MILITARY VEHICLE TRAFFICKING IMPACTS ON VEGETATION AND SOIL BULK DENSITY AT FORT BENNING, GEORGIA

A. Retta, L. E. Wagner, J. Tatarko

ABSTRACT. *Potential increases in wind erosion that might be brought about by military vehicles traveling off-road during training are of concern to the U.S. military because wind erosion and vehicle dust emissions contribute to land and air quality degradation and can cause adverse effects on respiratory health. Field studies were conducted in the summer of 2012 at Fort Benning, Georgia, to assess the effects of military vehicle trafficking intensity on susceptibility to dust emissions. Quantitative data on soil and vegetation parameters are needed to make appropriate estimates of the susceptibility to dust generation from the soil surface and the magnitude of those emissions. The experiment consisted of making multiple trafficking passes with both tracked and wheeled vehicles and then measuring wind erosion parameters. A tracked (M1A1) and wheeled (HMMWV) vehicle were driven in a figure-8 pattern within replicated 40 m $\times$ 80 m plots. On each plot, three levels of vehicle passes were made. On the tracked plots, the M1A1 was driven a cumulative total of 1, 5, and 10 passes. On the wheeled plots, the HMMWV was driven a cumulative total of 10, 25, and 50 passes. The vehicles were driven repeatedly over the same figure-8 path. Bulk density, aboveground biomass, and vegetative cover data were taken from the straight, curved, and cross-over sections of the vehicle tracks. Samples were also taken before the start of trafficking. Bulk density at three depths, total aboveground biomass, grass biomass, forb biomass, biomass by individual species, total cover, grass cover, and forb cover data were analyzed for differences between vehicles, vehicles passes, locations within the track sections, and their interactions. At the 5 cm depth, bulk density was significantly higher ($p \leq 0.05$) than the control in both the M1A1 and HMMWV tracks. There was no significant evidence of soil compaction below 5 cm. At the end of all trafficking, grass and forb species biomass was reduced 65% to 100%. Vegetation cover showed strong response to vehicle type, trafficking intensity, location (within the vehicle tracks), and their interactions. Regression equations relating trafficking intensity by vehicle to reduction in cover and biomass were obtained.*

Keywords. *Biomass, Cover, WEPS, Wind erosion.*

Recent environmental assessment reports (U.S. Army, 2007) indicate that vehicular travel can generate large amounts of dust both during the trafficking events and afterwards by leaving trafficked areas more susceptible to wind erosion. This leads to possible increases of PM_{10} and $PM_{2.5}$ (particulate matter smaller than 10 and 2.5 μm, respectively) loads in the area, which in some cases may lead to non-attainment of the EPA National Ambient Air Quality Standard (NAAQS) (USEPA, 1996) in nearby towns and cities (U.S. Army, 2007). The U.S. Army controls more than 10 million ha of land, a large part of which is devoted to training (Anderson et al., 2007), with Fort Benning currently having 17,454 ha of mechanized training area out of 46,210 ha of total training area (GlobalSecurity, 2011). The use of tracked and wheeled vehicles of various kinds is an integral part of military training exercises. However, repeated use of military vehicles on training maneuvers can damage vegetation, destroy the vegetative cover, and compact the soil, thus making the land more susceptible to soil erosion (Anderson et al., 2005) and potentially rendering the land unsuitable for training. An evaluation of the lands subjected to tracked vehicle traffic at many Army installations in the U.S. indicated that most locations suffered, among other impacts, loss of vegetative cover as well as compacted soil (Goran et al., 1983; Althoff et al., 2009; Althoff et al., 2010). Specifically, at Fort Benning, Garten et al. (2003) also found low organic matter (0.17% C) and higher bulk densities (1.53 g cm^{-3}) in the trafficked areas compared to un-trafficked areas (0.98% C and 1.38 g cm^{-3}).

Over the years, the U.S. Department of Defense has sponsored many research projects aimed at developing scientifically based methods for management of military training lands, so that the lands can remain sustainable for Army training exercises for as long as possible while minimizing adverse consequences. Susceptibility to wind erosion increases with decreases in vegetative cover (Hagen, 1996). Any activity that decreases cover creates more favorable

Submitted for review in July 2013 as manuscript number SW 10327; approved for publication by the Soil & Water Division of ASABE in July 2014. Presented at the 2013 ASABE Annual Meeting as Paper No. 131599028.

Mention of company or trade names is for description only and does not imply endorsement by the USDA. The USDA is an equal opportunity provider and employer.

Contribution No. 13-318-J from the Kansas Agricultural Experiment Station.

The authors are **Amare Retta,** Soil Scientist, **Larry E. Wagner, ASABE Member,** Agricultural Engineer, and **John Tatarko,** Soil Scientist, USDA-ARS Engineering and Wind Erosion Research Unit, Manhattan, Kansas. **Corresponding author:** Larry Wagner, USDA-ARS EWERU, 1515 College Ave., Manhattan, KS 66502; phone: 785-537-5544; e-mail: larry.wagner@ars.usda.gov.

conditions for wind erosion and vehicle dust emissions. Military vehicle trafficking inevitably decreases vegetative cover, the severity of which depends on many factors including: (1) vehicle type, weight, track and wheel (tire tread) design, speed, and turning radius; (2) soil type and moisture content; (3) amount and stage of vegetative growth; and (4) type of vegetative cover, etc. (Ayers, 1994; Anderson et al., 2007). It is virtually impossible to design a field experiment that can encompass all the relevant factors that influence the impact of trafficking on the short-term and long-term condition of the vegetation.

A limited number of field experiments have been executed in which only a few of the dominant wind erosion factors were studied using appropriate statistical designs to obtain soil and vegetation impact data with enough detail that could be used in modeling (Wilson, 1988; Althoff and Thien, 2005). Thus, the objectives of this experiment were to: (1) determine relative military vehicle multi-pass trafficking impacts and (2) determine initial relationships for changes in soil bulk density and vegetation as a function of vehicle type, traffic intensity, and patterns of trafficking (e.g., straight vs. curved) that would be useful for modeling.

The Wind Erosion Prediction System (WEPS) model (Wagner, 2013) developed by the USDA Agricultural Research Service (USDA-ARS) is a state-of-the-art, process-based, daily time step wind erosion model targeted initially for use on cultivated agricultural lands. It simulates hydrology, plant growth and decomposition, land management, and soil surface erodibility to simulate soil erosion loss by wind as affected by stochastically simulated local weather (Hagen, 2004). WEPS outputs provide estimated losses in terms of total (<2.0 mm), saltation and creep (2.0 to 0.1 mm), suspension (<0.1 mm), and PM_{10} particle sizes. Simulating the physical effects of military vehicle trafficking on the soil surface and vegetation could allow WEPS to become useful for military land managers to assess different training scenarios for wind erosion susceptibility.

The amount of dust that can be blown by wind is partially dependent on the vegetation structure covering the soil surface. Grantham et al. (2001) found a linear correlation between tracked vehicle trafficking intensity and the reduction in aerial cover, which in turn was linearly correlated to the threshold wind speed. WEPS uses different coefficients to account for the fact that flat vegetation provides less protection from wind erosion than standing vegetation (Hagen, 1996). Vehicle trafficking changes standing vegetation into mostly flat vegetation, some of which may become completely detached from its roots due to repeated trafficking or shearing of the surface during vehicle turns. Loose, flat vegetation gets readily blown by the wind and does not provide much protection from wind erosion. WEPS can simulate the flattening of vegetation as an operation (vehicle) effect by simulating this process using the necessary parameters provided in the operation record.

Another important aspect that needs to be evaluated is whether different species exhibit different levels of damage. Tank traffic may significantly alter species composition and resiliency depending on the intensity of trafficking (Wilson, 1988; Palazzo et al., 2005; Althoff et al., 2009). WEPS can be adapted as a decision-making tool in developing site-specific training schedules that minimize adverse impacts of excessive loss of vegetative cover and provide reasonably accurate estimates of increases in PM_{10} emissions from wind erosion resulting from training activity effects on the land.

