig. 4), developed by Mirzamostafa et al. (1998), was used for wind tunnel testing. The primary advantage of this sampler is that it can operate isokinetically at various wind speeds, providing close to 100% sampling efficiency for all particle sizes for the test conditions. The isokinetic conditions ensure that the sampler does not interfere with the movement of the air stream and allow for more accurate measurement of particulate emissions. The sampler has a 5 mm wide slot for particles to enter the system. The system also contains a cyclonic design inside, so saltation size or larger particles

Figure 4. Slot sampler: (left) side view and (right) front view.

Table 3. Sampling matrix for all triple replicated treatments.

M1A1 (Tracked Vehicle)										M925A1 (Heavy Wheeled Vehicle)				
Fort Benning					Fort Riley					Yakima Training Center				
Sample Location	Number of Passes 0	1	5	10	Sample Location	Number of Passes 0	1	5	10	Sample Location	Number of Passes 0	2	10	20
CO[a]	X	X	X	X	CO	X[b]	X	X	X	CO	X	X	X	X
CI	X	X	X	X	CI	X[b]	X	X	X	CI	X	X	X	X
SS	X	X	X	X	SS	X[b]	X	X	X	SS	X	X	X	X
HMMWV (Light Wheeled Vehicle)														
Fort Benning					Fort Riley					Yakima Training Center				
Sample Location	Number of Passes 0	10	25	50	Sample Location	Number of Passes 0	10	25	50	Sample Location	Number of Passes 0	10	25	50
CO	X	X	X	X	CO	X[b]	X	X	X	CO	X	X	X	X
CI	X	X	X	X	CI	X[b]	-	-	-	CI	X	X	X	X
SS	X	X	X	X	SS	X[b]	-	-	X	SS	X	X	X	X

[a] Sample locations: CO = curve outside, CI = curve inside, SS = straight section.

[b] Only one initial condition sample per figure-8 replication was taken at the Fort Riley site for each treatment.

Figure 3. Wind tunnel tray sample (122 cm long × 20 cm wide × 6 cm thick).

(>100 μm) are deposited into a catch pan located underneath the sampler. This sampler was an integral part of the wind tunnel tray experiments and allowed dust emissions of both suspension (<100 μm) and saltation plus creep (≥100 μm) size ranges to be captured and measured.

Two high-volume sampling blower motors were used during laboratory wind tunnel testing of the soil samples: one model GBM2000H motor assembly for the mass flow control (MFC) unit and one model GBM2000V motor assembly for the volume flow control (VFC) unit (General Metal Works, Cleves, Ohio). The MFC unit had an adjustable flow range of 0.00944 to 0.02831 m^3 s^{-1}, with a flow setpoint of 0.01888 m^3 s^{-1} at 115 V and flow control accuracy of ±2.5% over a 24 h sampling period. The VFC unit was connected to a variable voltage controller, and the flow was adjusted to match the internal pitot tube (inside the slot sampler) pressures with the external pitot tube (outside the slot sampler) pressures.

These blower motors were used to create negative pressure within the slot-sampler system. At the beginning of the experiments, one blower motor was voltage-adjusted to ensure that the total flow within the sampling system was equivalent to the moving air stream within the wind tunnel during the tests. The setpoint resulted in a flow rate of 0.0529 m^3 s^{-1}. The pressure was monitored in real time using pressure transducers connected to a computer.

Proper establishment of the upwind boundary layer conditions is an important factor to consider when using a wind tunnel to estimate particulate emissions as a result of wind erosion. Figure 5 shows a schematic of the wind tunnel. The tunnel is a 12.2 m length × 1.2 m width × 1.5 m height, push-type laboratory wind tunnel located at the USDA-ARS Wind Erosion Laboratory in Manhattan, Kansas. In the upwind portion of the tunnel, directly following the fan, is a screen followed by a honeycomb structure. This setup has been shown to decrease both lateral and longitudinal turbulence (Rae and Pope, 1984). The boundary layer turbulence was mechanical turbulence generated by the surface roughness. Spires extending upward from the floor surface are directly downwind of the honeycomb structure to generate turbulence near the floor, which serves to slightly increase the initial boundary layer. Pea-sized gravel was sieved to a size range of 5 to 7 mm and applied to the entire length of the tunnel floor to create a boundary layer depth of approximately 0.3 m, based on previous research with this wind tunnel (Mirzamostafa et al., 1998; Kohake et al., 2010). The gravel was used to simulate roughness conditions more similar to the soil surface (1.6 mm random roughness, as defined by Allmaras et al., 1966) than the smooth plywood tunnel floor. The roughness provided boundary layer conditions within the air stream that better replicate those found in actual field conditions (Kohake et al., 2010). Note that the initial surface roughness varied among the trays, and the roughness was further modified as the trays became armored (i.e., loose fines were removed) during testing. The aerodynamic roughness, excluding any standing residue effects, ranged from about 0.2 to 1.0 mm. At the beginning of each test, the soil tray surface heights were adjusted and leveled with the surrounding floor surface using two floor jacks underneath the trays. The edge of the trays was either level with or below the surrounding soil and pea gravel so as to not impede or otherwise alter the wind flow.

