EVALUATION OF BULK DENSITY AND VEGETATION AS AFFECTED BY MILITARY VEHICLE TRAFFIC AT FORT RILEY, KANSAS

A. Retta, L. E. Wagner, J. Tatarko, T. C. Todd

ABSTRACT. *Studies were conducted using military vehicles to determine the influence of repeated traffic on soil compaction and vegetative losses. The resultant data will eventually be incorporated into models such as the Wind Erosion Prediction System (WEPS). A replicated field experiment was conducted in the fall of 2010 on two soils that dominate the military training grounds at Fort Riley, Kansas. Treatments consisted of two vehicle types and three levels of vehicle passes. We used an Abrams M1A1 tank and a High-Mobility Multipurpose Wheeled Vehicle (i.e., Humvee), representing tracked and wheeled military vehicles, respectively. Bulk density, aboveground standing biomass, and plant cover were measured before and after vehicular traffic in the fall of 2010 as well as in the spring and summer of 2011. Samples were taken from curved, straight, and cross-over sections of the vehicle tracks. A mixed-model analysis of variance of these data indicated that the overall mean bulk density under the M1A1 was significantly greater than under the Humvee ($p \leq 0.05$). In general, as the number of passes increased, the bulk density under the M1A1 increased significantly ($p \leq 0.05$), but the increases under the Humvee were not significant ($p \leq 0.05$). Bulk densities were significantly greater in the curved part of the tracks than the straight part of the tracks. Reduction in standing biomass and vegetation cover was more severe on average under the M1A1 than under the Humvee (although not significant at $p \leq 0.05$). For both vehicles, biomass and cover were affected more at the curved sections of the track than the straight sections (significant at $p \leq 0.05$). Comparison of spring and fall bulk density data showed significant differences at the 0-5 cm and 5-10 cm depths, indicating that the winter freeze and thaw cycles loosened the top soil layers. Subsequent growth showed severe reduction in grass biomass growth in the curved sections of the tracked vehicle paths. Growth in forb species was not significantly affected.*

Keywords. *Forb biomass, Grass biomass, Humvee, M1A1, Military training, Wind erosion.*

Anderson et al. (2005) presented a review of the literature on the impacts of mechanized military maneuvers on soil and vegetation in the training grounds of different military bases. Vehicular traffic, especially from tracked vehicles, may remove much of the vegetative cover and destroy or degrade soil aggregates, thereby increasing the amount of loose material that can be readily dispersed by wind. Traffic also compresses the soil, making it less permeable to water and roots, and renders the land more susceptible to both water and wind erosion (Altoff et al., 2010). Increased dust levels in the atmosphere associated with training exercises may result in greater health risks due to a possible rise in PM_{10} and $PM_{2.5}$ (particulate matter smaller than 10 and 2.5 microns, respectively) concentration levels. Management of military lands in ways that minimize ecological damage and reduce health risks can enable the U.S. Department of Defense to carry out its training missions sustainably. The Wind Erosion Prediction System (WEPS) simulation model (Hagen, 1991, 1992; Wagner, 1996; Wagner and Tatarko, 2001), with proper modifications, has the potential to provide estimates of wind erosion from different training scenarios, thus allowing a manager to choose training regimes that reduce or eliminate the potential hazards from elevated dust levels in the environment. However, critical process parameters in WEPS that were developed for agricultural fields need to be adapted or modified for military lands. Among the parameters that should be characterized are changes that occur in indices that are used to measure soil compaction, and degradation of vegetative cover under different types of military vehicles and their trafficking intensity.

Bulk density is commonly used as an indicator of the degree of compaction that may be attributable to vehicular traffic (Braunack, 1986; Prosser et al., 2000). Freeze/thaw and wet/dry cycles have a tendency to loosen the soil and decrease bulk density (Halvorson et al., 2003), thus alleviating somewhat the compaction caused by vehicle traffic. Changes in vegetative cover and/or biomass before and after vehicle trafficking can indicate the severity of the de-

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struction of vegetation and the potential for creating an environment favoring increased prevalence of non-native species. Evaluation of vegetation growth following vehicular traffic is necessary to assess the lingering effects of trafficking on the recovery of vegetation (Palazzo et al., 2005).

A field experiment was designed and implemented at Fort Riley, Kansas, with the primary objective of collecting data that will be later used to obtain relationships of soil and vegetation variables to the type and intensity of vehicular traffic. Such relationships potentially can be incorporated into WEPS and other models to assist in identifying management strategies for long-term sustainability of military training lands.

METHODS AND MATERIALS

Rectangular field plots (40 m × 70 m) on which vehicles were driven in a figure-eight pattern were established at Fort Riley (39° 15′ N, 96° 50′ W), and the experiments were conducted in October (M1A1) and November (Humvee) 2010. The vegetation was dominated by native grasses: big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparium*), switchgrass (*Panicum virgatum*), tall dropseed (*Sporobolus compositus*), and Indiangrass (*Sorghastrum nutans*), with relative abundance on a mass basis of 31%, 26%, 14%, 12%, and 10%, respectively (August 2011 data). The experimental site was covered with a considerable amount of vegetation (810 g m^{-2}), which was mowed and raked clean to remove the excess biomass before the start of the trafficking treatments, leaving 130 g m^{-2}. The experiments were carried out on silt loam and silty clay loam soils (table 1), belonging to the Wymore-Irwin associations, which occupy over 65% of the training grounds at Fort Riley (Althoff et al., 2007).

The experimental treatments consisted of two vehicles, tracked and wheeled, arranged in a randomized block design with three replications for a total of six blocks. In the plots designated for treatment with a tracked vehicle, an M1A1 tank was used that weighed 57.2 tons, had a track width of 63.5 cm, and was driven at an approximate speed of 8 km h^{-1}. A Humvee (weighing approximately 5 tons and traveling at 25 to 30 km h^{-1}) was used on the wheeled plots. The number of trafficking passes for each vehicle was determined from test trials to represent a minimum measurable impact, a moderate impact, and a severe impact on the soil and surface state. Thus, the tracked plots were trafficked 1, 4, and 5 times with the M1A1 tank during the three passes, for a cumulative total of 1, 5, and 10 passes at the conclusion of each set of passes. The wheeled plots were trafficked 10, 15, and 25 times with the Humvee during the three passes, for a cumulative total of 10, 25, and 50 trafficking passes at the conclusion of each set of passes. The three sets of passes are referred to as p1, p2, and p3 when referring to both vehicle experiments.

The sequence of operations was as follows. The first set of trafficking passes was applied, at the end of which soil and plant samples were taken. The next set of passes was then applied to the same plot, and plant and soil samples were taken again. Finally, the last set of trafficking passes was applied, with plant and soil samples taken for a final time. The driver took extra care to ensure that the vehicle stayed in the same tracks during all trafficking passes. The degree of disturbance to the soil and the vegetation partly depends on how the vehicles are operated; disturbances on straight runs are less severe than when vehicles are making turns (Ayers, 1994). To accommodate both turning and straight runs, the vehicles were operated in a continuous figure-eight pattern with a turning radius of 20 m. Bulk density, gravimetric soil water content, standing biomass, and total vegetative cover data were sampled before and after the trafficking passes. Bulk density was taken using the core method (Grossman and Reinsch, 2002) with a core diameter of 4.83 cm. The soil cores were delineated into layers of 0-5, 5-10, and 10-15 cm and stored in soil moisture cans. The soil cores were weighed before and after drying in an oven at 105°C for at least 48 h. Bulk densities and moisture contents were calculated. Standing biomass within a 0.25 m^2 square frame was clipped to ground level and divided into grasses and forbs, with the species later identified. Clipped plants were dried at 60°C and weighed separately for the grass and forb species. Total vegetative cover was measured using a modified step-point method (Owensby, 1973). Statistical analysis was performed on all data using the PROC MIXED procedure in SAS (SAS Institute, Inc., Cary, N.C.).

