2007. Proceedings of the Indiana Academy of Science (116):126–138

VEHICLE IMPACTS ON VEGETATION COVER AT CAMP ATTERBURY, INDIANA: PART 1. INITIAL IMPACTS AND VEGETATION RECOVERY

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ABSTRACT. Geographic Positioning System (GPS) based vehicle tracking systems were installed on three military vehicle types (M88 tank recovery vehicle, M35A3 cargo truck, and M1009 utility cargo vehicle) at Camp Atterbury, Indiana, to assess the impact of vehicle traffic on vegetation. Vehicle tracking systems recorded the position of each vehicle every second. Instrumented vehicles were driven through courses of varying velocities and turning radii. GPS position data were used to calculate vehicle velocities and turning radii throughout the course. Vegetation damage along vehicle tracks was recorded immediately, 5 months (end of the first growing season) and 12 months after tracking. Vegetation damage was quantified by both the amount of vegetation lost and the area impacted. Vehicle type, turning radius (*TR*), velocity (*V*), and $TR \cdot V$ interaction were found to significantly affect all vegetation damage measures. The tracked M88 tank recovery vehicle caused more vegetation loss than either of the wheeled vehicles (M35A3 cargo truck and M1009 utility cargo vehicle). Decreasing turning radius increased vegetation loss for all vehicles. Increased vegetation loss associated with turning was a function of both greater vegetation loss within the track and a wider tracked area. Power equations using only turning radius and vehicle type as independent variables predicted vegetation damage measures with R^2 values ranging from 0.822 to 0.933. A critical turning radius between 15–20 m differentiated turning radii with relatively high vegetation loss as compared to straight-line tracking. Recovery of vegetation cover to pretreatment levels ranged from approximately 6–12 months, depending on impact treatment.

Keywords: Vehicle impacts, off-road, vegetation impact, impact assessment

The Department of Defense is responsible for administering more than 10 million hectares of federally-owned land in the United States. Military training, especially vehicular training, is an intensive land use that can negatively impact soil and vegetation (Goran et al. 1983; Demarais et al. 1999). Numerous studies have investigated the effects of vehicle traffic on soil and vegetation (Johnson 1982; Payne et al. 1983; Webb & Wilshire 1983; Prose 1985; Braunack 1986; Wilson 1988; Shaw & Diersing 1990; Ayers 1994; Trumbull et al. 1994; Demarais et al. 1999; Ayers et al. 2000; Hirst et al. 2000; Milchunas et al. 2000; Hirst et al. 2003). Potential consequences of vehicle traffic are loss of vegetation, exposed soil, increased erosion, soil compaction, soil puddling, displaced surface horizons, rut formation, decreased macropore space, restricted water movement, reduced soil strength and structure, and physical damage to root systems. The immediate physical disturbance affects not only vigor and mortality of current vegetation but also the rate of vegetation recovery (Thurow et al. 1995; Prosser et al. 2000; Lovich & Bainbridge 1999).

The amount of vegetation damage resulting from vehicle traffic is determined by vehicle characteristics and site conditions. Site conditions that are important in determining vegetation damage include soil type, soil moisture, slope, vegetation type, and plant growth stage (Payne et al. 1983; Wilson 1988; Thurow et al. 1995). Static vehicle characteristics important in determining vegetation damage include surface contact area, surface pressure, total weight, and track design (Ayers et al. 1994; Ayers et al. 2000). Dynamic vehicle properties important in determining vegetation damage include speed, turning radius, and driving pattern (Braunack 1986; Ayers et al. 2000; Halvorson et al. 2001).

A number of vehicle impact studies have assessed the impact of vehicle traffic on vegetation without characterizing the vehicles or activities that caused the disturbance (Johnson 1982; Shaw & Diersing 1990; Milchunas et al. 1999; Milchunas et al. 2000). Typically these studies compared vegetation on relatively large tracked and untracked sites. Usually vegetation impacts were assessed after an unknown period of time and/or by an unknown combination of vehicles using the study sites. Goran et al. (1983) reported a sequence of vehicle-induced effects on vegetation ranging from minor vegetation disturbance from apparent one-time only traffic, to increased bare ground and loss of sensitive plant species for occasional to frequent use, to complete vegetation loss and soil movement for frequently and intensely used areas. The authors also reported local site damage resulting from single turns as similar to intensely-used areas. While these studies are useful for quantifying the cumulative impact of tracking on vegetation, they provide little quantitative information that relates type and level of vehicle use to the amount of vegetation damage.