Testing was done for a period of 5 min at a mean wind speed of 14 m s^{-1}, in accordance with the procedure of Kohake et al. (2010), and was well above the observed threshold. The wind speed chosen was also near the upper limit of the tunnel. Wind speed was established at the centerline at a height of 0.75 m above the tunnel floor using a pitot static tube coupled with a pressure transducer.

Dust concentrations were measured with a Grimm spectrometer (model 1.108, Grimm Aerosol Technik GmbH, Ainring, Germany) from within the center of the ducting of the isokinetic sampling train shown in figure 5. The Grimm spectrometer uses light scattering for single-particle counts, with a semiconductor laser as the light source. The scattered signal from a particle passing through the laser beam is collected at approximately 90° by a mirror and transferred to a recipient diode. The signal from the diode passes, after a corresponding reinforcement, through a multichannel size classifier. A pulse height analyzer then classifies the signal transmitted in each channel. The ambient air, to be analyzed, is drawn into the unit by an internal volume-controlled pump at a rate of 1.2 L min^{-1}, and results are recorded every 6 s. The Grimm spectrometer provided data for determination of 15 individual size fractions (>0.3, >0.4, >0.5, >0.65, >0.8, >1.0, >1.6, >2.0, >3.0, >4.0, >5.0,

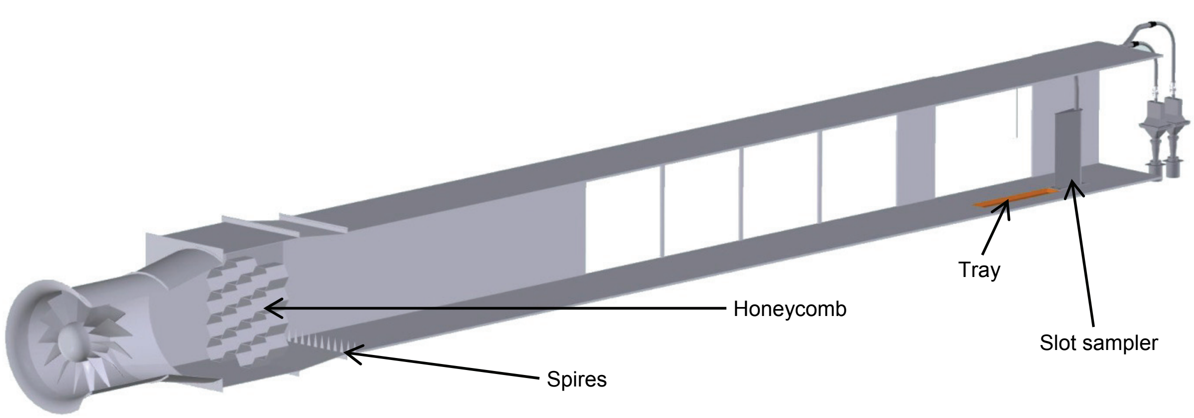

Figure 5. Schematic of the wind tunnel (12.2 m length × 1.2 m width × 1.5 m height).

>7.5, >10.0, >15.0, and >20.0 μm) of the suspended dust in mg L^{-1}. This allowed for the determination of the concentrations of particles in certain size ranges of interest, i.e., <2.5 μm, <10 μm, and total dust (<20 μm). From the measured concentrations, the volumetric flow rate through the Grimm spectrometer, and the duration of testing (5 min), the total mass of dust (<20 μm) emissions (mg) was determined. This value was divided by 0.0061 m^2 (length of the tray times the width of the slot opening) to determine the dust emission potential (mg m^{-2}) of the tray surface (eq. 1):

$$E = \frac{1}{A} \times \sum_{i=1}^{n} \left(C_i \times Q \times \Delta t \right) \tag{1}$$

where
- E = emission per area (mg m^{-2})
- A = effective area of the tray (0.0061 m^2)
- n = number of concentration measurements during the 5 min testing period
- C_i = PM concentration measurements every 6 s (mg m^{-3})
- Q = flow rate (m^3 min^{-1})
- Δt = time interval (min).

Background particulate concentration was measured before each run using the Grimm spectrometer. Additionally, the wind tunnel was thoroughly cleaned after each run using high-velocity wind and rapping in conjunction with compressed air cleaning of the sampling train while the high-volume samplers were running to clean any entrained particles from the system. A settling period was allowed after the high-velocity cleanout before starting the next sampling event. While the background concentration was not subtracted from the overall mass emission results, each test was run only after background concentration reached a non-detectable level.

Data Analysis

Dust emission data were analyzed independently for the three vehicle types (HMMWV, M1A1, and M925A1). For each of these analyses, there were three replications for each vehicle/soil texture combination at each site. In addition, tray samples, which were collected on the outside/inside curves (CO, CI) and straight sections (SS) within each figure-8 location after an increasing series of trafficking passes, were considered subsamples and averaged to obtain mean emissions from the entire figure-8 plot (fig. 2 and table 3).

For light wheeled vehicles (HMMWV), the experimental design was a completely randomized design with a split plot. Soil texture (i.e., silty clay loam, silt loam, loam, and loamy sand) was the fixed whole-plot treatment factor, and replication within soil texture was the random whole-plot error term. Split-plot fixed effects included the main effect of number of vehicle passes (0, 10, 25, and 50) and the interaction between soil texture and number of passes. The split-plot error term was the random effect due to the interaction between number of passes and replication within soil texture.