Availability of suitable data for use with WEPS is currently limited at most Army installations. To fill this knowledge gap, a project was initiated whereby field experiments of similar design were to be implemented at military bases in different geographical and climatic regions of the country that were particularly susceptible to wind erosion emissions. The first of these field experiments was conducted at Fort Riley in October 2010, and the results on vegetation and bulk density effects were reported by Retta et al. (2013). The second field experiment (which is the object of this study) was conducted in July 2012 at Fort Benning, Georgia, where, as at Fort Riley, soil, vegetation, and surface condition data before and after vehicular trafficking were obtained. Additional sites are the Yakima Training Center in Washington and the White Sands Missile Range in New Mexico. Data collected were bulk density, biomass, and vegetative cover before and after different trafficking intensities using different vehicle types. Soil data were collected, including aggregate size distribution, loose material on the surface, and surface roughness. In addition, Portable In-Situ Wind Erosion Laboratory (PI-SWERL) (Etyemezian et al., 2007) data, including wind tunnel tray samples, were also taken to determine the change in the soil surface's susceptibility to wind erosion, but these data are not discussed in this article.

Initial functional relationships (e.g., between both vegetative cover and biomass reduction and trafficking intensity) obtained from this experiment, later to be revised with additional data from other sites, will be incorporated into WEPS for use in the assessment of wind erosion emissions that may result from military training activities at Fort Benning and other military installations with similar environments.

METHODS AND MATERIALS

SITE DESCRIPTION

Fort Benning, the site of this experiment (Rowan Hill region), has a warm and humid temperate climate with a mean annual temperature of 18.3°C and precipitation of 130 cm (Garten and Ashwood, 2004). Vegetation consists of areas of grasses, forbs, small shrubs, and sparse small trees interspersed among longleaf pine. The soil is a Troup loamy sand (eroded, loamy, kaolinitic, thermic Grossarenic Kandiudult) (USDA, 2013). The Rowan Hill site (32° 24′ 13.8″ N, 84° 45′ 21″ W; elevation 145 m) had visible evidence of considerable disturbance on the surface. It was used for training until 1991 and has had little or no traffic since (Shannon Danley, personal communication). The average vegetation cover at baseline sampling (taken on 21-22 July 2012) was 65% with patches of bare or sparsely vegetated soil using the line transect method (Sloneker and Moldenhauer, 1977). Figure 1 shows the typical initial veg-

Figure 1. Typical vegetation and surface conditions at the Fort Benning (Rowan Hill) experimental site.

etation and surface conditions at the Fort Benning Rowan Hill site.

Particle size analysis of soil samples collected from the top 5 cm depth before the start of trafficking indicate that the surface soil texture is classified as sand, with 2.77% clay (SD = ±1.00%), 9.54% silt (±1.73%), and 87.69% sand (±2.43%). The initial water content of the surface soil (top 5 cm) and its bulk density were 2.31% (±1.42%) and 1.61 g cm^{-3} (±0.17 g cm^{-3}), respectively. The Proctor density (PD) of the soil was 1.82 g cm^{-3} (±0.05 g cm^{-3}) at an optimum water content (OWC) of 8.57% (±0.45%) per ASTM Standard D698 (ASTM, 2007).

VEHICLE DESCRIPTIONS

Two military vehicles representing tracked and wheeled vehicles were chosen for the trafficking tests. On the plots for tracked traffic, an M1A1 tank weighing approximately 61,500 kg was used. On the plots designated for wheeled traffic, a model M1151A up-armored High Mobility Multipurpose Wheeled Vehicle (HMMWV), commonly known as a Humvee, weighing approximately 3700 kg was used. Since vehicle weight is expected to influence bulk density, the vehicles chosen for this experiment represent weights near the two extremes of vehicles used in training activities.

PLOT AND TRAFFICKING DESCRIPTIONS

One of the important vehicle factors that affect the severity of the damage to the soil and vegetation, in addition to vehicle mass, speed, and transport system (wheeled vs. tracked), is whether the vehicle is traveling straight or making turning maneuvers. Other researchers have noted that loss of vegetative cover is more severe at points where a vehicle makes sharp turns than when it is traveling straight (Braunack, 1986; Ayers, 1994; Prosser et al., 2000; Anderson et al., 2007).

To represent the type of turns that military vehicles normally make during training maneuvers, a figure-8 pattern on six rectangular 40 m × 80 m plots was followed similar to that of Althoff and Thien (2005) and Retta et al. (2013). The inside turning radius of the vehicles within the figure-8 plots was approximately 10 m. In typical 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 experimental treatments consisted of two vehicle types (a tracked vehicle and a wheeled vehicle), three levels of intensity (number of repeated vehicle passes on the same track), and four sampling locations within the vehicle tracks. The vehicle types were the main plots and were randomized in three plot replications and vehicle passes as repeated measures for statistical analysis.

TRAFFICKING PASS TREATMENTS

The number of passes was established for each vehicle based on test runs representing minimum, medium, and severe relative levels of disturbance (trafficking intensity levels) that would also likely provide measurable differences among the trafficking intensity levels at Fort Riley (Retta et al., 2013). Based on the levels determined at Ft Riley, the same number of treatment passes was used at the Fort Benning experimental site and subsequent sites to facilitate comparisons of the same vehicle across soils and locations. For the M1A1, the three trafficking intensity levels consisted of one pass (designated p1), followed by four passes (p2 = total of five cumulative passes), and then followed by five passes (p3 = 10 total passes). For the HMMWV, the trafficking intensity levels consisted of 10 passes (p1), followed by 15 passes (p2 = 25 passes), and then followed by 25 passes (p3 = 50 passes). It was not the intent of this study to consider vehicle passes to have equal effects between vehicles, but out of general interest we statistically compared the minimum, medium, and severe levels between the two vehicles. However, such comparisons are not intended for inclusion in the WEPS model. The initial, zero pass, un-trafficked condition for both vehicles was designated p0. The M1A1 was driven at a typical off-road maneuvering speed of 8 km h^{-1}, and the HMMWV was driven at approximately 25 to 30 km h^{-1}. However, the speeds were adjusted at the discretion of the driver, with primary consideration of staying within the same vehicle tracks for every pass. Track/tire width and trafficking rut widths are provided in table 1 along with other pertinent vehicle specifications.

Within each of the figure-8 tracks, four sampling locations, representing the straight (SS), center cross (CC), curved outside track (CO), and curved inside track (CI) sections of the track were chosen. A schematic of the different sampling locations is shown in figure 2. The temperature two weeks prior to field sampling (21-22 July 2012 for pre-trafficking and 23-24 July 2012 for post-trafficking) averaged 34°C, with less than 60 mm of total precipitation.

Single measurements and samples were taken after each pass level (p1, p2, and p3) at the four locations shown in figure 2 as well as the initial condition (p0), which was taken in close proximity to each of these locations. These measurements were replicated in three figure-8 plots for each vehicle. Soil samples for dry bulk density, an indicator of soil compaction, were taken after each level of trafficking passes. The core method described by Grossman and Reinsch (2002), with an inner core diameter of 4.83 cm, was used for extracting the soil. The soil cores were split into layers of 0-5 cm, 5-10 cm, and 10-15 cm and stored in soil moisture cans. The soil cores (91.6 cm^3) were weighed before and after drying in an oven at 105°C for at least 48 h. Bulk densities and moisture contents were then calculated.

Table 1. Vehicle specifications and trafficking rut sizes.

Vehicle	Traction Type	Weight (kg)	Speed (km h^{-1})	Track/Tire Width (cm)	Rut Width[a] (cm)
M1A1 Abrams tank	Tracked	61500	8	61	189 ±54 84 ±35
M1151A HMMWV	Wheeled	3700	25-30	32	88 ±29 57 ±9

[a] These values were obtained from the White Sands Missile Range experiment. The upper values represent the average rut width in the curved sampling locations (CO and CI), and the lower values represent the average rut width in the straight sections (SS).

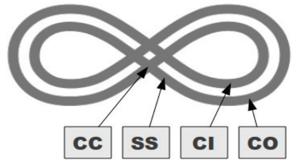


Figure 2. Figure-8 plot with relative sampling locations: CC = center cross, SS = straight section, CI = curve inside track, and CO = curve outside track.