Before the start of trafficking, a single initial set of samples was taken from each of the figure-eight plots. The purpose of taking these data from untrafficked segments was to assess the relative degree of compaction and vegetation removal that occurred under the different trafficking regimes from the original untrafficked condition. These data are referred to as "controls," "untrafficked," or "undisturbed" and designated as L0. These data were obtained from inside the figure-eight circles so that samples taken after trafficking would not be impacted. No additional data

Table 1. Dispersed particle size distribution (%), initial water content (%), and water content (%) at Proctor density of soils at the experimental sites at Fort Riley, Kansas. Data were taken in October 2010.

	Depth	Sand (%)[a]		Silt (%)		Clay (%)		Mass Water Content (%)			
Soil Type	(cm)	Mean	SD	Mean	SD	Mean	SD	Initial[b]	SD	Proctor[c]	SD
Silt loam	0-5	10.24	1.05	75.48	3.34	14.28	4.02	12.09	1.62	20.49	1.05
	5-10	7.25	1.11	73.03	3.75	19.71	4.44	18.00	2.28	-	-
	10-15	5.80	0.87	69.88	4.48	24.32	5.18	18.50	1.73	-	-
Silty clay loam	0-5	7.88	1.27	67.85	3.26	24.27	3.88	14.27	2.41	23.52	1.32
	5-10	5.40	1.32	62.34	4.72	32.26	5.97	20.75	2.44	-	-
	10-15	4.20	1.24	59.21	5.06	36.58	6.28	22.61	3.49	-	-

[a] Particle size determined by pipette method of Gee and Dani (2002).
[b] Water content before start of trafficking.
[c] Water content at maximum Proctor density.

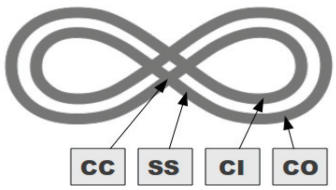

Figure 1. Figure-eight plot with relative sampling locations identified: CC = center cross, SS = straight section, CI = curve inside track, and CO = curve outside track. L0 (not shown) = untrafficked location inside figure-eight circles.

from undisturbed locations were taken after the start of trafficking.

In each of the figure-eight plots, samples were taken from four distinct segments within the vehicle tracks after the trafficking. The sampling segments were designated as straight section (SS), center cross (CC) (where the tracks crossed), curve outside track (CO), and curve inside track (CI), as shown in figure 1. These segments are referred to as "locations" in this study. Samples were taken from the center of the tracks in the trafficked locations, and the sampling sites from previous trafficking passes were avoided due to the destructive nature of the sampling methods. At each sampling location, bulk density, gravimetric soil water content, standing biomass, and total vegetative cover were determined after each set of vehicle passes. Note that bulk density measurements by depth were done from the existing surface at the time of sampling, even in the trafficked and sometimes deeply rutted areas (CI and CO locations). Therefore, the same soil mass in the original layers is not represented in the samples taken after trafficking at these locations, which exhibited shearing and removal of the surface soil, creating a rutted track on the curves. However, the impact of compaction on surface wind erosion processes and vegetation recovery is important in this study, and not the source of the soil mass that is compacted nor whether the vehicle caused all of the reported change in layer bulk density. Thus, it is still valid for the before and after bulk density samples to be compared by depth.

Surface compaction may recover after winter freeze and thaw cycles (Halvorson et al., 2003), but recovery of the vegetation to its original status may take longer (Althoff et al., 2009). To evaluate the lingering effects of multiple-pass trafficking on soil surface compaction as well as future growth and composition of vegetation, bulk density and biomass data were also collected in the spring and summer (following the fall trafficking) from the trafficked and untrafficked locations.

RESULTS AND DISCUSSION

BULK DENSITY DIFFERENCES DUE TO TREATMENTS

The analysis of variance of bulk density from trafficked locations indicates that the main factors of vehicle type, vehicle passes, sampling segment location, and soil depth were highly significant in both soils (table 2). Several two-way and one three-way interactions were also significant in both soils. The interactions that were significant in both soils will be discussed. The Vehicle × Pass interaction was highly significant ($p \leq 0.01$). At pass level p1, bulk densities from the M1A1 and the Humvee trafficked segments were not significantly different from each other. At pass levels p2 and p3, the bulk density from the M1A1 trafficked locations was significantly ($p \leq 0.01$) greater than from the Humvee treated locations. In the M1A1 trafficked segments, bulk density differences between pass levels p1 and p2 were significant in the silt loam soil; in the silty clay loam soil, differences between all pass levels were significant. For the Humvee bulk density, differences between passes were not significant (fig. 2). These results show that under the circumstances of this test, use of tracked vehicles, even for one pass, may result in significant near-surface soil compaction at the Fort Riley training grounds (0 to 15 cm), whereas multiple passes of a lightweight wheeled vehicle like the Humvee may not compact the soil surface to any significant degree at these depths, at least under the soil water content levels measured at the time of the trafficking (table 1).

Table 2. Analysis of variance for the influence of vehicle types (M1A1 and Humvee), and vehicle passes ((1, 5, 10 for M1A1; 10, 25, 50 for Humvee) on bulk densities taken at SS, CC, CO, and CI locations. Soil samples were taken from the center of the tracks in 0-15 cm depth increments of 5 cm.

Effect	Num DF	Den DF	Silt Loam		Silty Clay Loam	
			F-Value	Pr > F	F-Value	Pr > F
Vehicle (V)	1	2	20.87	0.0447	36.06	0.0266
Passes (P)	2	8	24.12	0.0004	16.35	0.0015
V × P	2	8	13.51	0.0027	16.29	0.0015
Location (L)	3	16	3.73	0.0331	5.66	0.0077
V × L	3	36	0.61	0.6111	0.76	0.5263
P × L	6	32	2.80	0.0264	3.16	0.0151
V × P × L	6	36	0.41	0.869	0.76	0.6055
Depth (D)	2	16	55.19	<0.0001	108.78	<0.0001
V × D	2	48	5.53	0.0069	23.06	<0.0001
P × D	4	32	0.56	0.6937	0.40	0.808
V × P × D	4	48	0.97	0.4308	3.30	0.0182
L × D	6	16	7.03	0.0008	4.21	0.0099
V × L × D	6	48	2.38	0.0431	5.70	0.0002
P × L × D	12	32	1.11	0.387	3.14	0.0048
V × P × L × D	12	48	0.24	0.9945	1.53	0.1458