A number of studies related the impact of specific vehicles to a specified level of use (Payne et al. 1983; Wilson 1988; Thurow et al. 1995; Prosser et al. 2000; Grantham et al. 2001). Typically these replicated studies involved repeated tracking of study plots with a specific vehicle. Thurow et al. (1995) assessed the impact of 1, 4, and 10 straight-line passes of a 22.5 metric ton (t) tracked M2 Bradley Infantry fighting vehicle on vegetation during wet and dry soil conditions. Similarly, Payne et al. (1983) assessed the impact of 2, 8, and 32 straight-line passes of a 2.2 metric ton (t) wheeled Chevy Blazer on vegetation over a period of time to quantify temporal effects of tracking on vegetation. While dynamic vehicle properties like velocity were not always reported in these studies, the vehicle's dynamic properties generally maintained constant throughout the disturbance regime. However, it is not clear if the dynamic vehicle properties used in these studies are representative of actual site use or include the most damaging vehicle activities. For example, Grantham et al. (2001) quantified the impact of 1, 2, 4, and 8 straight-line passes of a 62.6 metric ton (t) tracked M1A2 Abrams combat tank operating at 48 km per hr on vegetation. While turns were not included in the study design, the authors observed that single turns caused more site damage than the maximum 8 straight-line passes used in the study. Similarly, Prosser et al. (2000) assess the impact of 0, 37, and 74 straight-line passes of a 10.9 metric ton (t) tracked M113 personnel carrier on vegetation. While only straight-line tracking was included in the study, the authors also noted that turns caused substantially more damage than any straight-line tracking treatments. Belcher and Wilson (1989), while studying leafy spurge infestations on military lands, found the majority of infestations associated with vehicle turns rather than straight-line tracking because of the amount of bare soil exposed during turns. Wilson (1988), while assessing the impact of 4 to 35 straight-line passes of a combat tank on vegetation, noted a single vehicle turn had an obvious and immediate impact on vegetation by exposing bare ground and was much more severe than straight-line tracking.

Another group of vehicle impact studies included both straight-line tracking and turning in the study design (Braunack 1986; Watts 1998; Halvorson et al. 2001). Halvorson et al. (2001) assessed the impact of 1, 2, 4, and 8 straight-line passes and turns of a M1A2 Abrams combat tank on vegetation. Watts (1998) assessed the impact of a 60.8 t tracked M1 combat tank during straight-line tracking and turns on vegetation. In both studies, turns caused substantially more vegetation damage within the track than straight-line tracking. Braunack (1986) measured rut width of single pass straight-line and turning tracking of an M113. Turns damaged almost twice the area of straight-line tracking. These studies clearly quantified the impacts of both straight-line tracking and turns. However, these studies did not specify the type of turns included in the study.

Ayers (1994) assessed the impact of an M113 turning at radii of 30, 12, 8, and 4 m on vegetation damage. Sharper turns caused greater vegetation loss. However, the number of turning radii treatment was insufficient to accurately determine the shape of the relationship. Specifically, the data were insufficient to determine if there was a threshold turning-radius such that sharper turns disproportionately cause greater vegetation loss and if this threshold turning-radius was vehicle specific.

While a number of studies have assessed the impact of vehicle type, turning-radius, and number of vehicle passes on vegetation damage, little is know about the relative impact of these factors on vegetation loss. This lack of understanding results from studies that examine unique impact factors at different sites. The objective of our study was to quantify the impact of three military vehicles (M88 tank recovery vehicle, M35A3 cargo truck, and M1009 utility cargo vehicle) on vegetation cover loss and determine the relative impact of vehicle type, turning-radius, and velocity on vegetation cover loss. A secondary objective of this study was to estimate vegetation recovery times for the study site.

METHODS

Study site.—The study was conducted at Camp Atterbury, Indiana, an Army National Guard training facility that encompasses 144 km^2 in central Indiana (Tetra Tech 2000). Prior to establishment in 1942 as a military installation, historic land use consisted of intermixed farms and woodlands. The terrain ranges from fairly flat historically-agricultural land forms on the north, rolling hills in the central portion, to steep hills and valleys in extreme southern portion. Elevations range from 195–297 m above sea level. Temperatures range from −29° C in winter to 43° C in summer. The last killing frost averages 27 April and first killing frost averages 10 October. Summer months are characterized as hot, with prolonged dry conditions. Precipitation is distributed fairly evenly throughout the year, so there is no pronounced wet or dry season. Annual precipitation averages 104 cm, with 43 cm as snow. Vegetation ranges from open grasslands to hardwood forests.

The study site is located in training area 3A (39.33° N, 85.99° W). The study site was selected because it is representative of many areas on the installation used by vehicles. Study site soils were classified as a Genesee (Wigginton & Marshall 2004). The Genesee series is a fine-loamy, mixed, superactive, mesic Fluventic Eutrudept. Vegetation at the study site consists of native and introduced forbs and grasses. Common plant species occupying the site include annual ragweed (*Ambrosia artemisiifolia* L.), giant ragweed (*Ambrosia trifida* L.), common milkweed (*Asclepias syriaca* L.), mustards (*Brassica* spp.), trumpet creeper (*Campsis radicans* (L.) Seem. ex Bureau), thistle (*Cirsium* spp.), Queen Anne's lace (*Daucus carota* L.), blue boneset (*Eupatorium coelestinum* L.), morning-glory (*Ipomoea* spp.), fescue (*Lolium* spp.), white sweet clover (*Melilotus alba* Medikus), timothy (*Phleum pratense* L.), raspberry/blackberry (*Rubus* spp.), cereal rye (*Secale cereale* L.), Canada goldenrod (*Solidago canadensis* L.), eastern poison ivy (*Toxicodendron radicans* (L.) Kuntze), red clover (*Trifolium pratense* L.), and wild grape (*Vitis* spp.). Plant nomenclature follows USDA, NRCS (2004).