For tracked vehicles (M1A1), the experimental design and treatment structure was exactly the same as with the HMMWV, except that loam was excluded from soil texture and the number of passes was 0, 1, 5, and 10.

Heavy wheeled vehicles (M925A1) were tested only at one soil texture (loam). Therefore, the experimental design was a randomized complete block design in which the blocking factor was the replication and the treatment factor was number of passes (0, 2, 10, and 20).

All analyses were conducted using SAS software (ver. 9.3, SAS Institute, Inc., Cary, N.C.). Initial analyses assumed normality of responses and were conducted using the MIXED procedure. However, since residuals for each of the responses appeared rightwardly skewed (i.e., non-normal), a generalized linear mixed model (GLMM) with a gamma distribution and a log link function in the GLIMMIX procedure of SAS were used. See Stroup (2013) for technical details on GLMMs and the SAS online documentation (http://support.sas.com/documentation/onlinedoc/stat/) for technical details on the MIXED and GLIMMIX procedures. The selection of a gamma distribution ensured positive dust emission confidence limits while accounting for the heterogeneous variance experienced among soil textures. Due to unbalanced subsampling, the Satterthwaite denominator degree of freedom method was used. For light wheeled and tracked vehicle analyses, F-tests were calculated for the main effects of soil texture and number of passes and for the soil × pass interaction. For heavy wheeled vehicle analysis, the F-test was calculated only for number of passes. For all analyses, means and standard errors were also calculated for all effects. In addition, pairwise comparisons were performed for the main effect means using the Tukey adjustment for Type I error and are reported here.

Results and Discussion

Soil Properties

Soil properties measured in the upper 5 cm are presented in table 1. Clay content for the study sites ranged from 28 to 280 g kg^{-1}, while sand ranged from 79 to 877 g kg^{-1}, resulting in textures ranging from loamy sand to silty clay loam. Soils with less than 150 g kg^{-1} clay tend to have poorer aggregation and thus higher natural erodibility (Chepil, 1953, 1955). Organic matter contents ranged from 9 g kg^{-1} for the warm and humid sandy soil at Fort Benning to 41 g kg^{-1} for the tallgrass prairie soils at Fort Riley. Since higher organic matter contents were also found in soils with higher clay contents, the clay content is expected to dominate the aggregation processes in these soils. The soil samples were allowed to completely air-dry before the wind tunnel tests; therefore, the samples had similar moisture contents, and soil moisture at the time of the tests was assumed to have no effect on results. However, the initial moisture contents (i.e., prior to trafficking experiments) were considerably lower for the loam (0.01 kg kg^{-1}) and loamy sand (0.02 kg kg^{-1}) than for the silt loam (0.16 to 0.17 kg kg^{-1}) and silty clay loam (0.18 to 0.21 kg kg^{-1}). Initial bulk density ranged from 1.22 to 1.47 g cm^{-3}. These values were within expected ranges and, because bulk density has little effect on loose emissions of soil, they were also assumed to have a minimal effect on results.

The higher water contents during the trafficking experiments and the ability of the Fort Riley soils to consolidate better due to their higher clay contents may have limited the emissions potential from these soils. If these soils were present and tested under drier conditions with similar vegetation cover, like the other two sites, these soils may have generated emission levels more similar to the other soils. Additional experimentation is required to determine the actual effects, if any, that different soil water contents may have on emission potential due to repeated trafficking.

VEGETATION COVER

The trafficking passes degraded the vegetation cover for all vehicles on all soils. Figures 6, 7, and 8 show the changes in vegetative cover due to trafficking on the soils at the sites where each vehicle was used. Note that the tracked vehicle was more destructive than either of the wheeled vehicles with respect to vegetation cover. The denser prairie grass vegetation and soils with higher clay content at Fort Riley appeared to resist the destructive impact and shear forces in the curved regions of the multiple trafficking passes better than the Fort Benning and Yakima Training Center vegetation and soils. Vegetation cover appears to influence the emission of the soil surface, as expected (figs. 6, 7, and 8).

LIGHT WHEELED VEHICLE

Data were collected for the light wheeled vehicle (HMMWV) on four soil textures across the three experimental sites. The difference in mean emission potential (<20 µm) for each testing parameter (i.e., pass and soil)

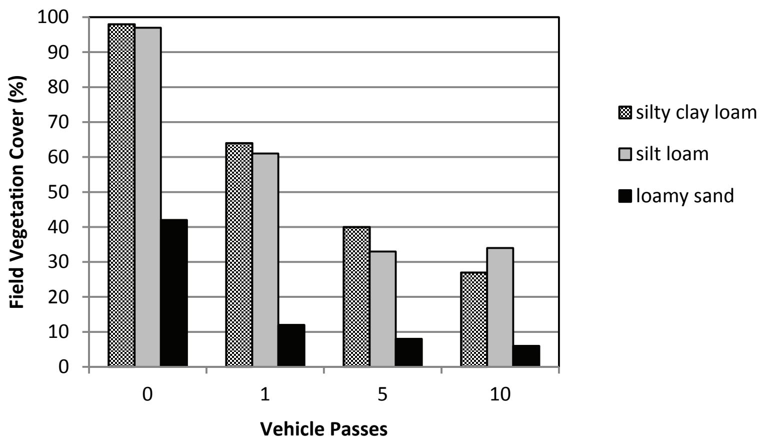

Figure 6. Vegetative cover after vehicular traffic (M1A1 tank) at Fort Riley and Fort Benning sites.