Pass × Location interactions were significant ($p \leq 0.05$) in both soils. Bulk density generally increased in all track locations as the number of passes increased. The changes in bulk density were greater and more consistent in the curved sections than in the straight sections for the M1A1. For a more detailed examination of the Pass × Location interaction, data were split by vehicle and graphed (fig. 3). In the Humvee tracks, bulk density did not increase appreciably in most locations with increase in vehicle passes (fig. 3). Bulk density from the M1A1 tracks was greater after every pass in most locations than the bulk density from the untrafficked location (L0). In the case of the Humvee tracks, differences between the trafficked and untrafficked bulk densities were minor across most locations and did not show any consistent pattern. This result indicates that when the M1A1 tank is driven in this terrain (with the initial water contents shown in table 1), it will compact the soil more with additional passes. This was likely due to the excessive shearing and displacement of the original drier surface layer on the curved regions while performing turning maneuvers, exposing the more compressible wetter soil below. In

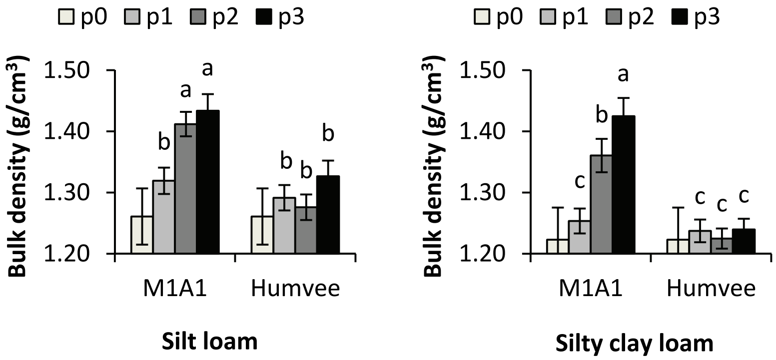

Figure 2. Average bulk density (0-15 cm) across all sampling locations (CC, SS, CI, and CO) from the silt loam and silty clay loam soils at different trafficking passes (1, 5, and 10 for the M1A1; 10, 25, and 50 for the Humvee); p0 (mean bulk density from undisturbed locations) was added for visual comparison. Bars with different letters within soil groups are significantly different (p ≤ 0.05); error bars are also shown.

contrast, the Humvee did not compact the soil to any significant level, even at points where the vehicle made turns (curved locations), due to its lighter overall weight and reduced surface soil shearing on the turns.

Due to the shearing and displacement of the surface layer of soil on the curved track portions of the figure-eight plots, subsequent bulk density measurements were not taken from the original soil layers in these locations (CI and CO). However, our concern is in the changes in the soil surface layer properties because they are of most interest from a wind erosion modeling and vehicle dust generation perspective. Therefore, no attempt was made to accurately reproduce the original soil layers in the pre-trafficking bulk density measurements when sampling the post-trafficking bulk density. Likewise, no direct measurements were attempted to determine the depth of soil displacement (rut depth) due to shearing on the curved track portions of the figure-eight plots.

Vehicle × Depth, Location × Depth, and Vehicle × Location × Depth interactions were significant ($p \leq 0.05$) in both soils (table 2). The Vehicle × Location × Depth interaction is shown in figure 4. At the 0-5 cm depth, differences in bulk density between the M1A1 and Humvee in the straight section (SS) and crossed tracks (CC), although small, were

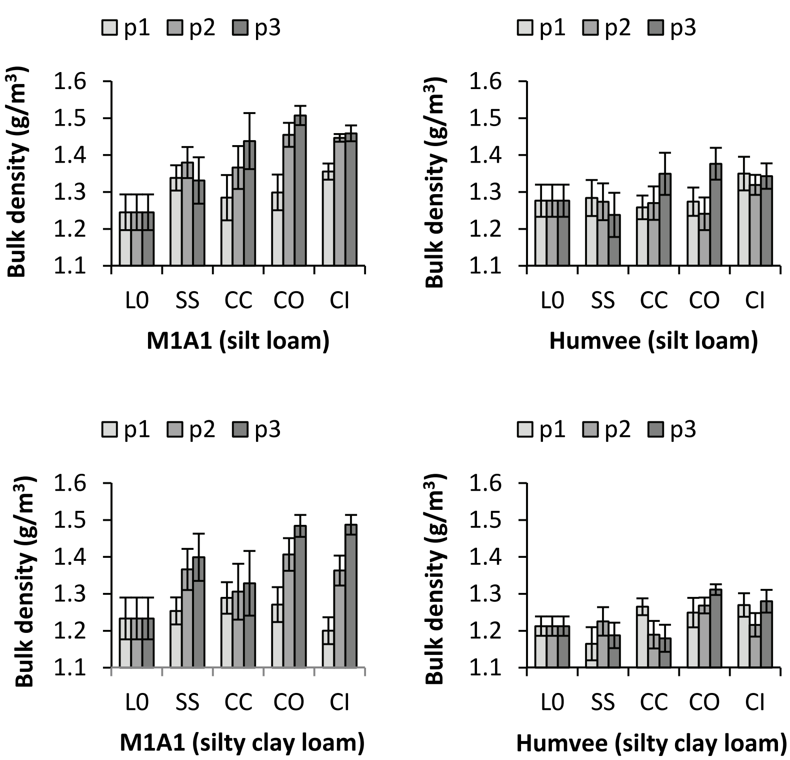

Figure 3. Bulk density (0-15 cm) from different locations in the M1A1 and Humvee tracks; p1, p2, and p3 represent 1, 5, and 10 passes for the M1A1 and 10, 25, and 50 passes for the Humvee (L0 = untrafficked, SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Error bars are also shown.