Study design.—A field study was conducted on 24 July 2001 using three vehicles: M88 tank recovery vehicle, M35A3 cargo truck, and M1009 utility cargo vehicle (Figs. 1–3). The M88 tank recovery vehicle is a tracked vehicle that is 8.52 m long, 3.40 m wide, 3.10 m high with a weight of 50.8 t. The M88 track width is 71.1 cm with pads that are 26.7 cm wide by 16.5 cm long. The M35A3 cargo truck is a six-wheeled vehicle with a 4.50 m total wheelbase, 2.40 m outside to outside width, and weight of 3.5 t. The M35A3 tire height is 107.0 cm with a tread width of 23.5 cm. Tire pressure was 345 kPa during the study. The M1009 utility cargo vehicle (similar to a Chevrolet CD-10506) is a four-wheeled vehicle with a 2.70 m wheelbase, 1.40 m width, and a weight of 2.4 t. The M1009 tire height is 78.7 cm with a tread width of 26.7 cm. Tire pressure was 345 kPa during the study.

Each vehicle drove a systematically planned course (spiral) within a randomly located treatment plot. Each vehicle tracked three treatment plots. Each spiral course within a treatment plot consisted of a section of straight-line travel followed by a section of constantly decreasing turning radius. The spiral was complete after reaching the vehicle's minimum turning radius. One spiral for each vehicle was traversed at a slow, medium, or fast velocity. A preliminary spiral path was marked in each treatment plot. However, vehicle drivers were allowed to deviate from the marked path to maintain a constant velocity. The fast velocity spiral represents the fastest

M88

M35A3

M1009

Figure 1–3.—Three vehicle types used in tracking study include the M88 tank recovery vehicle (Fig. 1), the M35A3 cargo truck (Fig. 2), and the M1009 utility cargo vehicle (Fig. 3).

velocity the vehicle could safely be driven for the site conditions. Maximum velocities used in this study are faster than a vehicle would typically be driven during a training event under similar conditions. Maximum velocities varied between vehicle types due to vehicle design capabilities.

Each vehicle was equipped with a vehicle tracking system (Ayers et al. 2000). The vehicle tracking system consisted of a 12 channel Trimble® GPS receiver with Omnistar® differential correction that logged location information, a data storage device and a power source. Vehicle position was recorded every second. Vehicle dynamic properties (velocity, turning radius) were calculated from the vehicle tracking system position data using the methods of Ayers et al. (2000).

Sampling methodologies.—Initial vehicle impacts were measured immediately after tracking as disturbed width and impact severity. All measurements were made along the inner track of each spiral. The first sample location was randomly located within the first 10 m of the straight-line tracking portion of each spiral. Subsequent samples were systematically located every 5 m along the vehicle track resulting in approximately 20 sample points per spiral. Each sample point consisted of a paired subplot. One subplot was located within the track and the other subplot was 0.5 m adjacent to and on the inside of the track in undisturbed vegetation.

Disturbed width (DW) was measured perpendicular to the vehicle track and encompassed the area where soil and/or vegetation were impacted by the vehicle tire/track. The disturbed width included areas where vegetation was flattened but not killed and areas where soil was removed or piled up.

Vegetation cover was estimated using a line transect established perpendicular to the track (same measurement line as the disturbed width measurement). A second line transect was established perpendicular to the track and a 0.5 m from the track. Each undisturbed paired plot was located to the inside of the spiral in untracked vegetation. For each line transect (within track and adjacent to the track), bare ground was visually estimated and reported as a percent of plot length. One observer estimated all sample plots.

Impact severity (IS) was defined as the percent vegetation cover within the disturbed vehicle track that was removed by the vehicle resulting in exposed bare soil. Impact severity was calculated by subtracting the disturbed vehicle track subplot vegetation cover estimates from the non-tracked subplot vegetation cover estimates. Impact severity ranged from 0 (no vegetation loss) to 100 (complete vegetation loss).

Payne et al. (1983) noted that single pass straight-line tracking by light vehicles often resulted in some crushed vegetation laying horizontal to the soil surface. They noted that some of this horizontal vegetation was dead while other vegetation was still viable and recovered within a few weeks. To help interpret recovery data from our study, we recorded the types of damage observed at each measurement location.

Vegetation impacts were measured a second time at the end of the growing season during which tracking treatments occurred. Due to an extremely warm fall and late winter, 14 Dec 2001 represented the end of the growing season. Impact severity was measured using the same methods as described for the original sampling. Impact severity was estimated for the original disturbed track width.

Vegetation impacts were measured a third time on 17 July 2002. Impact severity was measured using the same methods as described for the original sampling. Impact severity was estimated for the original disturbed track width. In addition, percent ground cover of forbs, grasses and total vegetation was recorded in the disturbed track and adjacent to the track. Cover of forbs, grasses, and total vegetation was visually estimated for a plot centered in the vehicle track and 0.5 m from the outside edge of the track. The dimension of each square plot was the track width. Cover estimates were made independent of other vegetation components and were not intended to sum up to total vegetation cover.

Soil moisture was determined gravimetrically on the day of tracking for the 0 to 10.16 cm depth using methods of Gardner (1986). Soil samples were dried at 105° C for 48 h in a conventional oven. Water content was calculated on a mass basis as a percentage of dry soil. Air temperature was recorded 1 m above the soil surface at the beginning and end of tracking treatments.

Statistical analysis.—Vehicle dynamic properties (velocity, turning radius) were calculated from the GPS vehicle tracking system position data using the methods of Ayers et al. (2000). Vehicle dynamic properties were calculated for each field data sample location within each tracking course.

Vehicles impact a larger area (disturbed width) during turns (Ayers 1994; Ayers et al. 2000). A cumulative impact (CI) measure was used to quantify overall vehicle impacts that incorporated both severity of vegetation damage and area affected. Cumulative impact was calculated as the product of the impact width and impact severity on a sample plot basis.