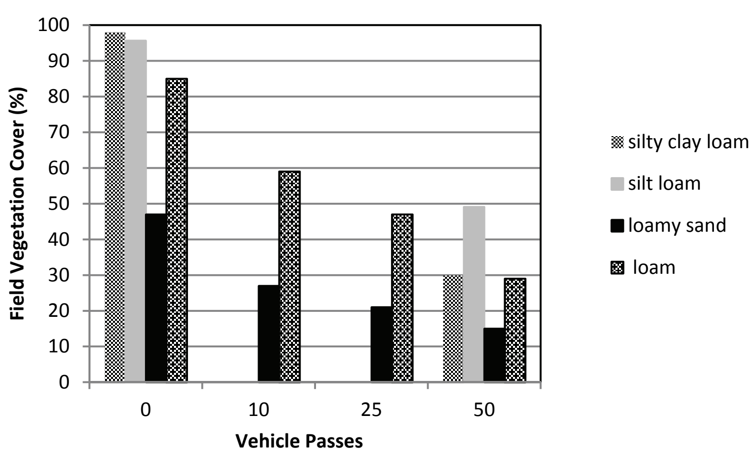

Figure 7. Vegetative cover after vehicular traffic (HMMWV) on all sites.

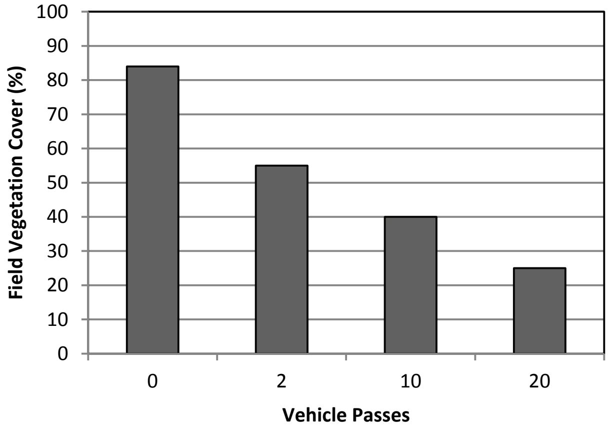

Figure 8. Vegetative cover after vehicular traffic (water tanker fire truck) on loam soil at Yakima Training Center.

was significant ($p < 0.05$) for all emissions tests. Table 4 shows the pairwise comparisons for both soil texture and number of passes for all tests. All comparison tests showed significant differences in emissions at the 5% level, except the two soil textures at Fort Riley (silt loam and silty clay loam). This result is not surprising, because the two soil textures have similar properties and were close in geographical proximity. In addition, there was no significant increase in emissions when the number of passes was doubled from 25 to 50 ($p = 0.66$). This result indicates that all emission increases generally occurred between undisturbed conditions and 25 passes. Table 4 also shows that, from undisturbed conditions to 10 passes, emissions increased by 357% on average for all light wheeled vehicle tests. From 10 to 25 passes, an additional 72% increase was observed.

Total dust emission potential as measured by the Grimm spectrometer was shown to be significantly influenced by both trafficking passes and soil texture. In general, the soil textures with more sand content were more susceptible to emissions, as shown in table 4. As shown in table 1, the two soils at the Fort Riley site had significantly less sand content at the surface, 7.9% (silty clay loam) and 10.2%

Table 4. Pairwise comparisons of total dust emissions (<20 μm) from wind tunnel tests (Grimm spectrometer), light wheeled vehicle (HMMWV).

Soil 1	Soil 2	Estimate	Difference between Treatments (%)	Adjusted p-Value
SiCL[a]	SiL	-0.60	82	0.13
SiCL	L	-1.94	598	0.0002
SiCL	LS	-2.71	1396	<0.0001
SiL	L	-1.35	284	0.0021
SiL	LS	-2.11	722	<0.0001
L	LS	-0.76	114	0.049
Pass 1	Pass 2			
0	10	-1.52	357	<0.0001
0	25	-2.06	686	<0.0001
0	50	-2.27	868	<0.0001
10	25	-0.54	72	0.031
10	50	-0.75	112	0.002
25	50	-0.21	23	0.66

[a] SiCL = silty clay loam (Fort Riley), SiL = silt loam (Fort Riley), L = loam (Yakima), and LS = loamy sand (Fort Benning).

(silt loam), than the other two sites, which had 51.3% (loam) and 87.7% (loamy sand). Initial moisture content (i.e., prior to trafficking experiments) also could have influenced the behavior of the soil during trafficking and the resulting emission potential. Note that the two soils at the Fort Riley site had initial moisture contents of 0.16 to 0.21 kg kg^{-1}, whereas the other two sites had initial moisture contents of 0.01 to 0.02 kg kg^{-1}. Although the effect of soil texture (combined with initial moisture content) was more distinct than the vehicle passes, from the data presented in table 4, there is evidence that trafficking intensity can influence increased emissions nearly as much as soil texture alone.