Vegetative cover, and to a lesser extent aboveground biomass, are commonly measured to gauge the impact of vehicular traffic on vegetation. Although much of the vegetation was standing before trafficking, most was flattened due to trafficking. To get an estimate of the influence of vehicle type and vehicle trafficking intensity on the original standing vegetation, a 0.25 m^2 square frame was randomly laid on the track location and both standing and attached flat biomass within the quadrat was clipped to ground level and placed in a bag. Biomass turned into loose or detached flat vegetation by the trafficking, as well as original litter biomass present prior to trafficking, was not included in these samples. The clipped plants were separated by species and placed in individual labeled bags. Plants were dried at 60°C for at least 48 h and weighed.

A more commonly used indicator of plant damage due to trafficking is vegetative cover (e.g., Prosser et al., 2000; Anderson et al., 2007). Vegetative cover can include cover from standing, attached flat, detached flat, and litter biomass. A 15 m long beaded string containing 100 evenly spaced beads (15.2 cm apart) was laid along a sampling track, and plant intersections were counted (Sloneker and Moldenhauer, 1977). All vegetation (standing, detached, and litter) was counted as cover. Individual grass, forb, and woody species were recorded separately, and the total cover from all species was computed. Cover data were not taken at the CC location because the sampling space was too small (~1 m^2) for this method with other repeated destructive sampling also being conducted. Other methods could possibly have been employed in this small space, but additional sampling, such as BD/MC, biomass, and PI-SWERL measurements disturbed the surface, so no cover data sampling was attempted at the CC location. Biomass and cover data were taken for all locations within the figure-8 plots before the start of trafficking to establish baseline data. The bulk density, biomass, and cover data were analyzed using the PROC MIXED procedure in SAS (SAS, 2009). Mean separation of the least square means where the F-ratio was significant was made using the DIFF option in the LSMEANS statement with a significance level of $p \leq 0.05$ as the default. Analysis of variance (ANOVA) of arcsine-transformed cover data was performed due to the skewed nature of these data.

RESULTS AND DISCUSSION

BIOMASS BEFORE AND AFTER TRAFFICKING

Analysis of variance (ANOVA) of total biomass shows that the pass (P) main effect was significant ($p \leq 0.01$; table 2). Vehicle, location, and other interactions were not significant. Biomass after relative disturbance (pass) levels p1 (one pass by the M1A1 and 10 passes by the HMMWV), p2 (5 total passes by the M1A1 and 25 passes by the HMMWV), and p3 (10 total passes by the M1A1 and 50 passes by the HMMWV) were significantly different from the un-trafficked biomass (p0) but were not significantly different across relative levels of disturbance (pass levels) and vehicles (table 2). These results show that a minimum relative level of disturbance, e.g., one pass by the

Table 2. Analysis of variance of total, grass, and forb anchored standing and flat biomass at Fort Benning, Georgia.

Parameter	Effect[a]	Num. DF	Den. DF	F-Value	Pr > F
Total biomass	V	1	2	2.21	0.275
	P	3	12	8.35	0.003
	V×P	3	12	0.33	0.805
	L	3	48	0.34	0.795
	V×L	3	48	0.61	0.609
	P×L	9	48	0.30	0.971
	V×P×L	9	48	0.74	0.675
Grass biomass	V	1	2	3.08	0.221
	P	3	12	3.77	0.041
	V×P	3	12	0.21	0.886
	L	3	48	1.25	0.302
	V×L	3	48	1.74	0.172
	P×L	9	48	0.45	0.899
	V×P×L	9	48	0.93	0.505
Forb biomass	V	1	2	0.21	0.693
	P	3	12	11.56	0.001
	V×P	3	12	0.24	0.868
	L	3	48	0.95	0.424
	V×L	3	48	1.73	0.174
	P×L	9	48	0.58	0.804
	V×P×L	9	48	0.94	0.500

[a] Main effects are vehicle (V), pass (P), and location (L).

Table 3. Analysis of variance of total, grass, and forb cover at Fort Benning, Georgia.

Parameter	Effect[a]	Num. DF	Den. DF	F-Value	Pr > F
Total cover	V	1	2	23.55	0.040
	P	3	12	28.58	<0.001
	V×P	3	12	5.94	0.010
	L	3	48	6.53	0.004
	V×L	3	48	1.45	0.249
	P×L	9	48	3.00	0.012
	V×P×L	9	48	0.64	0.695
Grass cover	V	1	2	63.73	0.015
	P	3	12	16.66	<0.001
	V×P	3	12	7.13	0.005
	L	3	48	3.27	0.051
	V×L	3	48	0.66	0.522
	P×L	9	48	2.19	0.070
	V×P×L	9	48	0.46	0.830
Forb cover	V	1	2	2.67	0.244
	P	3	12	30.02	<0.001
	V×P	3	12	1.86	0.190
	L	3	48	5.12	0.012
	V×L	3	48	2.93	0.068
	P×L	9	48	0.81	0.567
	V×P×L	9	48	1.21	0.327

[a] Main effects are vehicle (V), pass (P), and location (L).

M1A1 and 10 passes by the HMMWV, would result in a significant reduction of the vegetation biomass under the conditions of the experiment. On average, biomass was reduced by 84% in the M1A1 tracks and 49% in the HMMWV tracks after pass level p1. At the end of all trafficking, about 5% and 15% of the biomass was left in the M1A1 and HMMWV tracks, respectively (fig. 3). However, the measured differences were not statistically significant ($p \leq 0.05$). These losses in biomass due to trafficking intensity were similar to those found at Fort Riley, Kansas (Retta et al., 2013).

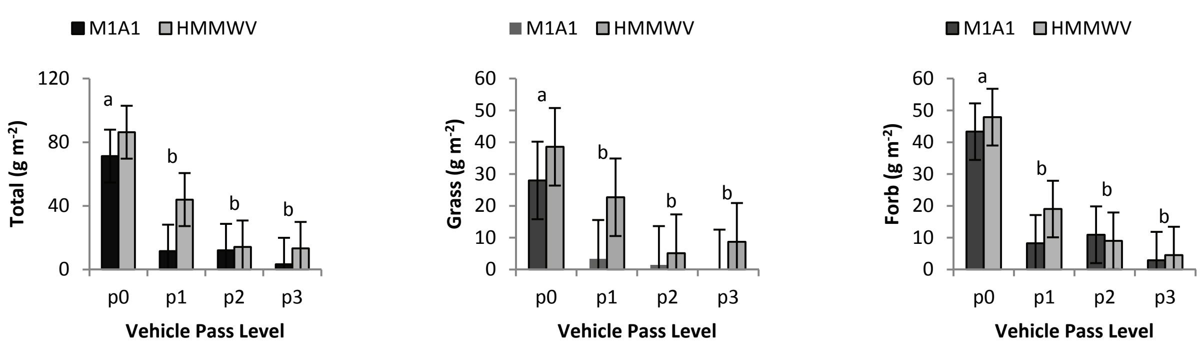
Analysis of variance was also performed separately on grass and forb biomass to examine whether trafficking effects were different for different plant types. The pass (P) main effect was still significant for both grass ($p \leq 0.05$) and forb biomass ($p \leq 0.01$), as shown in table 2.

Vegetation Cover Before and After Trafficking

For total cover, vehicle (V), pass (P), location (L), V×P, and P×L effects were significant ($p \leq 0.05$; table 3 and fig. 4a). For grass, vehicle (V), pass (P), location (L), and V×P were significant (fig. 4b). For forb, pass (P) and location (L) effects were significant (fig. 4c). At all relative levels of disturbance (pass levels), there was significantly more total and grass cover on the HMMWV tracks than on the M1A1 tracks (figs. 4a and 4b). Differences in forb cover between the M1A1 and HMMWV tracks were smaller than with grass cover (figs. 4b and 4c).