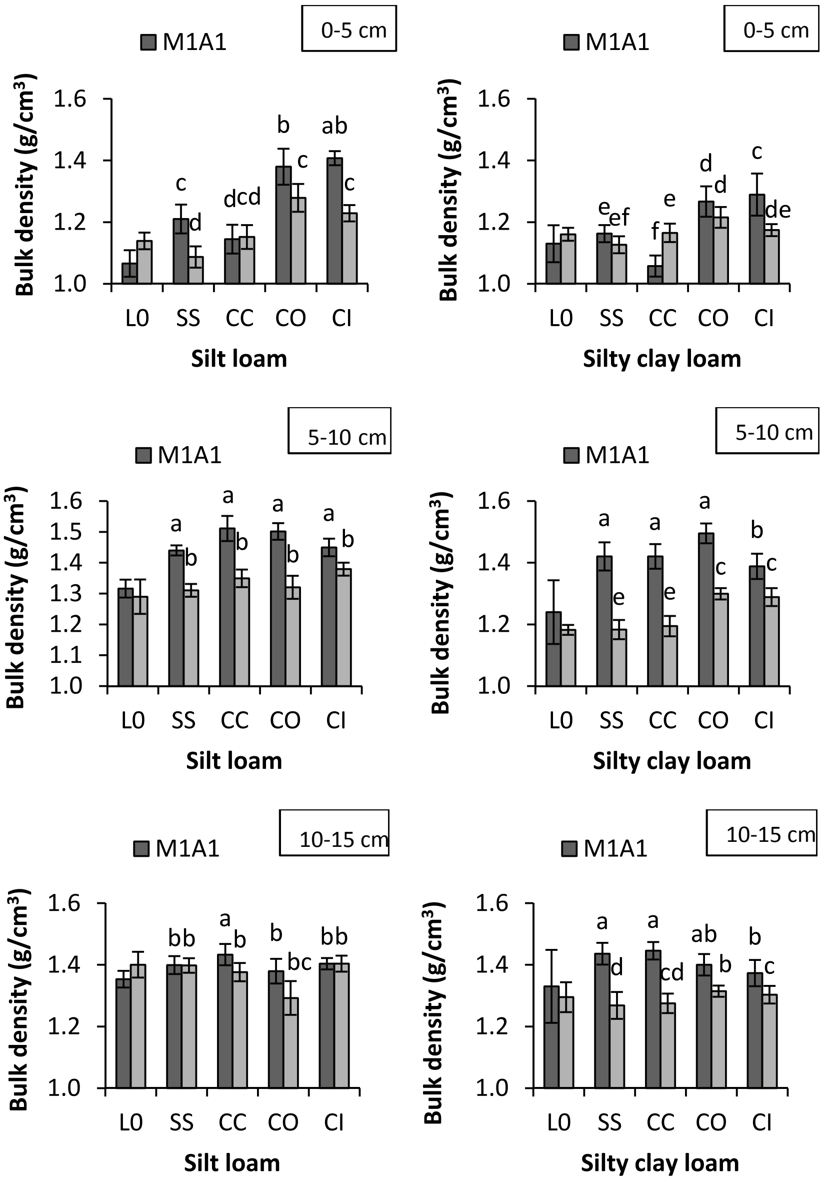

Figure 4. Vehicle × Location × Depth interaction was significant for both soils under M1A1 and Humvee tracks at different depths and sampling locations (SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). L0 (mean bulk density from an undisturbed location) is included for visual comparison and was not part of the analysis of variance. Error bars are also shown.

significant in both soils. In the curved tracks (CO and CI), differences between the M1A1 and Humvee were greater. This is again likely due to the M1A1's greater mass and its tendency to remove more of the drier surface layer due to shearing, exposing the wetter and more compressible soil at the surface. Likewise, at the 5-10 cm depth, the bulk density from the M1A1 tracks was significantly greater than from the Humvee tracks at all locations and in both soils. At the 10-15 cm depth, differences in bulk density were not significant at most locations in the silt loam soil but were significant at all locations in the silty clay loam soil (fig. 4). These results suggest that significant soil compaction under the M1A1 extended only to about the 10 cm depth in the silt loam; however, in the silty clay loam soil, compaction due to trafficking was still apparent at the 15 cm depth.

Relative Bulk Density Changes in Trafficked Locations

Effects of vehicular traffic on bulk density were analyzed in the previous paragraphs, and differences attributable to different factors were examined. However, it is necessary to determine whether there were significant differences between bulk densities before and after trafficking. To this end, a data set was generated using equation 1, in which bulk density differences between disturbed (trafficked) and undisturbed (control or untrafficked) were expressed as a fraction of the control (Althoff et al., 2009):

$$Y = (BD_T - BD_c)/BD_c \qquad (1)$$

where Y is bulk density disturbance index, BD_C is bulk density of controls, and BD_T is bulk density of tracked plots.

The analysis of variance table (not included) for these

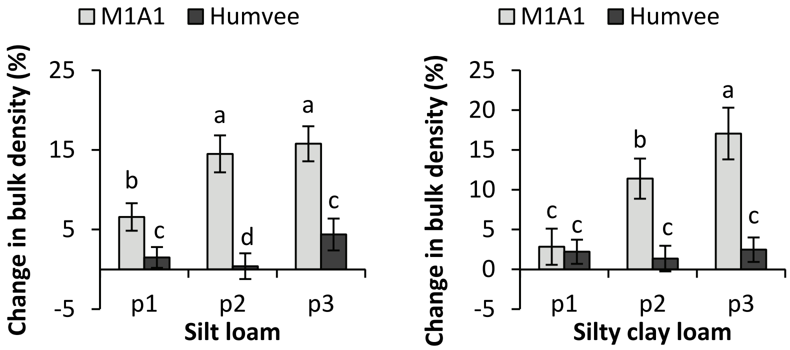

Figure 5. Vehicle × Pass interaction on relative changes in bulk density (0-15 cm) on the silt loam and silty clay loam soils. Passes p1, p2, and p3 represent 1, 5, and 10 passes for the M1A1 and 10, 25, and 50 passes for the Humvee. Bars with different letters within soil groups are significantly different ($p \le 0.05$); error bars are also shown.

data indicates that the Vehicle × Pass, Vehicle × Depth, Pass × Location, and Vehicle × Location × Depth interactions were significant in both soils ($p \le 0.05$). The Vehicle × Pass interaction is shown in figure 5. In the M1A1 tracks, in the silt loam soil, the bulk density (averaged over all locations and depths) was greater by 7%, 14%, and 16% after pass levels p1, p2, and p3 than the undisturbed bulk density, respectively. Similarly in the silty clay loam soil, the bulk density was greater by 3%, 11%, and 17% after pass levels p1, p2, and p3, respectively. Increases in the Humvee tracks were small and ranged from 0.4% to 4%.

The Vehicle × Location × Depth interaction is plotted in figure 6. The bulk density of the 0-5 cm depth from the M1A1 tracks in the silt loam soil rose by 14%, 7%, 29%, and 32% in the SS, CC, CO and CI locations. Similar increases by location were 9%, 15%, 14%, and 10%, respectively, at the 5-10 cm depth and 3%, 6%, 2%, and 4%, respectively, at the 10-15 cm depth. Bulk density increases in the silty clay loam soil were mostly similar to the response in the silt loam soil but were somewhat less. During the first turning pass, the M1A1 formed a rut as deep as 5 cm, which exposed a wetter soil that was more susceptible to compaction due to higher soil water content. Thus, the relatively large differences between pre- and post-trafficking

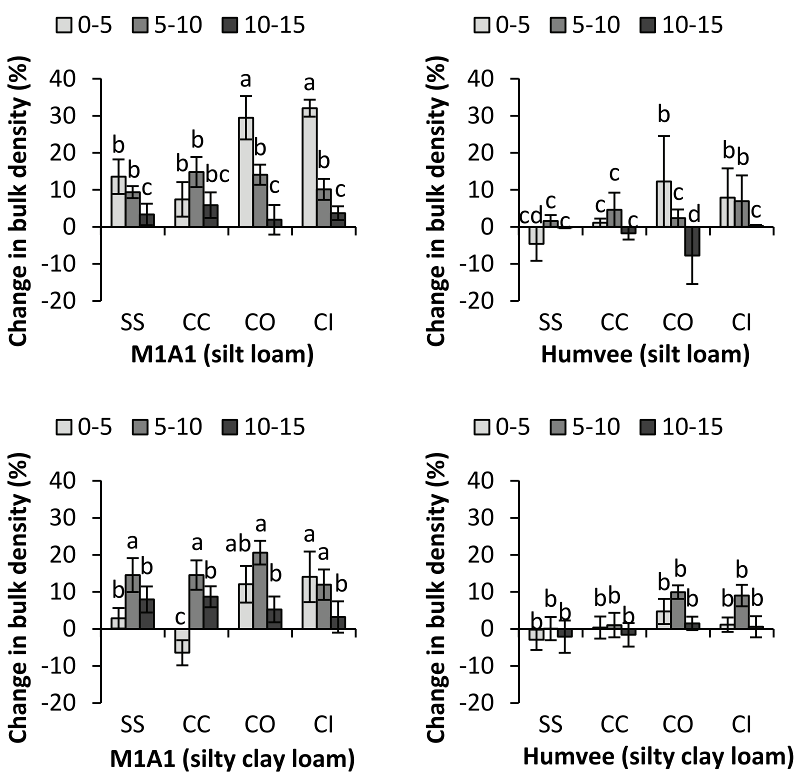

Figure 6. Interactive effects of Vehicle × Location × Depth on relative changes in bulk density expressed as a percentage of the control bulk densities for the silt loam and silty clay loam soils (SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Bars with different letters within soil groups are significantly different ($p \le 0.05$); error bars are also shown.