Vegetation impact data were analyzed using the Proc Reg procedure with the stepwise option of SAS® (SAS Institute Inc., Cary, North Carolina) to determine which factors significantly contributed to vegetation damage. Vehicle type, turning radius, velocity, and all interactions were included in the stepwise regression analysis as independent variables. Impact severity, impact width, and cumulative impact were each used as the dependent variable of the stepwise analysis. All dependent variables were transformed using a log transformation.

After significant model variables were determined from the stepwise regression analysis, nonlinear regression analyses were conducted using raw dependent and independent variables. Impact severity, impact width, and cumulative impact were each used as the dependent variable. Independent variables included in the model were variables found to be significant in the stepwise regression analysis and that also accounted for a meaningful amount of the variation in dependent variables. Independent variables included in the model were turning radius and vehicle type. Vehicle type was included in the model by the use of dummy variables such that $d_1 = 0$ and $d_2 = 0$ for the M88 tank recovery vehicle, $d_1 = 1$ and $d_2 = 0$ for the M1009 utility cargo vehicle and $d_1 = 0$ and $d_2 = 1$ for the M35A3 cargo truck Model parameters were estimated using SAS® Proc Model. The general model has the form

$$y = [a + (a_1 \cdot d_1) + (a_2 \cdot d_2)]x^{[b+(b_1 \cdot d_1)+(b_2 \cdot d_2)]}$$

where y is the dependent impact variable (IS, DW, or CI), x is the independent variable for vehicle dynamic property, d_1 is the dummy variable to indicate the M1009 utility cargo vehicle, d_2 is the dummy variable to indicate the M35A3 cargo truck, a is the intercept coefficient for the M88 tank recovery vehicle, a_1 is the intercept shift coefficient for the M1009 utility cargo vehicle, a_2 is the intercept shift coefficient for the M35A3 cargo truck, b is the slope coefficient for the M88 tank recovery vehicle, b_1 is the slope shift coefficient for the M35A3 cargo truck, b_2 is the slope shift coefficient for the M1009 utility cargo vehicle.

Model parameters and R^2 values were estimated with all model terms included in the model. Model terms were then systematically removed in a stepwise manner to determine the simplest model that adequately characterized the relationship between impact measure and vehicle dynamic properties. The adjusted R^2 value of the model was used as the criteria for model selection.

Site recovery times were estimated as the number of months required for vegetation cover to in the disturbed subplots to reach undisturbed subplot vegetation cover levels. Recovery times are based solely on total vegetation cover.

Differences in forb and grass cover between tracked and untracked paired plots were calculated. An analysis of variance for forb and grass cover was conducted using track and vehicle type. Track types are curved (<20 m radius) and straight (>20 m radius). Vehicle types are M88 tank recovery vehicle, M35A3 cargo truck, and M1009 utility cargo vehicle. Tukey's Honestly Different Test was used to test differences among means.

RESULTS

Initial vehicle impacts.—Vegetation cover for undisturbed sample points averaged 100 indicating a densely vegetated site. Soil water content in the 0 to 10.16 cm layer. at the time of tracking, averaged 5%. This moisture content represents a relatively dry soil condition typical for many maneuver activities at this site. Air temperature ranged from 34–36° C during tracking treatments. Average M88 tank recovery vehicle course velocities ranged from 5.04 km per hr for the slow course to 16.92 km per hr for the fast course. Average M35A3 cargo truck course velocities ranged from 8.28 km per hr for the slow course to 15.48 km per hr for the fast course. Average M1009 utility cargo vehicle course velocities ranged from 8.28 km per hr for the slow course to 24.12 km per hr for the fast course.

For all vehicles, straight-line tracking generally resulted in flattened vegetation with little to no rutting or exposed soil. Shearing of vegetation and horizontal movement of soil primarily occurred for tracked vehicles at smaller turning radii.

Impact severity, disturbed width, and cumulative impact increased exponentially with decreasing turning radii (Figs. 4–6). The M88