Figure 9 shows the total Grimm measured dust emission potential (particles <20 μm) for treatment interaction effects of soil texture and number of passes. The silty clay loam and silt loam soil textures (with high initial moisture contents) at the Fort Riley site had relatively low emission potential compared with the other sites. In addition, although no significant ($p > 0.05$) increase in emissions was detected between 25 and 50 passes, the loamy sand soil continued to increase between these two treatment levels. Statistical analysis indicated significant ($p < 0.05$) effects of both trafficking passes and soil texture, as well as their interaction.

Fort Benning (loamy sand) showed a 1,953% increase in emissions of total dust (<20 μm) between undisturbed conditions and 25 passes, and Yakima Training Center (loam) had a 3,119% increase for the same treatment. Figure 10 illustrates the trend for the loam and loamy sand soils for total suspended particles (<20 μm, <10 μm, and <2.5 μm).

Tracked Vehicle

For all one-way tests, the main effects of soil and trafficking passes were significant ($p < 0.05$). The interaction effect between soil and pass was not significant ($p > 0.05$) for all tests, with the exception of emission potential of dust <2.5 μm. Note that the tracked vehicle testing represents fewer data points than the light wheeled vehicle testing.

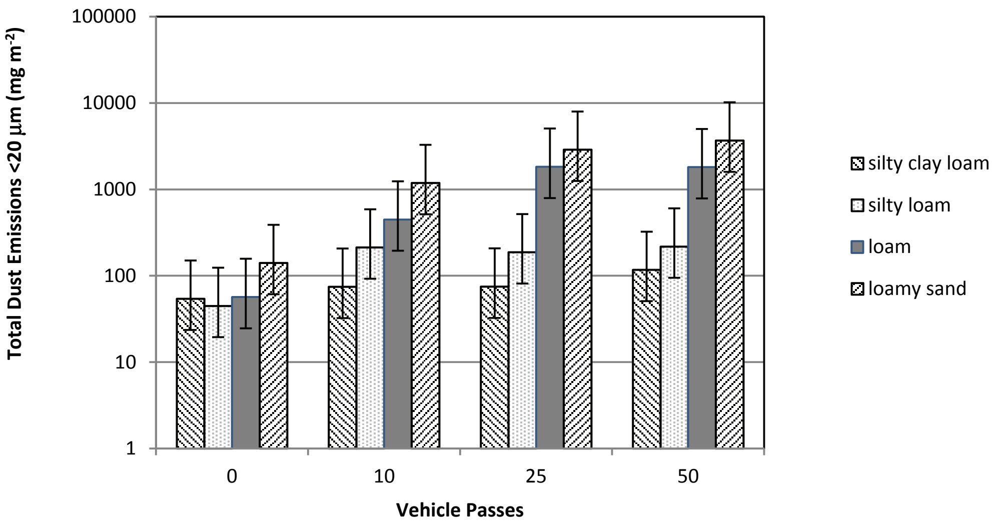

Figure 9. Total dust emissions (<20 µm) from wind tunnel tests (Grimm spectrometer), light wheeled vehicle (HMMWV). Error bars represent 95% confidence limits of three replications.

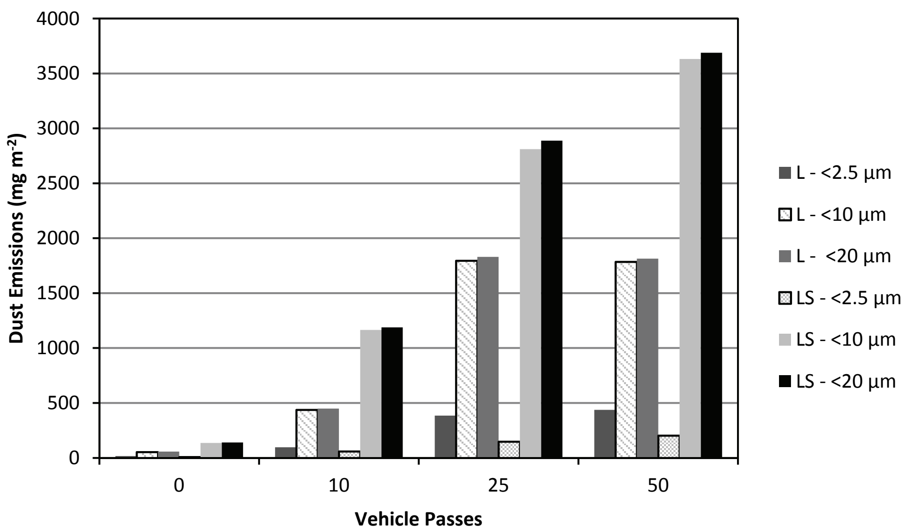

Figure 10. Trend similarities between particle sizes for the loam (L) and loamy sand (LS) for light wheeled vehicle (HMMWV).

This is due to the tracked vehicle being unavailable at the Yakima site as originally planned. It is recommended that further investigation into the effects of a tracked vehicle on emission potential be conducted.