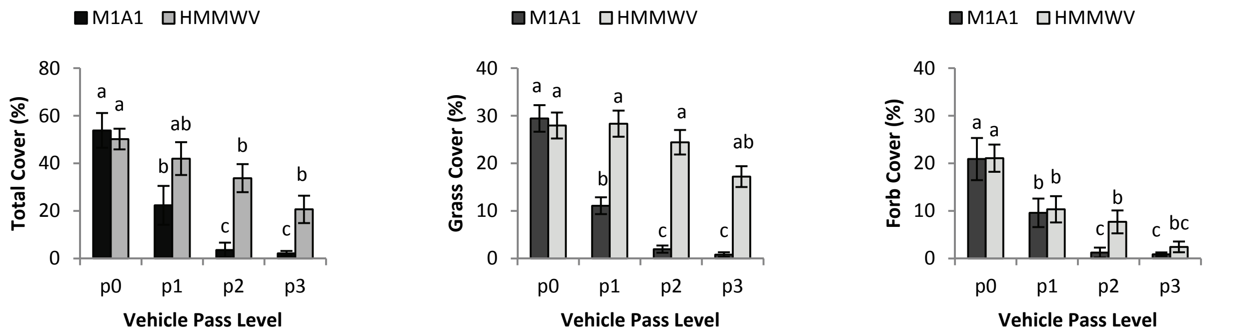
Vegetative Biomass Regression Equations

Biomass data at each of the trafficking locations were converted to biomass as percent of the control (pre-trafficking) biomass. The percent biomass data was fit to a two-parameter exponential decay function using SigmaPlot (Systat, 2004) curve-fitting software (eq. 1):



(a) (b) (c)

Figure 3. Influence of vehicle pass intensity level on (a) total, (b) grass, and (c) and forb biomass across all sampling locations: p0 is from an untrafficked location, and p1, p2, and p3 represent 1, 5, and 10 passes with the M1A1 and 10, 25, and 50 passes with the HMMWV, respectively. Bars with different letters are significantly different ($p \leq 0.05$) for the main effect of vehicle pass.



(a) (b) (c)

Figure 4. Influence of vehicle pass intensity level on (a) total, (b) grass, and (c) forb cover across all sampling locations: p0 is from an un-trafficked location, and p1, p2, and p3 represent 1, 5, and 10 passes with the M1A1 and 10, 25, and 50 passes with the HMMWV, respectively. Bars with different letters are significantly different (p ≤ 0.05).

$$y = a[\exp(-bx)] \quad (1)$$

where

y = percent biomass of the control

x = number of trafficking passes

a and b = regression parameters.

Regression equations relating trafficking intensity to percent biomass at the straight and curved locations of the track for each vehicle were obtained (fig. 5 and table 4). These initial relationships, to be later revised with data from additional sites, will be used in WEPS to estimate loss of standing and attached vegetation biomass resulting from trafficking intensity. As mentioned earlier, the degree of removal of standing and attached vegetation has a strong influence on soil erosion by wind.

The plots in figure 5 indicate that the curved sections under the M1A1 have nearly total biomass removal after one initial pass, while the straight section had a steady decline in biomass. This might be expected since the tracked vehicle exhibits much more surface shearing action as the vehicle turns on the curve as compared to the minimal shearing on the straight portions. However, the HMMWV has independent wheels with less shear on the curved sections compared to the straight section and therefore shows a steady decline in biomass for all locations. The steady decline in biomass for the M1A1 straight section as well as all

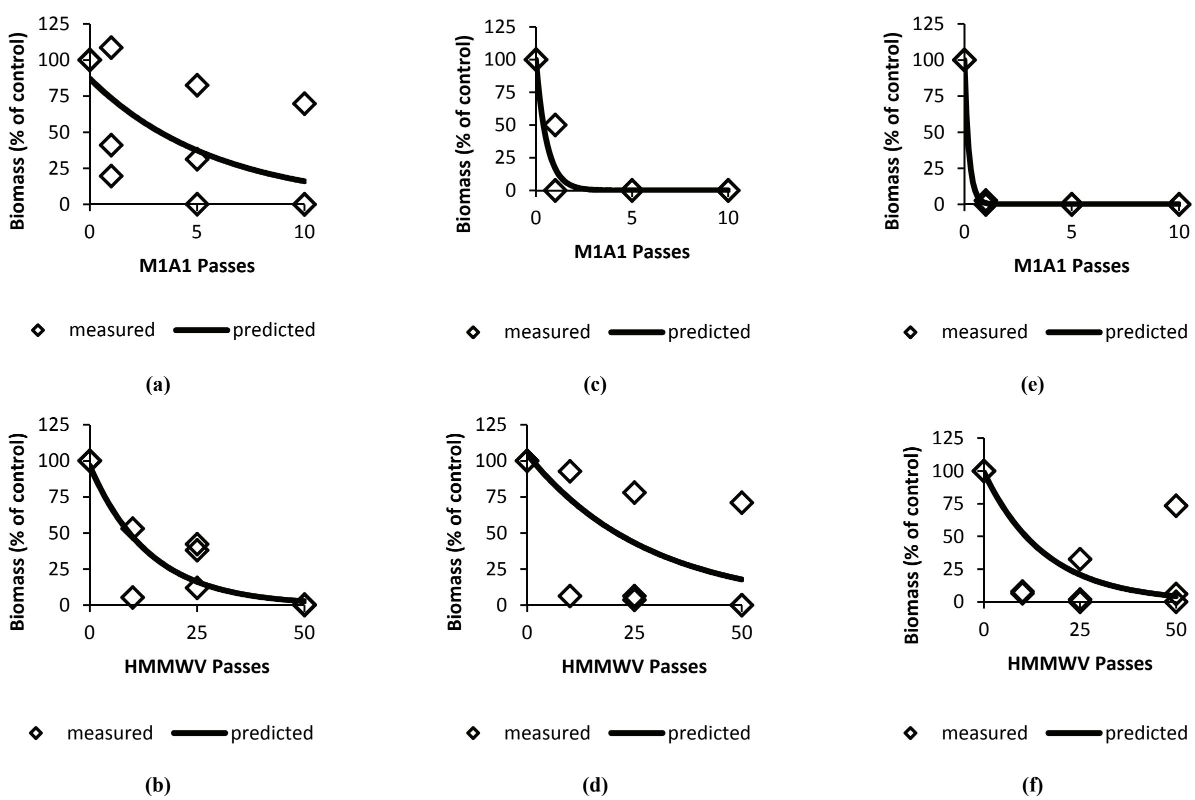


Figure 5. Comparison of measured and regressed biomass (expressed as percent of control) at the (a and b) straight, (c and d) outside curve, and (e and f) inside curve locations for the two vehicles at Fort Benning.

Table 4. Regression parameters for two-parameter exponential decay function relating trafficking intensity to biomass and cover.[a]

Parameter	Vehicle	Track Location[b]	*a*	*b*	r^2
Biomass	M1A1	SS	87.105	0.091	0.40
		CO	99.972	1.779	0.27
		CI	100.000	4.722	1.00
	HMMWV	SS	96.519	0.072	0.81
		CO	104.634	0.035	0.38
		CI	99.006	0.062	0.39
Cover	M1A1	SS	117.825	0.202	0.76
		CO	99.939	1.134	0.94
		CI	100.000	0.247	0.98
	HMMWV	SS	116.742	0.014	0.19
		CO	99.085	0.005	0.54
		CI	89.741	0.007	0.43

[a] Regression equation: $y = a[\exp(-bx)]$.

[b] SS = straight section, CI = curve inside, and CO = curve outside.

locations for the HMMWV is likely due to the simple pulverization of biomass as the vehicle passes over it.

Vegetative Cover Regression Equations

Vegetative cover is one of the most common measures used to evaluate the impact of trafficking. The strong response of cover to type of vehicle and intensity of trafficking found in this field study lends itself to the development of regression models that can be used for prediction purposes. Cover data from trafficked locations were expressed as percent of the control and fit to the same two-parameter exponential decay function used for the biomass relationships (eq. 1), except percent cover of the control was used rather than percent biomass. A graphical representation of the fitted data is shown in figure 6, and the regression parameters are shown in table 4. These initial regression relationships between trafficking intensity and loss of vegetative cover, to be later revised with data from other sites, can be used in the management of military training activities either directly or in conjunction with the WEPS model for wind erosion assessment.

As expected, and as shown in figure 6, the heavier M1A1 was much more effective at reducing the vegetative cover due to repeated trafficking than the HMMWV at all sampling locations, e.g., in both the straight section and the curves. In addition, the M1A1 also removed nearly all of the cover in the curved locations (figs. 6c and 6e) on the first trafficking pass due to the shearing action of the tracks while following the curved section of the figure-8 plots. A similar shearing action on the curves was also visually evident with the HMMWV, but the effects were not nearly as pronounced as the M1A1 due to both the weight difference and the transport mechanism being tires rather than tracks.