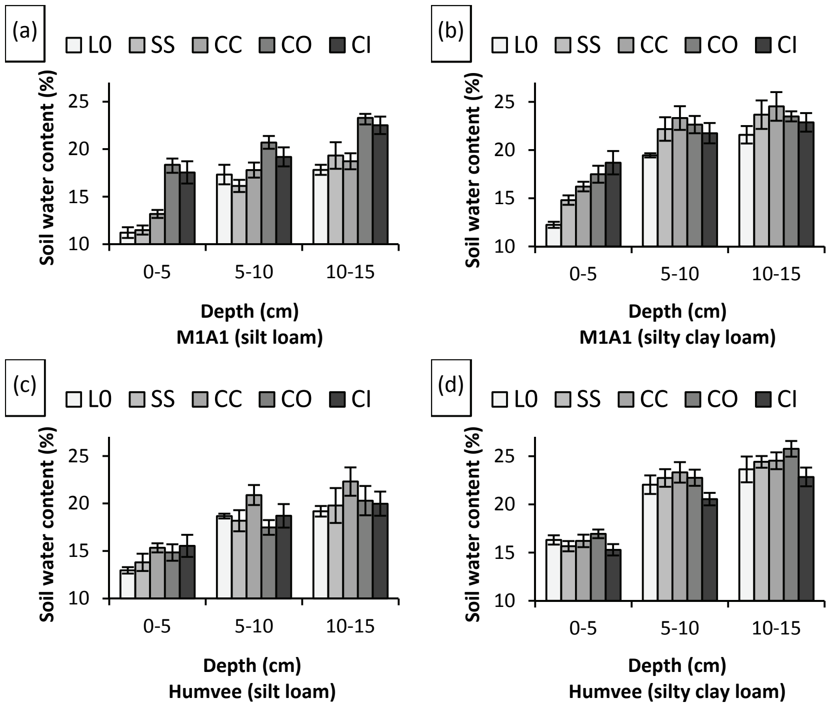

Figure 7. Soil water content at different depths and locations from the (a and b) M1A1 and (c and d) Humvee tracks in the (a and c) silt loam and (b and d) silty clay loam soil (LO = untrafficked, SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Error bars are also shown.

bulk density may partly be a reflection of the fact that a portion of the soil surface was sheared off and displaced to the side during turning by the M1A1 tank treads. In the Humvee tire tracks, bulk density increases in the 0-5 cm depth in the silt loam soil were -5%, 1%, 12%, and 8% in the SS, CC, CO, and CI locations, respectively, which are much less than the changes in the M1A1 tracks. However, even for the Humvee, the trend was for greater compaction in the curved portions of the figure-eight track, which was likely partially due to the displacement of some soil at the surface in those regions as well.

SOIL WATER CONTENT

The analysis of variance of soil water content (gravimetric) data indicates that soil moisture varied significantly by vehicle type, location within vehicle tracks, and soil depth depending on the soil type. In the silt loam, Vehicle × Location was highly significant ($p \leq 0.01$), but not in the silty clay loam. Vehicle × Depth was highly significant ($p \leq 0.01$) in the silty clay loam soil, but not in the silt loam. Although Vehicle × Location × Depth was not significant in either soil, it conveniently summarizes the changes in soil water resulting from vehicular traffic (fig. 7). At the 0-5 cm depth, in the M1A1 tracks, water content steadily rose, with the highest water content in the curved sections. There did not appear to be any increases in water content in the Humvee tracks.

To provide a clearer picture of the extent of changes in water content brought about by trafficking, a data set was generated using equation 2, in which changes in water content after trafficking were expressed as a fraction of the water content before trafficking, and subjected to analysis of variance:

$$Z = (WC_f - WC_c)/WC_c \qquad (2)$$

where Z is water content change index, WC_c is water content of controls, and WC_f is water content of tracked plots. In both soils, the Vehicle × Location and Vehicle × Depth effects were highly significant ($p \leq 0.01$).

Water content increased to some degree in all locations with increasing depth and for both vehicles, except at CI in the Humvee tracks. In the M1A1 tracks, the increase in soil water content at the curved sections was much greater than at the straight locations. Differences in the changes in water content between the M1A1 and Humvee tracks were much greater in the curved sections than in the straight sections of the track (fig. 8). At the 0-5 cm depth, the water content change in the M1A1 tracks was significantly greater than in the Humvee tracks (fig. 9). Differences in changes in water content between the M1A1 and Humvee tracks at the 5-10 cm and 10-15 cm depths were not significant (fig. 9).

The relatively high changes in water content (mirroring the changes in bulk density discussed earlier) in the 0-5 cm depth at the curved sections of the M1A1 tracks were definitely a reflection of the displacement of the soil surface due to lateral shear during turning, thus exposing a wetter soil surface. These observations are similar to those made by Althoff and Thien (2005).

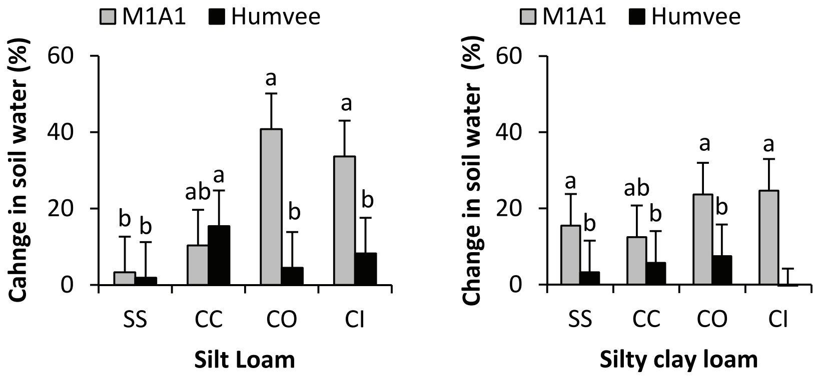

Figure 8. Vehicle × Location interaction of the relative changes in soil water content (0-15 cm) under the M1A1 and Humvee tracks at different locations in the silt loam and silty clay loam soils (SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Bars with different letters within soil groups are significantly different (p ≤ 0.05); error bars are also shown.

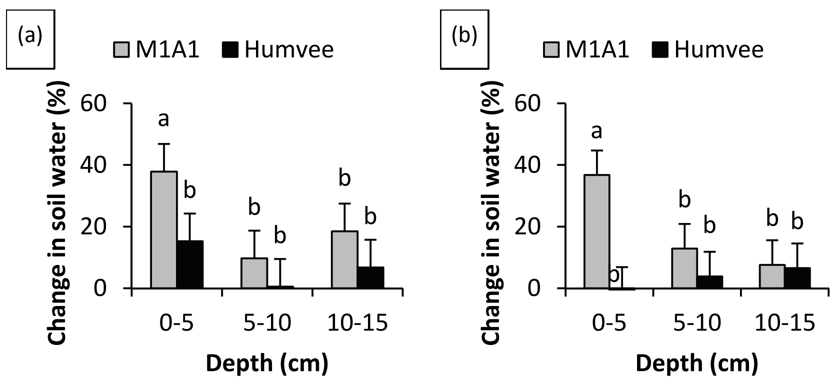

Figure 9. Vehicle × Depth interaction of the relative changes in moisture content in the (a) silt loam and (b) silty clay loam soils. Bars with different letters within soil groups are significantly different (p ≤ 0.05); error bars are also shown.