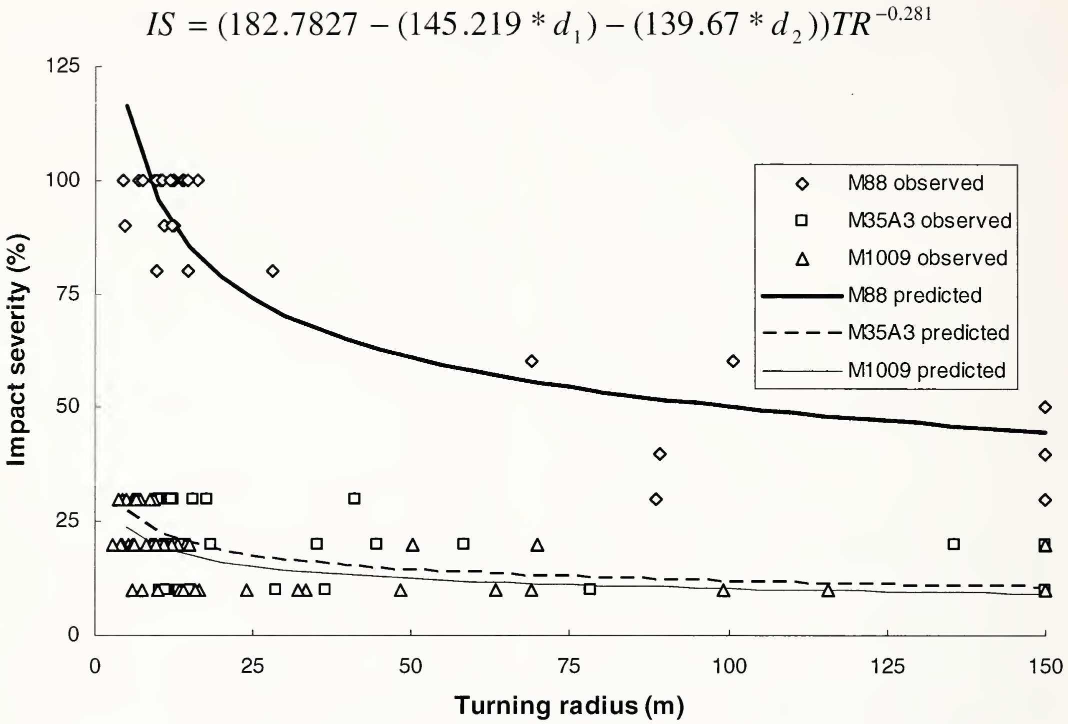

Figure 4.—Impact Severity (IS) as a function of turning radius (TR) for the M88 tank recovery vehicle, M35A3 cargo truck and M1009 utility cargo vehicle. Parameterized power equation for fitted lines provided at the top of the graph. Variables d_1 and d_2 are dummy variables that account for vehicle type. The dummy variables d_1 and d_2 have the value of $d_1 = d_2 = 0$ for the M88, $d_1 = 0$ and $d_2 = 1$ for the M35A3, and $d_1 = 1$ and $d_2 = 0$ for the M1009. R^2 fit for the equation is 0.924.

caused substantially more damage than either of the other two vehicles. For wheeled vehicles (M35A3 cargo truck, and M1009 utility cargo vehicle), disturbed width increased as turning radii decreased because rear wheels did not track directly behind front wheels during turns. For the tracked vehicle (M88 tank recovery vehicle), disturbed width increased with decreasing turning radii because the vehicle would pivot on a portion of the track causing the rear portion of the track to slide outward. This sliding action resulted in vegetation and soil being scraped out of the tracked area.

Impact measures increased suddenly at turning radii less than approximately 15–20 m for all vehicle types. Despite drastically different static vehicle design characteristics, the critical turning radii for site damage were very similar among vehicles.

Natural logarithm transformations of all impact measures (impact severity, disturbed width, and cumulative impact) and vehicle dynamic properties (turning radius and velocity) resulted in linear relationships between dependent and independent variables. Figure 7 shows a typical relationship between transformed impact measure and vehicle dynamic property.

In the stepwise regression, vehicle type, turning radius, velocity, and turning radius by velocity interaction were found to significantly ($P < 0.10$) affect impact severity, disturbed width, and cumulative impact. Model R^2 values were 0.789, 0.743, and 0.853 for impact severity, disturbed width, and cumulative impact, respectively. Even though velocity and turning radius by velocity interaction model terms were significant, they accounted for little variation in impact measures after vehicle type and turning radius were already included in the model. Partial R^2 values for velocity and turning radius by velocity interaction model terms never exceeded 0.044 after vehicle type and turning radius were already included in the model.