For both the M1A1 and the HMMWV, the straight section locations did not experience the shearing effect seen in the turns, and thus a more gradual degradation of cover was due primarily to the repeated pulverization action of the tracks and wheels running over the same surface multiple times (figs. 6a and 6b). The cover data include contributions from both flat and standing biomass. If the standing biomass is only flattened, with little or no removal of biomass, then an increase in cover would be expected due to the flattening of standing biomass occurring in the initial trafficking passes on the straight locations. This effect is

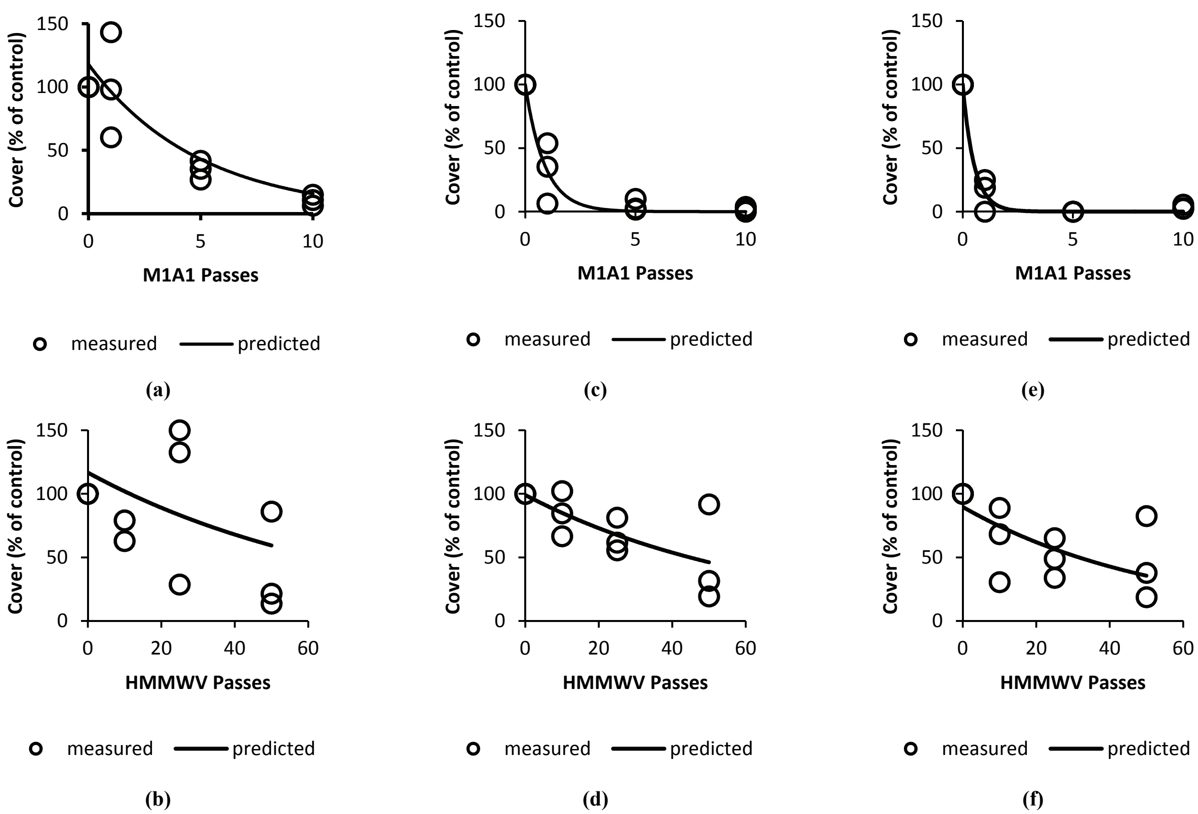


Figure 6. Comparison of measured and regressed vegetation cover (expressed as percent of control) at the (a and b) straight, (c and d) outside curve, and (e and f) inside curve track locations of the two vehicles at Fort Benning.

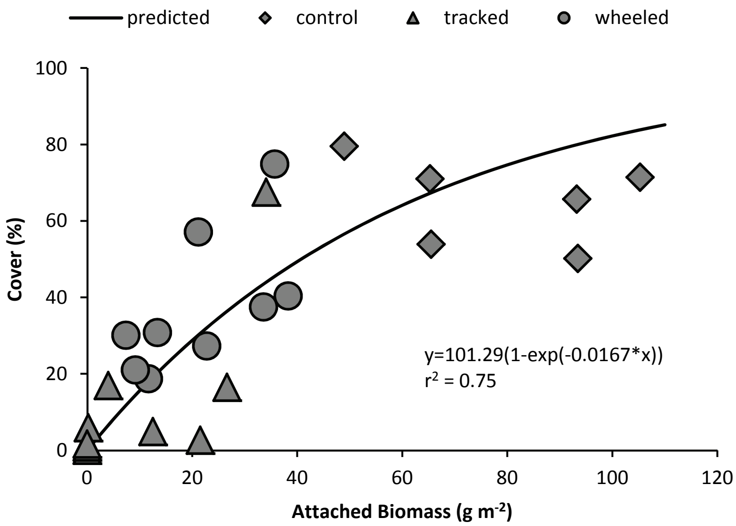


Figure 7. Biomass vs. cover relationship for all data from Fort Benning.

shown by regression coefficient *a* being greater than 100 for both the M1A1 and HMMWV for the straight section locations (table 4).

Vegetative Cover to Biomass Relationship

The general relationship of biomass to cover data before and after trafficking was explored using an exponential model. The data used for the regression consisted of all data from the control, the M1A1, and the HMMWV tracks. Gregory's mass to cover equation (Gregory, 1982), which is widely used in agronomic studies, was used for the regression relationship. The regression model fit the data with an r^2 of 0.75 (fig. 7). This regression equation could be used to estimate cover using standing and flat anchored biomass data if cover data are not available.

Vegetation Diversity

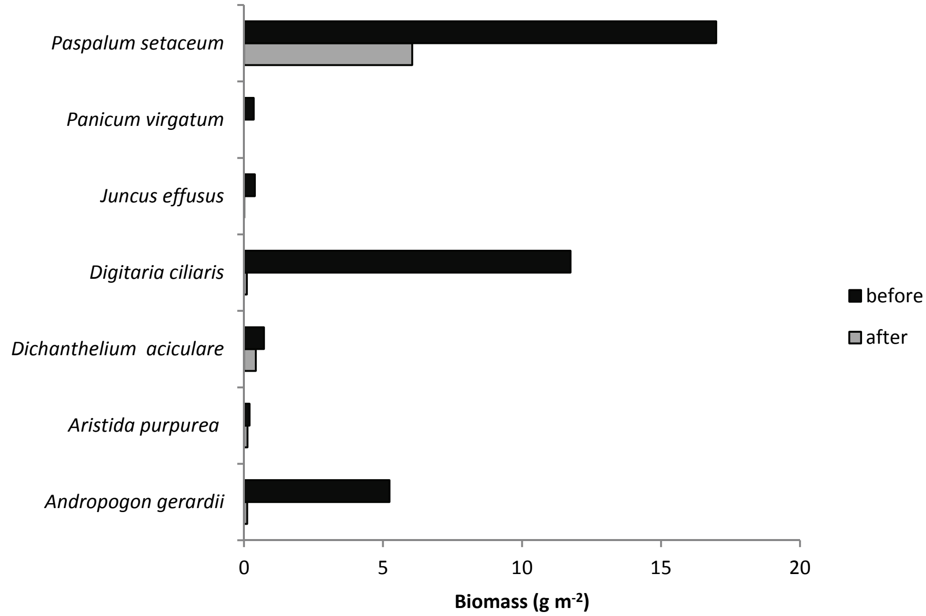
The most common grass and forb species that were in the experimental area are shown in figure 8. The status of each species was evaluated before and after trafficking. All species suffered reductions of 65% or more in biomass and frequency of occurrence (presence or absence of a species in a quadrat) at the end of all trafficking (figs. 8 and 9). The relative frequency is the ratio of the number of quadrats containing the species to the total number of times the quadrat was thrown (i.e., number of sampling locations), as defined by Curtis and McIntosh (1950).