BIOMASS AND COVER

Analysis of variance of biomass data shows that the main effects of pass and location were significant ($p \leq 0.01$) in both soils. In the silty clay loam soil, two-way interactions of Vehicle × Location and Passes × Location were highly significant ($p \leq 0.01$). In addition, in the silty clay loam soil, the Vehicle × Passes × Location interaction was highly significant ($p \leq 0.01$) and is represented in the bottom graphs of figure 10.

The Vehicle × Passes × Location interaction in the silt loam soil, although not significant, is included in figure 10 for comparative purposes. In the curved sections of the track, standing biomass was virtually reduced to zero by both vehicles (fig. 10). In both soils, the trends were essentially the same. In most of the straight section of the tracks (SS and CC), biomass was progressively reduced as the trafficking passes were increased. In the curved sections (CO and CI), standing biomass was reduced to almost zero after passes p1 or p2. These data indicate that both vehicles degraded the standing biomass to similar levels.

Analysis of variance of vegetative cover indicates that the main factors of vehicle type, trafficking passes, and location within vehicle tracks were significant in silt loam, but only location was significant in the silty clay loam soil ($p \leq 0.05$). Interactive effects of Vehicle × Location (fig. 11) and Pass × Location (fig. 12) were significant ($p \leq 0.01$) in both soils. At the straight location (SS), cover was nearly 100% under both vehicles and in both soils. This is because the vehicles flattened standing biomass but did not redistribute or remove residue from the surface. Cover at the curved (CO and CI) locations was significantly reduced by both vehicles, but there was significantly ($p \leq 0.05$) more cover in the Humvee tracks (40%) than in the M1A1 tracks (20%). Due to the excessive lateral shear on the turns by the M1A1 tank treads, a greater amount of the vegetation and soil from the surface were displaced than with the Humvee. There was no significant response in plant cover to vehicle passes over the straight section; however, at the curved sections, cover was reduced after each set of passes, with the largest reduction occurring after the first and second pass levels (p1 and p2), as shown in figure 12. The cover data indicate that disturbance to vegetation due to trafficking is less severe than is indicated by the biomass data. The cover data include standing, flat, and detached vegetation, while the biomass data consist of only the standing vegetation or vegetation that was not detached from its roots. Additionally, biomass data were obtained from smaller, 0.25 m^2 regions of the curved section of the tracks, whereas the step-point method for obtaining cover data necessitated data collection over a much larger (longer) portion of the curved section of the tracks.

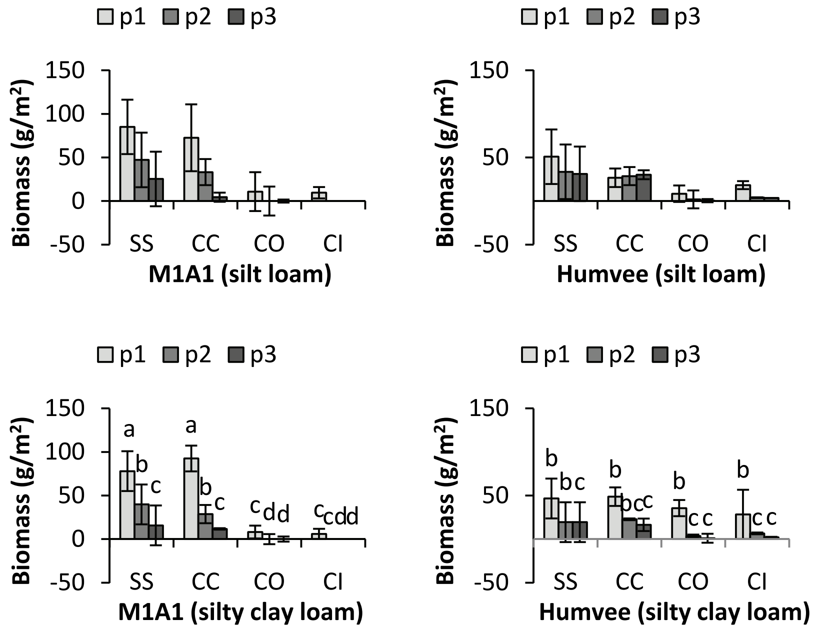

Figure 10. Vehicle × Pass × Location interaction of standing biomass; p1, p2, and p3 represent 1, 5, and 10 passes for the M1A1 and 10, 25, and 50 passes for the Humvee (SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Bars with different letters within soil groups are significantly different ($p \leq 0.05$); error bars are also shown.

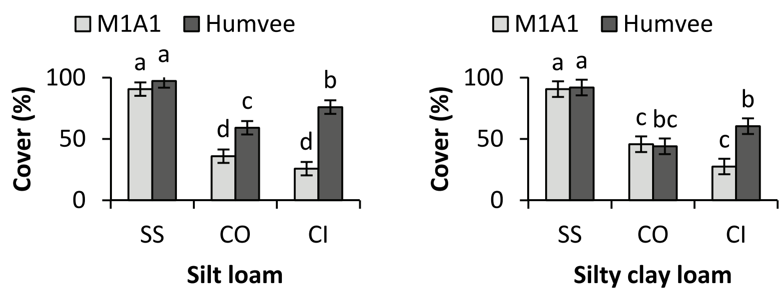

Figure 11. Vehicle × Location interaction for biomass cover from the two soils for each vehicle. Sampling locations: SS = straight section, CO = curve outside track, and CI = curve inside track. Bars with different letters within soil groups are significantly different ($p \leq 0.05$); error bars are also shown.

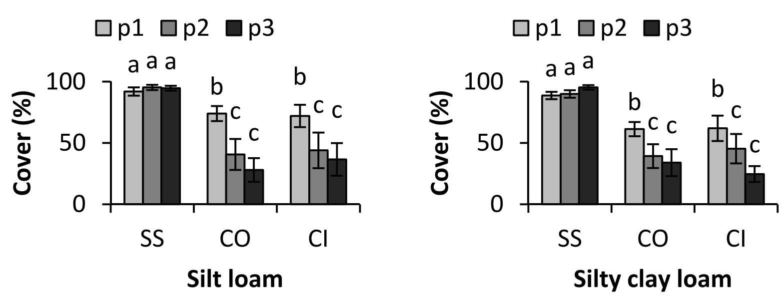

Figure 12. Pass × Location interaction for biomass cover from the silt loam and silty clay loam soils; p1, p2, and p3 represent 1, 5, and 10 passes for the M1A1 and 10, 25, and 50 passes for the Humvee (SS = straight section, CO = curve outside track, and CI = curve inside track). Bars with different letters within soil groups are significantly different ($p \leq 0.05$); error bars are also shown.