Table 5 shows the pairwise comparison of the effects of soil and trafficking passes on total dust emission (<20 µm) potential. As seen with the light wheeled vehicle testing, the two Fort Riley soils showed no significant ($p > 0.05$) difference across all trafficking tests. Although there was a significant ($p < 0.05$) increase in emissions from undisturbed condition to any number of passes, no significant ($p > 0.05$) difference was observed between 1, 5, and 10 passes. In addition, unlike the results from the light wheeled vehicle testing, interaction effects between soil texture and number of vehicle passes on total dust emission (<20 µm) potential was not significant ($p > 0.05$). One possible explanation for these results is that tracked vehicle

Table 5. Pairwise comparisons of total dust emissions (<20 µm) from wind tunnel tests (Grimm spectrometer), tracked vehicle (M1A1).

Soil 1	Soil 2	Estimate	Difference between Treatments (%)	Adjusted p-Value
SiCL[a]	SiL	-0.15	16	0.90
SiCL	LS	-1.91	575	0.0028
SiL	LS	-1.76	481	0.0042
Pass 1	Pass 2			
0	1	-1.90	569	<.0001
0	5	-1.71	453	<.0001
0	10	-2.30	896	<.0001
1	5	0.19	-17	0.86
1	10	-0.40	49	0.38
5	10	-0.59	80	0.11

[a] SiCL = silty clay loam (Fort Riley), SiL = silt loam (Fort Riley), and LS = loamy sand (Fort Benning).

testing was completed on only three soil textures, and two of the three soils (silt loam and silty clay loam) were high in clay content and relatively low in sand content (table 1), making them much less susceptible to emissions. In addition, the tracked vehicle sheared the surface on the curves, removing the top soil and most of the vegetation on the first pass (fig. 6). Subsequent passes resulted in similar behavior while exposing more moist soil below the surface, especially at the Fort Riley site. In contrast, many more passes with the light wheeled vehicle were required to completely shear through the vegetation and physically remove some of the top soil from the wheel tracks (fig. **7**).

Figure 11 illustrates the soil-pass interaction plot of total dust emissions (<20 μm) for the tracked vehicle. Although most of the pass interaction effects were not significant ($p > 0.05$) for the tracked vehicle testing, the soil interaction effect for dust <20 μm was significant ($p < 0.05$).

HEAVY WHEELED VEHICLE

Significant ($p < 0.05$) treatment effects were observed for all heavy wheeled vehicle tests (fully loaded M925A1 fire water tanker) at Yakima. After 20 passes of the heavy wheeled vehicle, the soil surface showed a 5,276% increase in dust (<20 μm) emission potential over undisturbed conditions. In contrast to the light wheeled and tracked vehicles, the emission increase between each pass level was significant ($p < 0.05$).

Figure 12 shows an increase in dust emission potential with each subsequent increase in vehicle passes for each treatment level up to 20 passes. The light wheeled vehicle

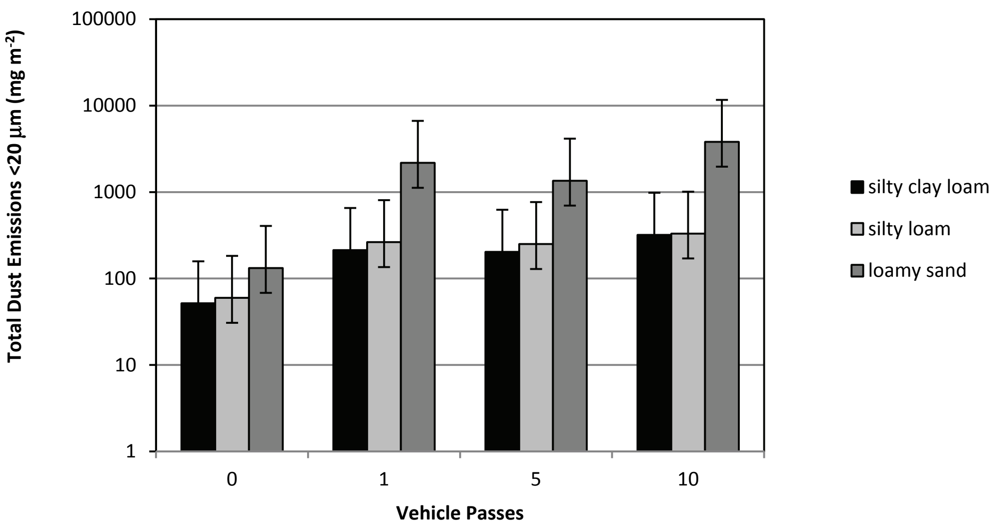

Figure 11. Total dust emissions (<20 μm) from wind tunnel tests (Grimm spectrometer), tracked vehicle (M1A1). Error bars represent 95% confidence limits of three replications.