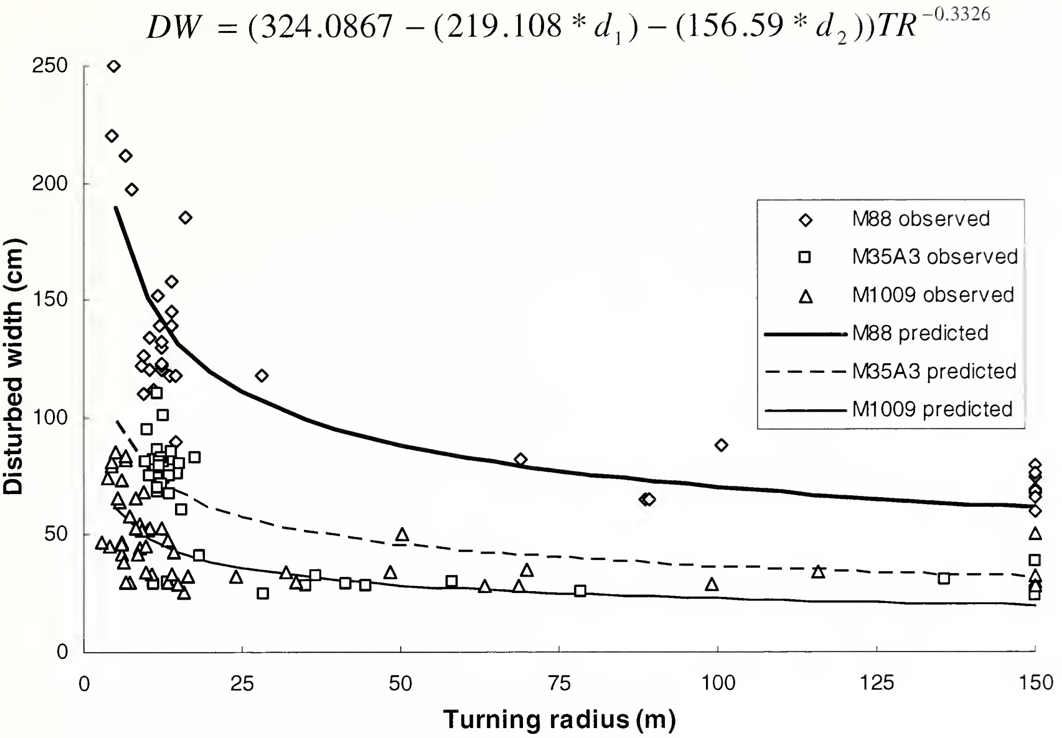

Figure 5.— Disturbed Width (DW) as a function of turning radius (TR) for the M88 tank recovery vehicle, M35A3 cargo truck and M1009 utility cargo vehicle. Parameterized power equation for fitted lines provided at the top of the graph. Variables d_1 and d_2 are dummy variables that account for vehicle type. The dummy variables d_1 and d_2 have the value of $d_1 = d_2 = 0$ for the M88, $d_1 = 0$ and $d_2 = 1$ for the M35A3, and $d_1 = 1$ and $d_2 = 0$ for the M1009. R^2 fit for the equation is 0.822.

When analyzing only straight-line tracking data (straight-line tracking is defined as turning radius greater than 20 m), velocity did not significantly ($P < 0.05$) affect impact severity, disturbed width, or cumulative impact. Only vehicle type significantly affected impact measures.

Variation in vegetation loss in straight-line portions of the vehicle course for individual vehicles appears to be due to small-scale variation in surface roughness. Most straight-line tracking resulted in compression type vegetation damage and little exposed soil for all vehicle types. Where bare ground was exposed, the track or wheel frequently passed over small depressions or hills. Hills and depressions approximately ⅛ the height or depth of the vehicle track or wheel were associated with increased bare ground. At these locations the track or wheel came in contact with the soil surface at an angle rather than parallel to the soil surface. Though not quantified in this study, observations indicate that sites with greater surface roughness resulted in greater vegetation loss during straight-line tracking.

Modeling vehicle impacts.—Natural logarithm transformations of impact measures and vehicle dynamic properties resulted in linear relationships between the variables. For all impact measures, vehicle type and turning radius were the first variables included in models during stepwise regression analysis. Additional model terms, though significant, accounted for little additional variation in the dependent variables. Based on these findings, we chose to develop models to explain the relationship between vehicle dynamic properties and impact measures using a power equation with vehicle type and turning radius as model terms. Table 1 shows alternative forms of the power equation evaluated and corresponding R^2 values for each of the three impact measures. Model 1 represents a model that accounts for turning radius but does not

$$CI = (538.2323 - (501.464 * d_1) - (473.774 * d_2))TR^{-0.5764}$$

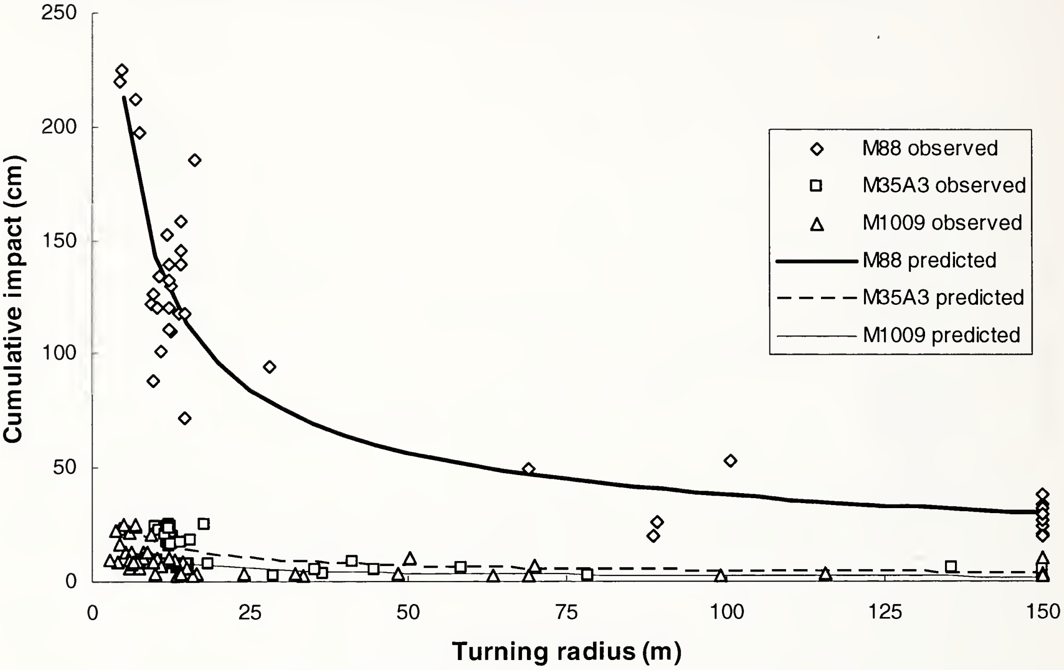

Figure 6.—Cumulative impact (CI) as a function of turning radius (TR) for the M88 tank recovery vehicle, M35A3 cargo truck and M1009 utility cargo vehicle. Cumulative impact was calculated as the product of the impact width and impact severity. Parameterized power equation for fitted lines provided at the top of the graph. Variables d_1 and d_2 are dummy variables that account for vehicle type. The dummy variables d_1 and d_2 have the value of $d_1 = d_2 = 0$ for the M88, $d_1 = 0$ and $d_2 = 1$ for the M35A3, and $d_1 = 1$ and $d_2 = 0$ for the M1009. R^2 fit for the equation is 0.924.

differentiate between vehicle types. Model 4 represents a model that accounts for vehicle type in both the '*a*' and '*b*' terms of the power model. Models 2 and 3 represent models that account for vehicle type in only the '*a*' or '*b*' term of the model, respectively. Model 2, which only accounts for vehicle type in the '*a*' term of the model was found to best fit the data for all impact measures or fit the data nearly as well as more complex models. Table 2 shows parameter estimates, standard errors, and R^2 values for the selected power models used to characterize the relationship between vehicle dynamic properties and impact measures. Model R^2 values exceeded 0.82 for all impact measures using only vehicle type and turning radius as independent variables. Figures 4–6 show model predictions and field observations for each vegetation impact measure.