The most abundant grasses were *Paspalum setacum* (thin paspalum) and *Digitaria ciliaris* (southern crabgrass), comprising about 80% of the total grass biomass before trafficking. After trafficking, most of the grass species were reduced to almost zero except for *Paspalum setacum*, which retained about 35% of its biomass (fig. 8). Similarly, most of the forb species were reduced to almost zero after trafficking except for *Hypericum gentianoides* (orangegrass), which had about 22% remaining, and *Desmonium strictum* (pine barren ticktrefoil), which had about 15% remaining (fig. 8). Average trends in biomass as affected by trafficking intensity of both vehicles for the most common grass (*Paspalum setaceum*) and forb (*Desmodium strictum*) species are shown in figure 10.

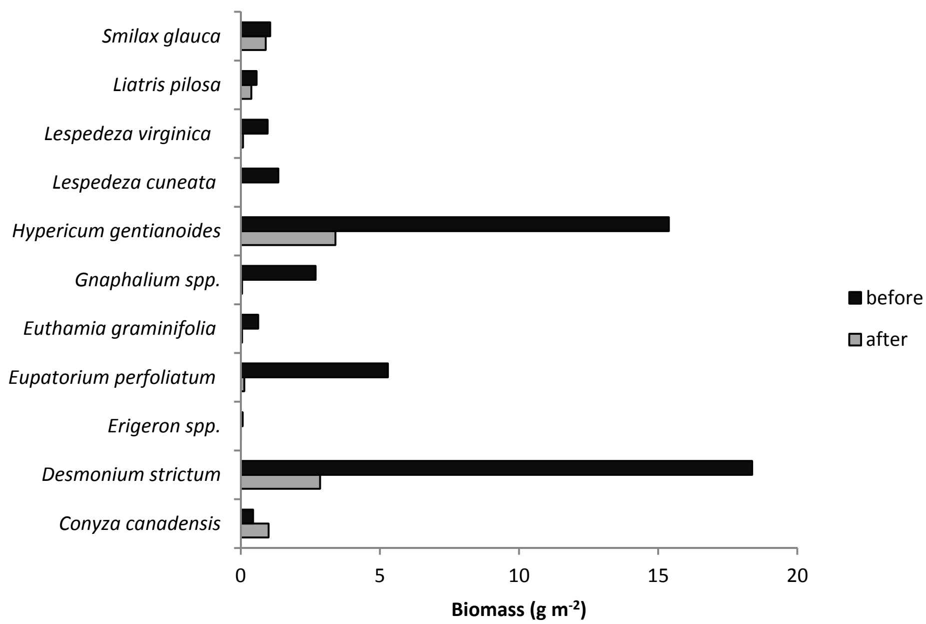
Bulk Density and Soil Water Content

The ANOVA for bulk density (table 5) shows that depth (D), vehicle (V) × depth, pass (P) × depth, and V × P × D were significant. The V × P × D interaction is shown in figure 11. For clarity, the bulk density of the control (untrafficked) and the bulk density after all trafficking are presented. At the 5 cm depth, the bulk density was significantly greater than the control by 16% in the M1A1 tracks and by 8% in the HMMWV tracks. Differences in bulk density after trafficking between the M1A1 and the HMMWV were not significant. These results indicate that under the conditions of this trafficking experiment, significant soil compaction below the 5 cm layer did not occur. In contrast, at Fort Riley, soil compaction rates and depth of compaction differed significantly between vehicle types, number of passes, and locations within the tracks. The soils at the Fort Benning experimental site were subjected to many years of trafficking prior to 1991 and as a result were already severely compacted. There was also evidence that they had been eroded (to the B horizon). The low moisture content of these soils was probably a contributing factor to the lack of significant compaction below the 5 cm depth.

The ANOVA for gravimetric soil water content indicates that the main factors of pass (P), location (L), and depth (D) were significant for soil water content. Two-way interactions of V × L and P × L and three-way interactions of V × P × D and V × L × D were significant. Graphs of the V × P × D interactions are shown in figure 12, which indicates a general decline in soil water content after trafficking in both the M1A1 and HMMWV tracks. This decline in water content appears to be caused by the breaking up of the lightly crusted surface and the mixing of the deeper soil, which had a higher water content initially that became conducive to evaporative drying. This was especially true in the M1A1 tracks.



(a)



(b)

Figure 8. Biomass before and after all trafficking for (a) grass and (b) forb species at Fort Benning.

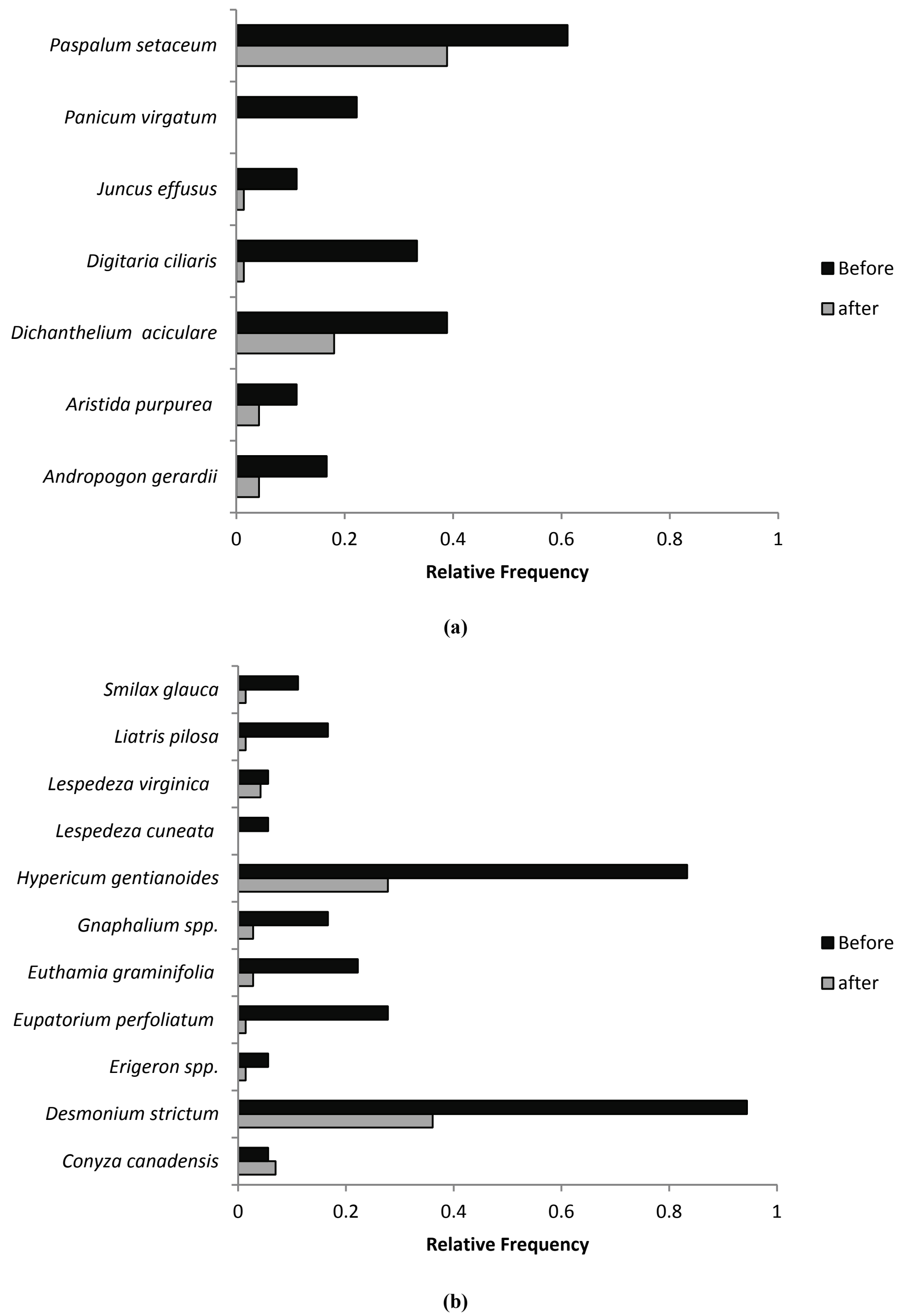


Figure 9. Relative frequency of occurrence of (a) grass and (b) forb species before and after all trafficking at Fort Benning.