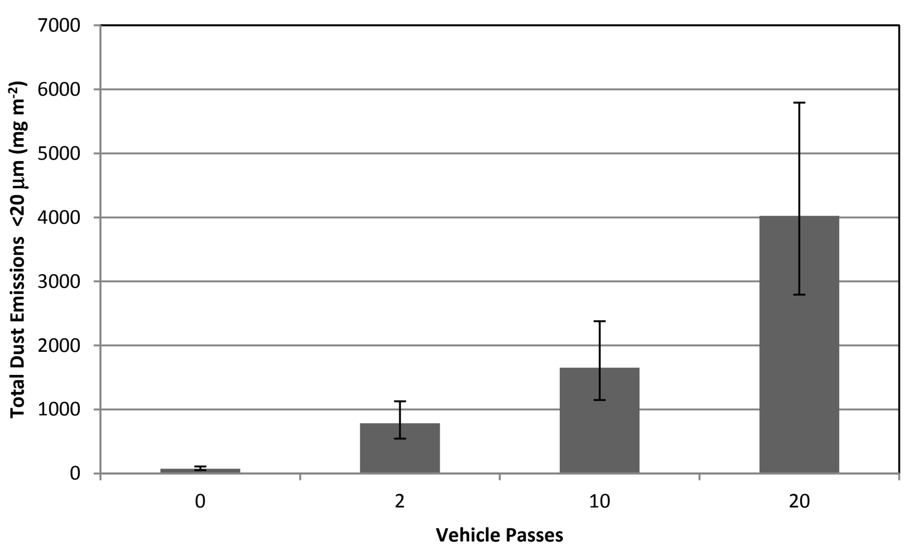

Figure 12. Total dust emissions (<20 μm) from wind tunnel tests (Grimm spectrometer), heavy wheeled vehicle (M925A1). Error bars represent 95% confidence limits of three replications.

showed less increase in emissions at a higher number of passes; however, the heavy wheeled vehicle did not show the same increasing trend for the same soil texture. Note, however, that the number of passes went up to only 20, whereas the light wheeled vehicle used 50 passes as the upper level. This indicates that additional passes are necessary to determine the maximum effect on the soil with the heavy wheeled vehicle.

CONCLUSIONS

Multi-pass military vehicle trafficking experiments were conducted at three military training installations. Dust emission potential was measured in a laboratory wind tunnel (with a Grimm spectrometer). The following conclusions were drawn from this research.

Wind tunnel testing showed a significant impact of off-road trafficking passes on total dust emissions (<20 μm) for most tests, except for the heavy wheeled vehicle. For both the light wheeled and tracked vehicles, there seemed to be a threshold of maximum increase in emission potential. For the light wheeled vehicle, from undisturbed conditions to 10 and 25 vehicle passes, emissions increased significantly ($p < 0.05$); however, when the number of passes doubled from 25 to 50, the increase was not significant ($p > 0.05$). For the tracked vehicle, emissions increased significantly ($p < 0.05$) from undisturbed conditions to one pass, but when the number of passes was increased, the emissions increase was not significant ($p < 0.05$). The heavy wheeled vehicle did not exhibit exactly this behavior with the number of passes tested (2, 10, and 20), although that may be due to an insufficient number of passes being conducted with this vehicle.

For the tracked vehicle, in general, emission potential increased in soils with higher sand content (and low initial moisture content). In addition, dust emissions increased significantly from undisturbed conditions to any number of passes with the tracked vehicle.

The tracked vehicle was more destructive than either of the wheeled vehicles with respect to vegetation cover, especially when turning. This is due to the significant shearing action in the curved regions and was likely intensified by the extra weight of the tracked vehicle. The denser prairie grass vegetation and soils with higher clay content at Fort Riley appeared to resist the destructive impact and shear forces in the curved regions better than the Fort Benning and Yakima Training Center vegetation and soils. The heavy wheeled vehicle was more destructive of the vegetation than the light wheeled vehicle at the Yakima Training Center site, which can be attributed to the extra weight of the heavy wheeled vehicle. Whether the difference would be similar or different on other soils is unknown because the heavy wheeled vehicle was not used at the other sites during this study.

In general, soil texture (combined with initial moisture contents) played an important role in dust emissions, but vehicle passes can produce an effect nearly as pronounced. Because of the lack of a significant increase in emissions between 25 and 50 passes for light wheeled vehicles and multiple passes (>1) for the tracked vehicle, intensive vehicle training should be conducted, when possible, on lands that have been previously disturbed to reduce the amount of land requiring remediation after trafficking.

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REFERENCES

Allmaras, R. R., Burwell, R. E., Larson, W. E., & Holt, R. F. (1966). Total porosity random roughness of the interrow zone as influenced by tillage. Conservation Report No. 7. Washington, D.C.: USDA Agricultural Research Service.

Althoff, P. S., & Thien, S. J. (2005). Impact of M1A1 main battle tank disturbance on soil quality, invertebrates, and vegetation characteristics. *J. Terramech., 42*(3-4), 159-176. http://dx.doi.org/10.1016/j.jterra.2004.10.014.

Althoff, P. S., Thien, S. J., & Todd, T. C. (2010). Primary and residual effects of Abrams tank traffic on prairie soil properties. *SSSA J., 74*(6), 2151. http://dx.doi.org/10.2136/sssaj2009.0091.

Ashbaugh, L. L., Carvacho, O. F., Brown, M. S., Chow, J. C., Watson, J. G., & Magliano, K. C. (2003). Soil sample collection and analysis for the fugitive dust characterization study. *Atmos. Environ., 37*(9-10), 1163-1173. http://dx.doi.org/10.1016/S1352-2310(02)01022-1.