Vegetation recovery.—Recovery times for total vegetation canopy cover ranged from less than 5 months to about 12 months for all vehicle and impact types (Fig. 8). Recovery times for the M1009 utility cargo vehicle where shorter than the M35A3 cargo truck, which were shorter than the M88 tank recovery vehicle. Recovery times were similar for straight-line tracks and curves despite differences in initial impacts.

Though total vegetative cover returned to pretreatment levels after approximately one year for the most severely impacted areas, other measures of site condition might not have fully recovered in this period. To evaluate if differences in species composition existed between impacted areas and adjacent areas, we measured percent grass and forb cover. No significant difference ($P < 0.05$) in grass cover between tracked and untracked areas was evident one year after tracking for any vehicle type. No significant difference ($P < 0.05$) in forb cover between tracked and untracked areas was evident for the M1009 util-

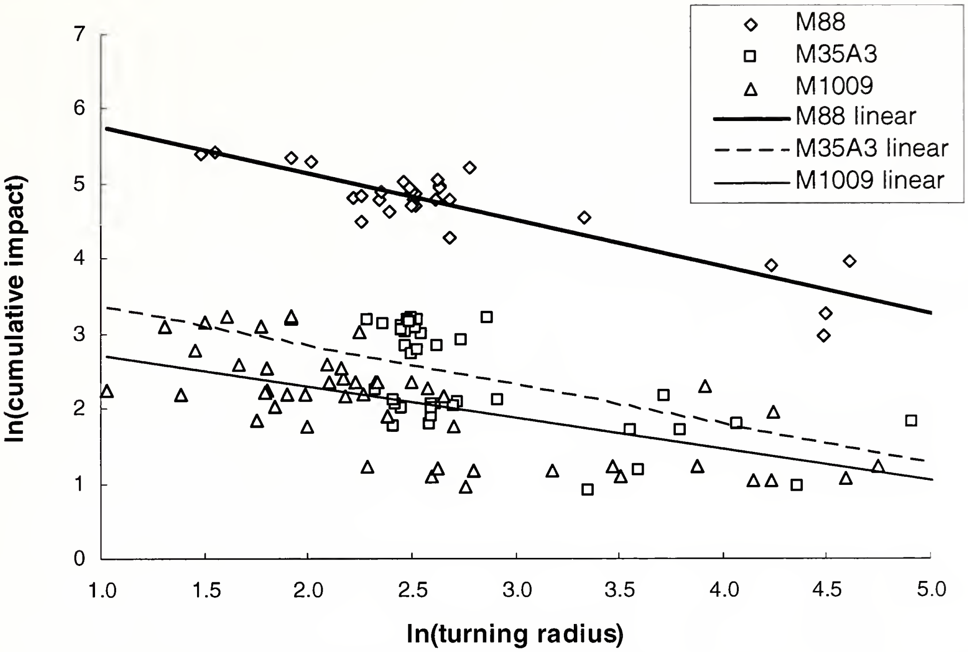

Figure 7.—Relationship between logarithmic transformation of both cumulative impact and turning radius data by vehicle type. Lines show best fit for linear relationship between variables. R^2 fit for M88 tank recovery vehicle, M35A3 cargo truck and M1009 utility cargo vehicle are 0.90, 0.40, and 0.49, respectively.

ity cargo vehicle or M35A3 cargo truck. However, the M88 tank recovery vehicle tracks with turning radii less than 20 m had 17.7% less forb cover than untracked areas (significant at $P < 0.05$). Visual observation of plots indicated that in compressed vegetation areas (primarily straight-line tracking) many of the same individual plants regenerated. In turns where the track or wheel exposed soil and created piles of soil adjacent to the track, new plants colonized the disturbed area. New plants were from seed, rhizomes, or stolons remaining in the soil.

DISCUSSION

Results of this study are consistent with previously published studies. Vehicle turns caused more damage than straight-line travel (Braunack 1986; Belcher & Wilson 1989; Ayers 1994; Watts 1998; Prosser et al. 2000; Halvorson et al. 2001). Smaller vehicle turning radii caused more vegetation loss than larger turning radii (Ayers 1994). We also found that velocity and turning radius by velocity interaction significantly affects vegetation loss that has not previously been reported in the literature.

The vehicles tested in our study had critical turning radii between 15 and 20 m where vegetation loss dramatically increased at smaller turning radii. This critical turning radius is similar to those reported for other sites (Haugen et al. 2003).

Table 1.—Adjusted R^2 values for alternative models considered in the model selection process.