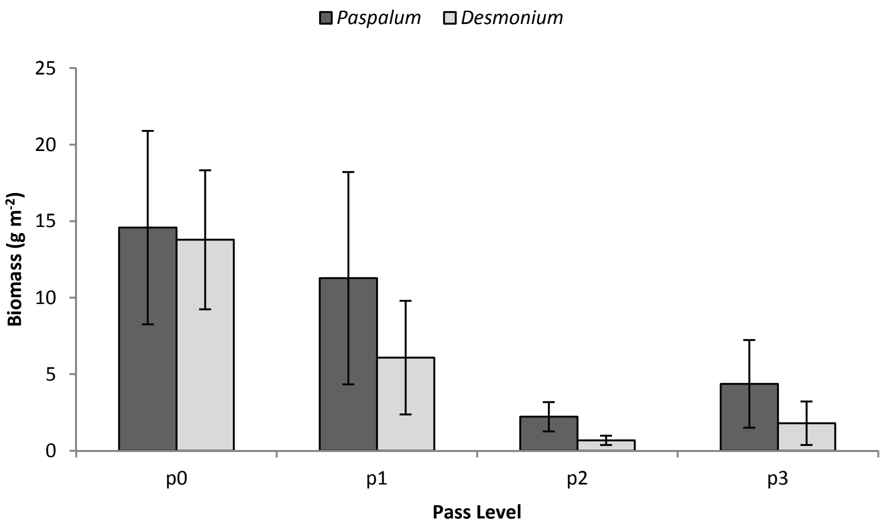


Figure 10. Average trends in biomass as affected by trafficking intensity of both vehicles on the most common grass (*Paspalum setaceum*) and forb (*Desmodium strictum*) species (p0, p1, p2, and p3 represent 0, 1, 5, and 10 passes by the M1A1 or 0, 10, 25, and 50 passes by the HMMWV, respectively).

Table 5. Analysis of variance of bulk density and soil water content at Fort Benning, Georgia.

Effect[a]	Num. DF	Den. DF	Bulk Density F-Value	Bulk Density Pr > F	Water Content F-Value	Water Content Pr > F
V	1	2	1.73	0.32	3.59	0.20
P	3	12	2.19	0.14	19.93	<0.0001
V×P	3	12	1.15	0.37	2.93	0.08
L	3	16	0.85	0.49	3.25	0.05
V×L	3	48	1.50	0.23	3.26	0.03
P×L	9	48	0.87	0.56	2.06	0.05
V×P×L	9	48	0.55	0.83	1.48	0.18
D	2	16	46.66	<0.0001	109.89	<0.0001
V×D	2	64	11.80	<0.0001	0.64	0.53
P×D	6	48	4.02	0.00	0.93	0.48
V×P×D	6	64	3.94	0.00	2.76	0.02
L×D	6	16	0.34	0.91	1.27	0.32
V×L×D	6	64	2.14	0.06	2.57	0.03
P×L×D	18	48	0.80	0.69	1.08	0.40
V×P×L×D	18	64	0.92	0.56	0.65	0.85

[a] Main effects are vehicle (V), pass (P), location (L), and depth (D).

Summary and Conclusions

Biomass showed significant reduction as the number of trafficking passes increased. On average, biomass was reduced by 97% and 84% at the end of all trafficking by the M1A1 and the HMMWV, respectively. Severe reduction in attached (especially standing) biomass deprives the soil of the type of cover that is most effective in reducing wind erosion (Hagen, 1996). The obtained regression equations relating attached biomass to trafficking intensity for each vehicle type should prove useful in evaluating the effects of trafficking in degrading attached vegetative cover and thus making the soil more vulnerable to wind erosion. Losses in biomass in both grass and forb species were similar, which means that the grass and forbs in this area showed similar vulnerability to trafficking. The grass (*Paspalum setacum*) and forb (*Desmonium strictum*) species that were the most abundant before trafficking remained the most abundant after trafficking.

For the study site, significant soil compaction was found

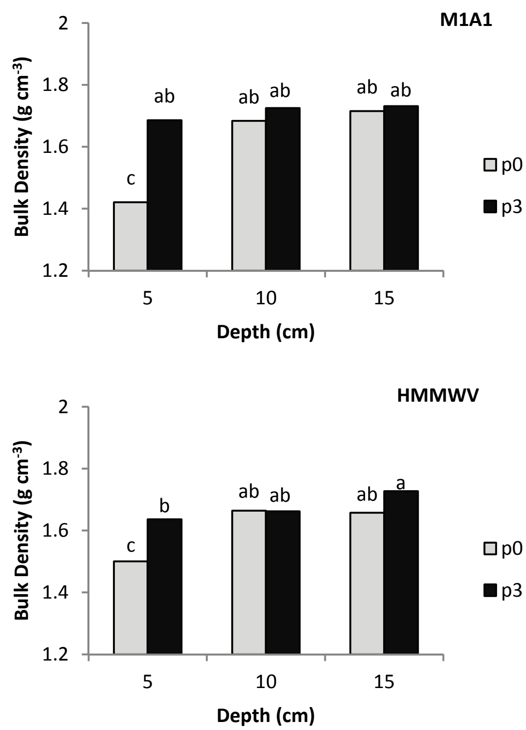


Figure 11. Vehicle × pass × depth interactive effects for bulk density. Graphs show bulk density before (p0) and after (p3) all trafficking in the M1A1 and HMMWV tracks at Fort Benning. Bars with different letters are significantly different (p ≤ 0.05).

only in the 0-5 cm layer. Although one would expect vehicle ground pressure (vehicle weight per contact area) to increase the bulk density, it is hypothesized that the lack of significant compaction below 5 cm may be attributed to the site's history of use, the low strength of the sandy soil, and the soil's low moisture content. In addition, the M1A1 has a reported ground pressure of 100 kPa (Cooke, 2010),

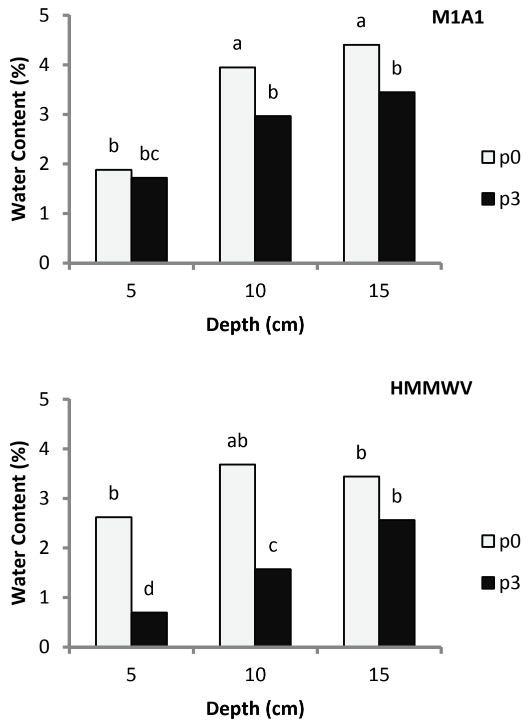


Figure 12. Vehicle × pass × depth interactive effects for soil water content in the M1A1 and HMMWV tracks at Fort Benning. Bars with different letters are significantly different (p ≤ 0.05).

which is similar to our computed value for the HMMWV of 96.5 kPa (four tires, each with a 930 cm^2 footprint, and using the vehicle weight listed in table 1). Therefore, for this study, the ground pressure difference between vehicles was not considered a major factor for compaction nor the cause of the measurable differences seen in vegetation and cover loss. The data from the Fort Riley experiments showed significant increases in bulk density below 5 cm, but the soil moisture content was much higher and the soils also had significantly higher organic matter and clay contents (Retta et al., 2013).