Chepil, W. S. (1953). Factors that influence clod structure and erodibility of soil by wind: I. Soil texture. *Soil Sci., 75*(6), 473.483. http://dx.doi.org/10.1097/00010694-195306000-00008.

Chepil, W. S. (1955). Factors that influence clod structure and erodibility of soil by wind: IV. Sand, silt, and clay. *Soil Sci., 80*(2), 155-162. http://dx.doi.org/10.1097/00010694-195508000-00009.

Diaz-Nigenda, E., Tatarko, J., Jazcilevich, A. D., Garcia, A. R., Caetano, E., & Ruiz-Suarez, L. G. (2010). A modeling study of Aeolian erosion enhanced by surface wind confluences over Mexico City. *Aeolian Res., 2*(2-3), 143-157 http://dx.doi.org/10.1016/j.aeolia.2010.04.004.

DoD. (2013). Base structure report: Fiscal year 2013 baseline. A summary of the Department of Defense's real property inventory. Washington, D.C.: U.S. Department of Defense. Retrieved from www.acq.osd.mil/ie/download/bsr/Base%20Structure%20Report%202013_Baseline%2030%20Sept%202012%20Submission.pdf.

EPA. (2010). Fort Riley, Kansas: Site description. EPA No. KS6214020756. Washington, D.C.: U.S. Environmental Protection Agency. Retrieved from www.epa.gov/region07/cleanup/npl_files/ks6214020756.pdf.

Gee, G. W., & Dani, O. (2002). Particle-size analysis. In J. H. Dane & G. C. Topp (Eds.), *Methods of Soil Analysis: Part 4. Physical Methods* (pp. 255-293). Madison, Wisc.: SSSA.

Gillies, J. A., Etyemezian, V., Kuhns, H., Nikolic, D., & Gillette, D. A. (2005). Effect of vehicle characteristics on unpaved road dust emissions. *Atmos. Environ., 39*(13), 2341-2347. http://dx.doi.org/10.1016/j.atmosenv.2004.05.064.

Guoliang, L., Xuan, J., & Park, S. (2003). A new method to calculate wind profile parameters of the wind tunnel boundary layer. *J. Wind Eng. Ind. Aerodynamics, 91*(9), 1155-1162. http://dx.doi.org/10.1016/S0167-6105(03)00057-6.

Kohake, D. J., Hagen, L. J., & Skidmore, E. L. (2010). Wind erodibility of organic soils. *SSSA J., 74*(1), 250-257. http://dx.doi.org/10.2136/sssaj2009.0163.

Marticorena, B., & Bergametti, G. (1997). Factors controlling threshold friction velocity in semiarid and arid areas of the United States. *J. Geophys. Res., 102*(D19), 23277-23287. http://dx.doi.org/10.1029/97JD01303.

Mirzamostafa, N., Stone, L., Hagen, L. J., & Skidmore, E. L. (1998). Soil aggregate and texture effects on suspension components from wind erosion. *SSSA J., 62*(5), 1351-1361. http://dx.doi.org/10.2136/sssaj1998.03615995006200050030x.

NCDC. (2011). U.S. local climatological data. Asheville, N.C.: National Climatic Data Center. Retrieved from www.ncdc.noaa.gov/most-popular-data#loc-clim.

Rae, W. H., & Pope, A. (1984). *Low-Speed Wind Tunnel Testing.* New York, N. Y.: John Wiley and Sons.

Retta, A., Wagner, L. E., Tatarko, J., & Todd, T. C. (2013). Evaluation of bulk density and vegetation as affected by military vehicle traffic at Fort Riley, Kansas. *Trans. ASABE, 56*(2), 653-665. http://dx.doi.org/10.13031/2013.42687.

Skidmore, E. L., & van Donk, S. J. (2003). Chapter 9: Soil erosion and conservation. In D. W. Benbi, & R. Neider (Eds.), *Handbook of Processes in the Soil-Plant Systems: Modeling Concepts and Applications* (pp. 227-260). Binghamton, N.Y.: Haworth Press.

Sloneker, L. L., & Moldenhauer, W. C. (1977). Measuring the amount of crop residue remaining after tillage. *J. Soil Water Cons., 32*(5), 231-236.

Stroup, W. (2013). *Generalized Liner Mixed Models: Modern Concepts, Methods, and Applications.* Boca Raton, Fla.: CRC Press.

Sweeney, M., Etyemezian, V., Macpherso, T., Nickling, W., Gillie, J., Nikolich, G., & McDonald, E. (2008). Comparison of PI-SWERL with dust emission measurements from a straight-line field wind tunnel. *J. Geophys. Res., 113*(F1), 1-12. http://dx.doi.org/10.1029/2007JF000830.

Swift, R. S. (1996). Organic matter characterization. In J. M. Bartels (Ed.), *Methods of Soil Analysis: Part 3. Chemical Methods* (3rd ed., pp. 1011-1069). Madison, Wisc.: SSSA.

Van Pelt, R. S., Zobeck, T. M., Baddock, M. C., & Cox, J. J. (2010). Design, construction, and calibration of a portable boundary layer wind tunnel for field use. *Trans. ASABE, 53*(5), 1413-1422. http://dx.doi.org/10.13031/2013.34911.