Model	Model parameters	Impact severity	Disturbed width	Cumulative impact
1	$y = a_0 TR^{b_0}$	0.027	0.120	0.054
2	$y = [a_0 + (a_1 \cdot d_1) + (a_2 \cdot d_2)] TR^{b_0}$	0.924	0.822	0.933
3	$y = a_0 TR^{[b_0 + (b_1 \cdot d_1) + (b_2 \cdot d_2)]}$	0.000	0.763	0.924
4	$y = [a_0 + (a_1 \cdot d_1) + (a_2 \cdot d_2)] TR^{[b_0 + (b_1 \cdot d_1) + (b_2 \cdot d_2)]}$	0.924	0.831	0.932

Table 2.—Independent model variables, parameter estimates, and R^2 values for selected nonlinear regression models.

Model parameter	Impact severity		Disturbed width		Cumulative impact	
	Estimate	Std error	Estimate	Std error	Estimate	Std error
a_0	182.7833	8.930	324.087	21.029	538.232	38.489
a_1	−145.219	7.949	−219.108	17.102	−501.464	37.076
a_2	−139.670	7.663	−156.590	13.779	−473.774	35.241
b_0	−0.281	0.017	−0.333	0.024	−0.576	0.030
Model R^2	0.924		0.822		0.933	

Vegetation recovery times were relatively short (less than or equal to one year) on our site compared to more arid ecosystems that had recovery times ranging from a few years to a hundreds of years (Thurow et al. 1995; Lovich & Bainbridge 1999; Prosser et al. 2000). Recovery times for our study site were comparable to other grassland sites (Payne et al. 1983; Prosser et al. 2000). Payne et al. (1983) observed recovery times of about one year for an upland grassland prairie in Montana. Similarly, Prosser et al. (2000) observed recovery times for grasslands in North Dakota to be less than two years. The vegetation, soil and climate found at our study site help explain the short recovery times observed. Our study site has relatively fertile soils, sufficient moisture, and primarily early succession plant species adapted to colonizing disturbed areas.

In our study, vehicle impacts were quantified when the soil was relatively dry. Althoff & Thein (2005) demonstrated that vegetation loss by vehicle traffic increases with soil moisture. Vegetation recovery rates may have been longer if we conducted our study when the soils were wetter.

Carrying capacity models currently used by the military to estimate the capacity of lands

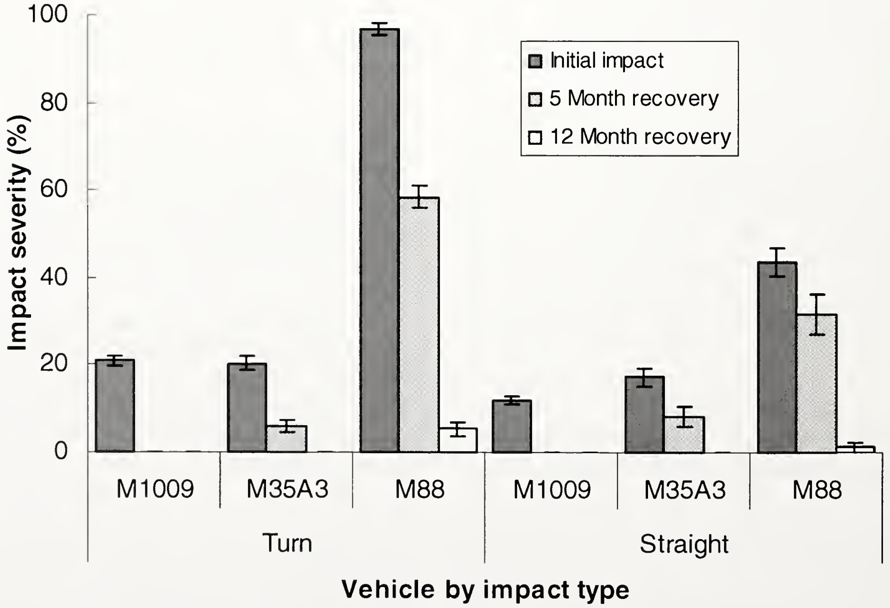

Figure 8.—Impact severity by vehicle type (M88 tank recovery vehicle, M35A3 cargo truck and M1009 utility cargo vehicle) for straight-line and turn tracking immediately, 5 months and 12 months following tracking. Straight-line tracking includes all data for turning radii greater than or equal to 20 m. Turn tracking includes all data for turning radii less than 20 m. Error bars represent ± one standard error. Impact severity at 5 and 12 months for M1009 is zero for both turn and straight tracking. Impact severity at 12 months for M35A3 is zero for both turn and straight tracking by 12 months.

to support vehicle-training activities incorporate vegetation impact and recovery time estimates from tracking studies (Diersing et al. 1988; Wilson 1988; Shaw & Diersing 1989; Anderson et al. 1996; Concepts Analysis Agency 1996). Typically, straight-line tracking study data have been used to estimate vegetation loss in these carrying capacity models. Haugen et al. (2003) found that approximately 16% of vehicle activities during real training exercises are at turning radii less than the critical turning radii determined in our study. As a result, carrying capacity estimates based on straight-line tracking data may over estimate training land capacity by underestimating vehicle impacts. The magnitude of the overestimate depends on the manner in which vehicles are used.

ACKNOWLEDGMENTS

We acknowledge the Strategic Environmental Research and Development Program (SERDP) and the Army Environmental Quality Technology program for providing financial support for this study. We gratefully acknowledge Dr. George Gertner, Dr. Guangxing Wang, and Dr. Shoufan Fang for their guidance on statistical analysis of the data.

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