Cover showed a strong response to vehicle type, trafficking intensity, location within figure-8 segment, and their interactions. Other researchers have found similar results (Wilson, 1988; Grantham et al., 2001; Anderson et al., 2007). Regression equations relating trafficking intensity to reduction in cover were obtained. Good correlation was also found between biomass and cover.

Currently, WEPS is primarily used to predict wind erosion from agricultural lands, and biomass growth and residue decomposition are simulated with biomass cover estimated from the type and quantity of aboveground biomass. At present, WEPS does not have the capability to directly calculate biomass growth for a distribution of heterogeneous individual plant species common in military training areas (range lands). However, even in the absence of the capability to model range vegetation in this manner, WEPS can still represent a distribution of plant species as a "composite single species" if the effects are similar among the individual species. Thus, erosion from trafficked locations at Fort Benning (in areas similar to the experimental site) can be calculated, once the soil and vegetation disturbance due to military vehicle trafficking have been properly represented within WEPS operation records. If only pre-trafficking values or estimates of biomass are available, the equation in figure 7 can be used to estimate cover. The regression equation in table 4, to be later revised with data from additional sites and their soils, can then be used to calculate the level of degradation of vegetative cover as a function of the frequency of trafficking. This in turn will allow WEPS to estimate the change in susceptibility to wind erosion as a result of military maneuvers using different types of vehicles on a variety of soil and soil surface conditions.

This study indicates that vehicle trafficking response using measured standing and attached biomass data is more sensitive than that using measured total cover. In future studies of this kind, it may be worthwhile to attempt to measure the cover of the standing and attached vegetation in addition to the total cover. It should be noted that the regression equations obtained in this study apply to military training areas in Fort Benning with soil and vegetation characteristics similar to the experimental site. Similar analysis will be made of data taken from other military sites, as part of this project, to extend the applicability of these types of relationships to other military training areas.

Acknowledgements

Funding for this project was provided by the Strategic Environmental Research and Development Program (SERDP). We thank Shannon Danley for help coordinating field operations and for taking the time to identify the vegetation species; the army personnel who drove the vehicles; T. C. Todd of Kansas State University for help with the statistical analysis; and student employees Michelle Busch, Neil Baker, and Chris Shultz for help with sampling and processing of the data.

References

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., Kirkham, M. B., Todd, T. C., Thien, S. J., & Gipson, P. S. (2009). Influence of Abrams M1A1 main battle tank disturbance on tallgrass prairie plant community structure. *Range Ecol. Mgmt., 62*(5), 480-490. http://dx.doi.org/10.2111/REM-D-09-00022.1.

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), 2151-2161. http://dx.doi.org/10.2136/sssaj2009.0091.

Anderson, A. B., Palazzo, A. J., Ayers, P. D., Fehmi, J. S., Shoop, S., & Sullivan, P. (2005). Assessing the impacts of military vehicle traffic on natural areas: Introduction to a special issue and review of the relevant military vehicle impact literature. *J. Terramech., 42*(3-4), 143-158. http://dx.doi.org/10.1016/j.jterra.2005.01.001.

Anderson, A. B., Ayers, P. D., Howard, H., & Newlin, K. D. (2007). Vehicle impacts on vegetation cover at Camp Atterbury, Indiana: Part 1. Initial impacts and vegetation recovery. *Proc.*

Indiana Acad. Sci., 116(2), 126-138.

ASTM. (2007). D698: Standard test methods for laboratory compaction characteristics of soil using standard effort. West Conshohocken, Pa.: ASTM International.

Ayers, P. D. (1994). Environmental damage from tracked vehicle operation. *J. Terramech., 31*(3), 37-50. http://dx.doi.org/10.1016/0022-4898(94)90014-0.

Braunack, M. V. (1986). The residual effects of tracked vehicles on soil surface properties. *J. Terramech., 23*(1), 37-50. http://dx.doi.org/10.1016/0022-4898(86)90030-3.

Cooke, G. W. (2010). Gary's Combat Vehicle Reference Guide: M1 Abrams main battle tank. Retrieved from www.inetres.com/gp/military/cv/tank/M1.html.

Curtis, J. T., & McIntosh, R. P. (1950). The interrelations of certain analytic and synthetic phytosociological characters. *Ecology, 31*(3), 433-455. http://dx.doi.org/10.2307/1931497.

Etyemezian, V., Nikolich, G., Ahonen, S., Pitchford, M., Sweeney, M., Purcell, R., Gillies, J., & Kuhns, H. (2007). The portable *in situ* wind erosion laboratory (PI-SWERL): A new method to measure PM_{10} potential for windblown dust properties and emissions. *Atmos. Environ., 41*(18), 3789-3796. http://dx.doi.org/10.1016/j.atmosenv.2007.01.018.

Garten Jr., C. T., & Ashwood, T. L. (2004). Modeling soil quality thresholds to ecosystem recovery at Fort Benning, GA USA. *Ecol. Eng., 23*(4-5), 351-369. http://dx.doi.org/10.1016/j.ecoleng.2004.11.009.

Garten Jr, C. T., Ashwood, T. L., & Dale, V. H. (2003). Effect of military training on indicators of soil quality at Fort Benning, Georgia. *Ecol. Indic., 3*(3), 171-179. http://dx.doi.org/10.1016/S1470-160X(03)00041-4.

GlobalSecurity. (2011). Fort Benning. Alexandria, Va.: Global Security.org. Retrieved from www.globalsecurity.org/military/facility/fort-benning.htm.

Goran, W. D., Radke, L. L., & Severinghaus, W. D. (1983). An overview of the ecological effects of tracked vehicles on major U.S. Army installations. USA-CERL Technical Report. N-142. Champaign, Ill.: U.S. Army Corps of Engineers, Construction Engineering Research Laboratory.

Grantham, W. P., Redente, E. F., Bagley, C. F., & Paschke, M. W. (2001). Tracked vehicle impacts to vegetation structure and soil erodibility. *J. Range Mgmt., 54*(6), 711-716. http://dx.doi.org/10.2307/4003676.

Gregory, J. M. (1982). Soil cover prediction with various amounts and types of crop residue. *Trans. ASAE, 25*(5), 1333-1337. http://dx.doi.org/10.13031/2013.33723.

Grossman, R. B., & Reinsch, T. G. (2002). Bulk density and linear extensibility. In *Methods of Soil Analysis: Part 4. Physical Methods* (pp. 201-228). Madison, Wisc.: SSSA.

Hagen, L. J. (1996). Crop residue effects on aerodynamic processes and wind erosion. *Theor. Appl. Climatol., 54*(1-2), 39-46. http://dx.doi.org/10.1007/BF00863557.

Hagen, L. J. (2004). Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. *Environ. Model. Software, 19*(2), 171-176.

Palazzo, A. J., Jensen, K. B., Waldron, B. L., & Carry, T. J. (2005). Effects of tank tracking on range grasses. *J. Terramech., 42*(3-4), 177-191.

Prosser, C. W., Sedivec, K. K., & Barker, W. T. (2000). Tracked vehicle effects on vegetation and soil characteristics. *J. Range Mgmt., 53*(6), 666-670. http://dx.doi.org/10.2307/4003164.

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.

SAS. (2009). SAS v. 9.2. Cary, N.C.: SAS Institute, Inc.

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

Systat. (2004). SigmaPlot for Windows, ver. 9. San Jose, Cal.: Systat Software, Inc.

U.S. Army. (2007). Final programmatic environmental impact statement. Aberdeen, Md.: Aberdeen Proving Ground, U.S. Army Environmental Command.

USDA. (2013). Web soil survey of Chattahoochee and Marion counties, Georgia. Athens, Ga.: USDA Natural Resources Conservation Service. Retrieved from http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm.

USEPA. (1996).Air quality criteria for particulate matter. EPA/600/P-95/001aF. Research Triangle Park, N.C.: U.S. Environmental Protection Agency, Office of Research and Development.

Wagner, L. E. (2013). A history of wind erosion prediction models in the United States Department of Agriculture: The Wind Erosion Prediction System (WEPS). *Aeolian Res., 10*, 9-24. http://dx.doi.org/10.1016/j.aeolia.2012.10.001.

Wilson, S. D. (1988). The effect of military tank traffic on prairie: A management model. *Environ. Mgmt., 12*(3), 397-403. http://dx.doi.org/10.1007/BF01867529.