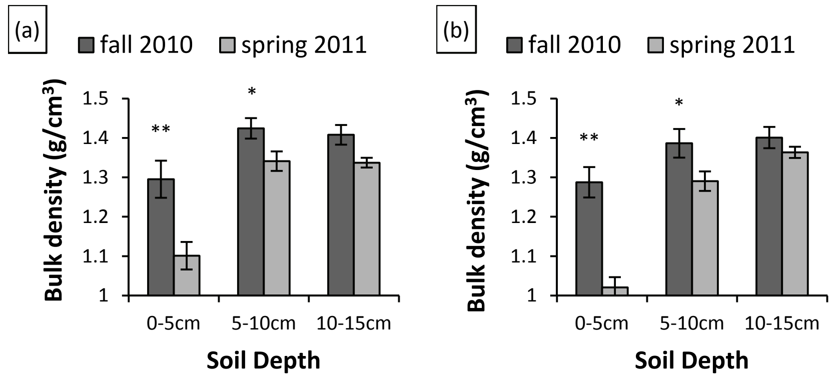

Figure 13. Comparison of fall and spring bulk density by depth from the (a) silt loam and (b) silty clay loam soils. Asterisks indicate significant differences at p = 0.05 (*) and p = 0.01 (**); error bars are also shown.

Table 3. PROC MIXED analysis of variance of vegetation sampled in the spring and summer following trafficking the previous fall in 2010.

Sampling Date	Parameter	Soil Type	Effect	Num DF	Den DF	F-Value	Pr > F
6 June 2011	Grass biomass	Silt loam	Vehicle (V)	1	2	4.88	0.1579
			Location (L)	4	16	22.38	<.0001
			V × L	4	16	4.86	0.0093
		Silty clay loam	Vehicle (V)	1	2	0.13	0.7573
			Location (L)	4	18	5.36	0.0051
			V × L	4	18	2.66	0.0665
	Forb biomass	Silt loam	Vehicle (V)	1	2	0.28	0.6521
			Location (L)	4	16	2.54	0.0804
			V × L	4	16	0.47	0.7593
		Silty clay loam	Vehicle (V)	1	2	9.31	0.0927
			Location (L)	4	18	1.6	0.2181
			V × L	4	18	0.26	0.9011
8 August 2011	Grass biomass	Silt loam	Vehicle (V)	1	2	1.58	0.3352
			Location (L)	2	8	6.81	0.0188
			V × L	2	8	1.69	0.2434
		Silty clay loam	Vehicle (V)	1	2	1.26	0.3782
			Location (L)	1	8	3.81	0.0688
			V × L	1	8	0.79	0.4871
	Forb biomass	Silt loam	Vehicle (V)	1	2	2.67	0.2442
			Location (L)	2	8	0.13	0.8758
			V × L	2	8	0.11	0.8932
		Silty clay loam	Vehicle (V)	1	2	1.21	0.3866
			Location (L)	2	8	1.68	0.2455
			V × L	2	8	2.13	0.1807

Recovery of Bulk Density and Vegetation

Freeze/Thaw Effects on Bulk Density

Bulk density samples were taken on 6 April 2011 from all the sampling segments sampled in the fall of 2010. Analysis of variance was performed using the PROC MIXED procedure in SAS. In both soils, the Season × Depth interaction was significant ($p \leq 0.05$). Bulk densities at the 0-5 cm and 5-10 cm depths at all sampling locations for both vehicles taken in the spring were significantly ($p \leq 0.05$) less than those taken in the fall (fig. 13), implying that the winter freeze and thaw cycles loosened the upper layers. The effect of the freeze and thaw cycles on the 10-15 cm layer was not significant.

Spring and Summer Biomass Growth

Analysis of variance was performed on grass and forb biomass data collected on 6 June and 8 August 2011 (table 3). For the data taken on 6 June 2011, there was significant Vehicle × Location interaction for grass biomass in the silt loam soil ($p < 0.01$) and, to a lesser extent, in the silty clay loam soil ($p \leq 0.07$) (table 3). In the M1A1 tracks, spring grass growth showed large differences between the different locations (fig. 14). Spring vegetation growth in the Humvee tracks was significantly less than the control, but differences between locations did not show a consistent trend (fig. 14). In the curved sections, grass growth in the Humvee tracks was consistently greater than in the M1A1 tracks. In the analysis of variance test of forb biomass in the spring, Vehicle and Location effects or their interactions were not significant ($p < 0.05$). However, in the silty clay loam soil, forb biomass was consistently lower in the M1A1 tracks than in the Humvee tracks (fig. 15).

Analysis of variance of grass biomass data, sampled on 8 August 2011, showed that the Location effect was significant at $p \leq 0.05$ in the silt loam and significant at $p \leq 0.07$ in the silty clay loam. Vehicle × Location was not significant (table 3). Forb biomass did not show significance for Vehicle, Location, or their interactions (table 3). Graphical representation of component biomass by vehicle and location is shown in figure 16 for grass species, figure 17 for forb species, and figure 18 for total aboveground biomass.

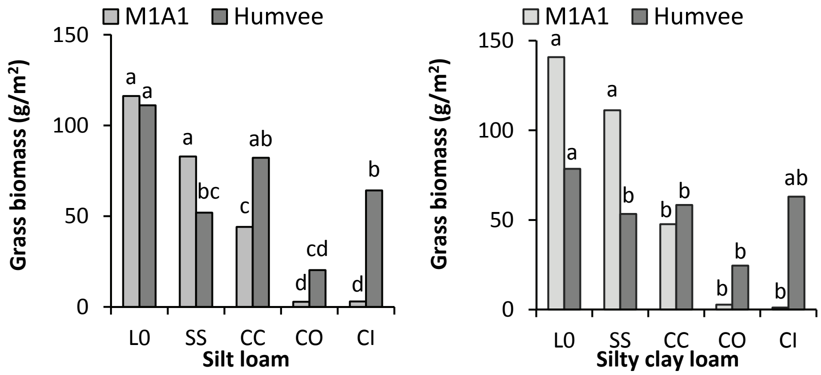

Figure 14. Vehicle × Location interaction of dry weight of grass species (L0 = untrafficked, SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Sampling date was 6 June 2011. Bars with different letters within soil groups are significantly different ($p \leq 0.05$).

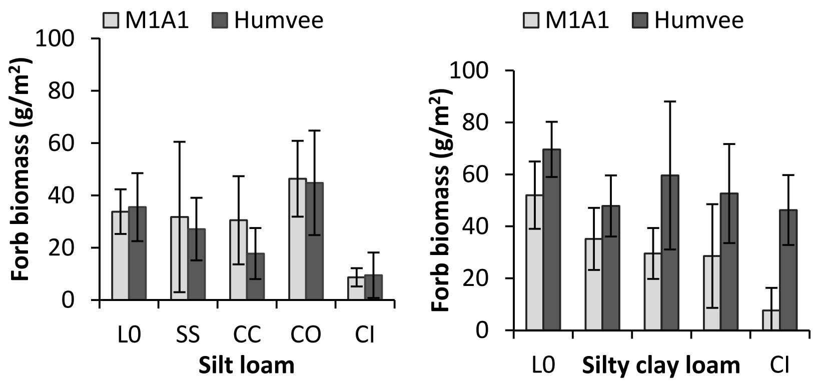

Figure 15. Vehicle × Location interaction of dry weight of forb species was not significant ($p \leq 0.05$) (L0 = untrafficked, SS = straight section, CC = center cross, CO = curve outside track, and CI = curve inside track). Sampling date was 6 June 2011. Error bars are also shown.

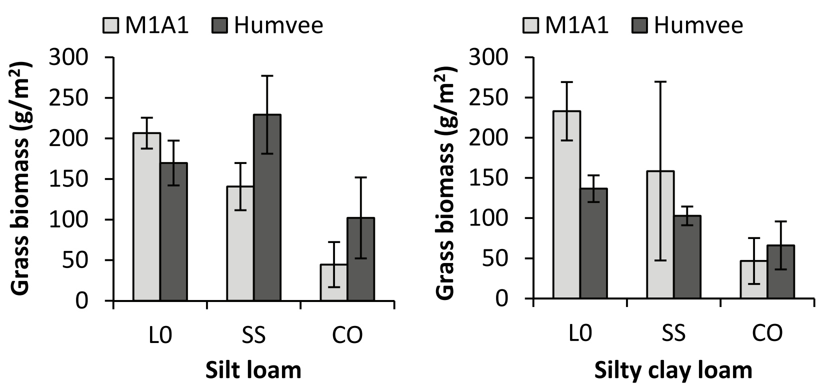

Figure 16. Dry weight of grass species at different locations (L0 = untrafficked, SS = straight section, and CO = curve outside track). Sampling date was 8 August 2011. Error bars are also shown.

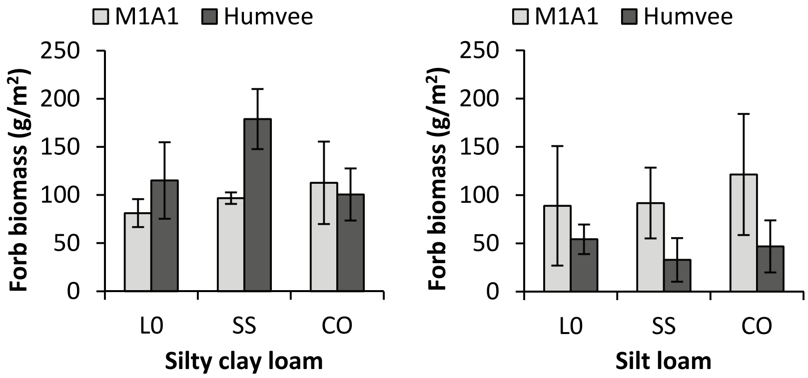

Figure 17. Dry weight of forb species at different locations (L0 = untrafficked, SS = straight section, and CO = curve outside track). Sampling date was 8 August 2011. Error bars are also shown.

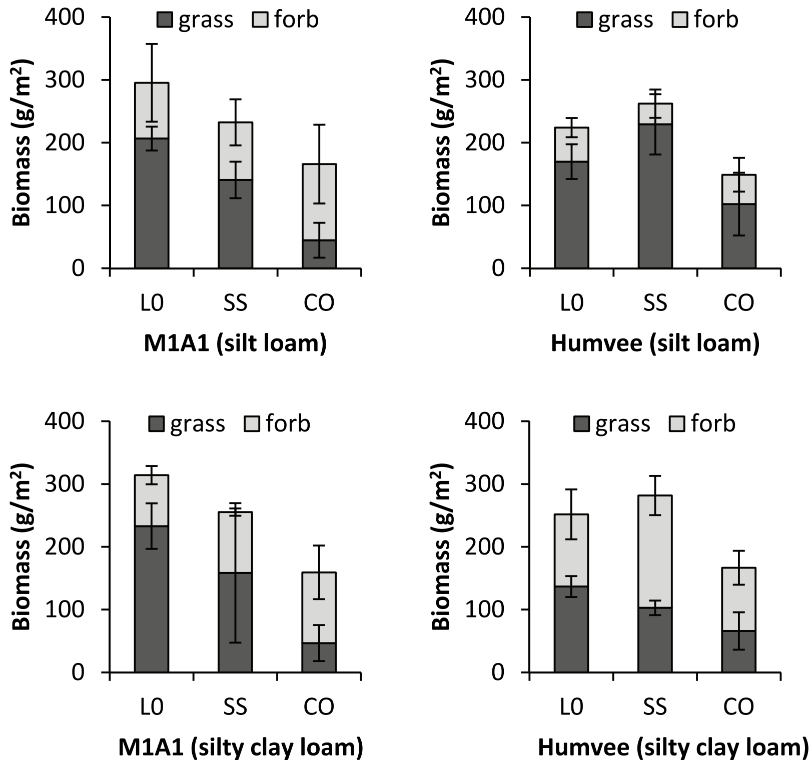

Figure 18. Average aboveground biomass at different locations in the silt loam and silty clay loam soils (L0 = untrafficked, SS = straight section, and CO = curve outside track). Sampling date was 8 August 2011. Error bars are also shown.

Summary and Conclusions

Bulk density under the M1A1 tank was generally greater than under the Humvee at all track locations and soil depths. As the number of passes increased, bulk density under the M1A1 increased significantly, whereas increases in the Humvee were much smaller. The contrast between the two vehicles becomes clearer when changes in bulk density relative to the undisturbed status are compared. Overall relative increase in bulk density in the M1A1 tracks was 16%, and about 2% in the Humvee tracks. However, the increases in bulk density were much greater in the curved sections of the track than in the straight sections, likely due to shearing and removal of the drier surface soil exposing the wetter, more compactable soil beneath with the M1A1. The weight of a vehicle is one of the primary factors for determining the degree of soil compaction (Ayers, 1994; Anderson et al., 2007). In spite of the fact that the Humvee traveled at much faster speeds and made 50 passes, while the M1A1 made only 10 passes traveling at much lower speeds, the weight difference between the M1A1 and the Humvee may largely account for the differences in their impacts on bulk density. The greater bulk densities under the M1A1 tracks were registered at the 0-5 cm and 5-10 cm depths in the silt loam soil and at the 0-5 cm, 5-10 cm, and 10-15 cm depths in the silty clay loam soil. The greater moisture content in the silty clay loam soil may have made it more susceptible to compaction to greater depths than the silt loam soil. Results of this study, which showed significant increases in bulk density under the M1A1 tracks, were similar to those reported by Halvorson et al (2003) and Althoff and Thien (2005), although depths of bulk density measurements were not identical. Lindsey et al. (2012), in experiments similar to ours, did not find significant compaction at the 20 cm depth.

Bulk densities at the 0-5 cm and 5-10 cm layers were lower in the spring than in the fall, which is likely an indication of the ameliorating effects of the winter freeze/thaw and spring wet/dry cycles.

Reductions in biomass, relative to undisturbed samples, on the average ranged from 83% in the straight sections to 99% in the curved sections for both vehicles. Standing biomass appears to be a stronger indicator of vehicle damage to vegetation than cover data. However, the cover data included areas of the less damaged part of the curved section, whereas biomass was taken from a smaller area of the more damaged part of the curved track.

Grass spring growth was severely retarded in the curved sections of the M1A1 tracks but showed considerable recovery during the summer. Forb growth in the spring and summer did not show significant ($p \leq 0.05$) response to trafficking.

The results of this investigation, in conjunction with similar data from experiments that are planned at various military bases across the U.S., will allow the development of appropriate relationships that can be incorporated into WEPS. Bulk density is an important soil property that is used in the hydrology and soils subroutines of WEPS. Thus, it is necessary to obtain relationships that can be used to indicate how bulk density changes in response to different repeated trafficking scenarios. Similarly, obtaining patterns of loss of vegetative cover that occur under military trafficking is critical before WEPS can be used to aid in evaluating training programs that minimize adverse impacts on the environment.

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