EVALUATION OF EROSION AND SEDIMENTATION ASSOCIATED WITH TRACKED VEHICLE TRAINING

Jackie F. Crim, Jon E. Schoonover, Karl W.J. Williard, John W. Groninger, James J. Zaczek, and Charles M. Ruffner[1]

Abstract.—A project was designed to assess erosion and sedimentation associated with tracked vehicle training in the Ft. Knox Military Reservation in Kentucky. The project provided an extensive physical and biotic characterization of the training area, including hydrology, water quality, soils, and vegetation. To determine any changes in channel morphology, cross sections were established and surveyed in June 2008 and 2009 in the four stream channels. All four sampled streams experienced net erosion, losing between 0.31 and 44.45 m^3 of sediment a year. Otter Creek, the final receiving stream for the training areas, was sampled weekly from March 2008 through December 2008 just before it entered the training area and upon exiting the training area. Stream TSS concentrations were greater exiting compared to entering the training area. Results will provide baseline data to assist in the development of a plan for sustainable management of the training areas.

INTRODUCTION

The Department of Defense owns more than 10.1 million ha of land dedicated to military training. Military land managers face the difficult task of balancing necessary and realistic military training with protecting and maintaining environmental resources. Natural or anthropogenic changes (such as military training) to the landscape may alter the hydrologic response across a range of scales from a point to an entire drainage basin (Wigmosta and others 2009). Streams are connected to their surrounding watersheds; therefore, disturbances to the linked terrestrial ecosystems are important determinants of stream ecosystem functions and properties (Vannote and others 1980). Disturbances (e.g., soil compaction, and vegetation removal) occurring in military training areas can have significant impacts on the streams draining these areas; increased surface runoff can increase sediment inputs to streams. Managers of military land in the past have overlooked the interrelationships between soil and vegetation variables and the hydrologic impacts of tracked vehicle training (Fuchs and others 2003).

Military training activities involving large-vehicle maneuvers are a land use that has consistently shown negative effects across a variety of terrestrial ecosystems (Quist and others 2003). In terms of increased scour and sediment deposition in streams, disturbances on military lands are similar to forest land clearing for urban and agricultural development (Howarth and others 1991, Quist and others 2003). Most sediment transport from upland erosion in logged areas is facilitated by compacted, disturbed surfaces such as skidder tracks or roads (Croke and others 1999). However, because disturbance from military training is continuous and often lasts for decades (compared to short-term urban or agricultural development, where denuded soils are stabilized by vegetation), catchments within military installations may be subjected to prolonged, repeated

[1]Researcher II (JC), Assistant Professor (JS), Professor (KW), Professor (JG), Professor (JZ), Associate Professor (CR), Department of Forestry, Southern Illinois University Carbondale, 1205 Lincoln Drive, Carbondale, IL 62901;
KW is corresponding author: to contact, call (618) 453-7478 or email at williard@siu.edu.

surficial soil disturbance that can lead to sustained impacts on stream ecosystems (Maloney and others 2005). Large tracked and wheeled vehicles can traverse thousands of hectares in a single training exercise. Soil compaction, loss of vegetative cover, soil erosion, and increased abundance of introduced species are common responses to military training (Goran and others 1983, Milchunas and others 1999, Quist and others 2003).

Soil compaction and the resulting erosion are major impacts of tracked vehicles on military lands. The degree of soil compaction typically varies in proportion to the surface pressure applied (Goran and others 1983). Compaction can be slight with a single vehicle pass, while repeated passes may cause permanent damage to the landscape. An M-1 Abrams tank weighs 58 metric tons (unarmed) and applies approximately 9,200 kg m^{-2} of standing ground pressure on the soil surface (Fuchs and others 2003). These tracked vehicles are especially damaging to soil surfaces, and the skidding effect associated with sharp turns crushes and uproots the vegetation and compacts the soil (Diersing and others 1990, Fuchs and others 2003). The collapsed pore structure of the soil reduces infiltration, increases runoff, negatively impacts soil fertility, and inhibits vegetation growth.

It is necessary for land managers to properly manage these areas to keep the land usable for training while minimizing the environmental impacts of the training activities. The Army Sustainable Range Program (SRP) (Army Regulation 350-19) defines responsibilities and policies for maintaining Army-controlled lands. Specifically, the Integrated Training Area Management Program (ITAM) of the SRP is designed to integrate mission requirements with environmental requirements and conservation management practices to ensure that Army lands remain viable for future military training operations. To develop a management plan, a full assessment of the land conditions is needed. The objective of this study was to characterize two extensively used training areas on the Ft. Knox Military Reservation in Kentucky and investigate the impacts training had on soil erosion and stream water quality. This characterization will provide insight into baseline conditions following 40 years of training on this site and a basis for ITAM coordinators to develop a sustainable management plan for these training areas.

STUDY AREA

This study focused on training areas (TAs) 9 and 10 within the Ft. Knox Military Reservation, approximately 50 km southwest of Louisville, KY (Fig. 1). Watersheds in TAs 9 and 10 were delineated and surface flow paths modeled using Light Detection and Ranging (LIDAR) data. Watersheds ranged in size from approximately 12 to 39 ha. Two watersheds within each TA were chosen to examine site and stream characteristics and ultimately to investigate sediment rates exiting the TAs. This area of Kentucky features karst uplands with more than 20 sinkholes in each TA and steep hills along Otter Creek. The upland area, where training occurs, is underlain by the Mississippian St. Louis Limestone. This formation is particularly susceptible to karstification, resulting in typical surficial karst features and limited surface stream development (Connair and Murray 2002).

Soils are fine-grained silts and clays and have significant erosion potential. Within the studied watersheds, soils were fairly homogenous throughout, with Baxter soils and Hammack-Baxter complex soils on the uplands (where vehicle training occurs) and Westmoreland-Caneyville complex soils on the steep slopes along Otter Creek. Baxter soils are severely to very severely eroded and are characterized by very gravelly silty clay loam on the top 15 cm, followed by gravelly clay to a depth of 230 cm. Hammack soils are eroded soils similar to Baxter, except they are overlain by thin fine-silty loess. They are characterized by silty loam on the top 23 cm,

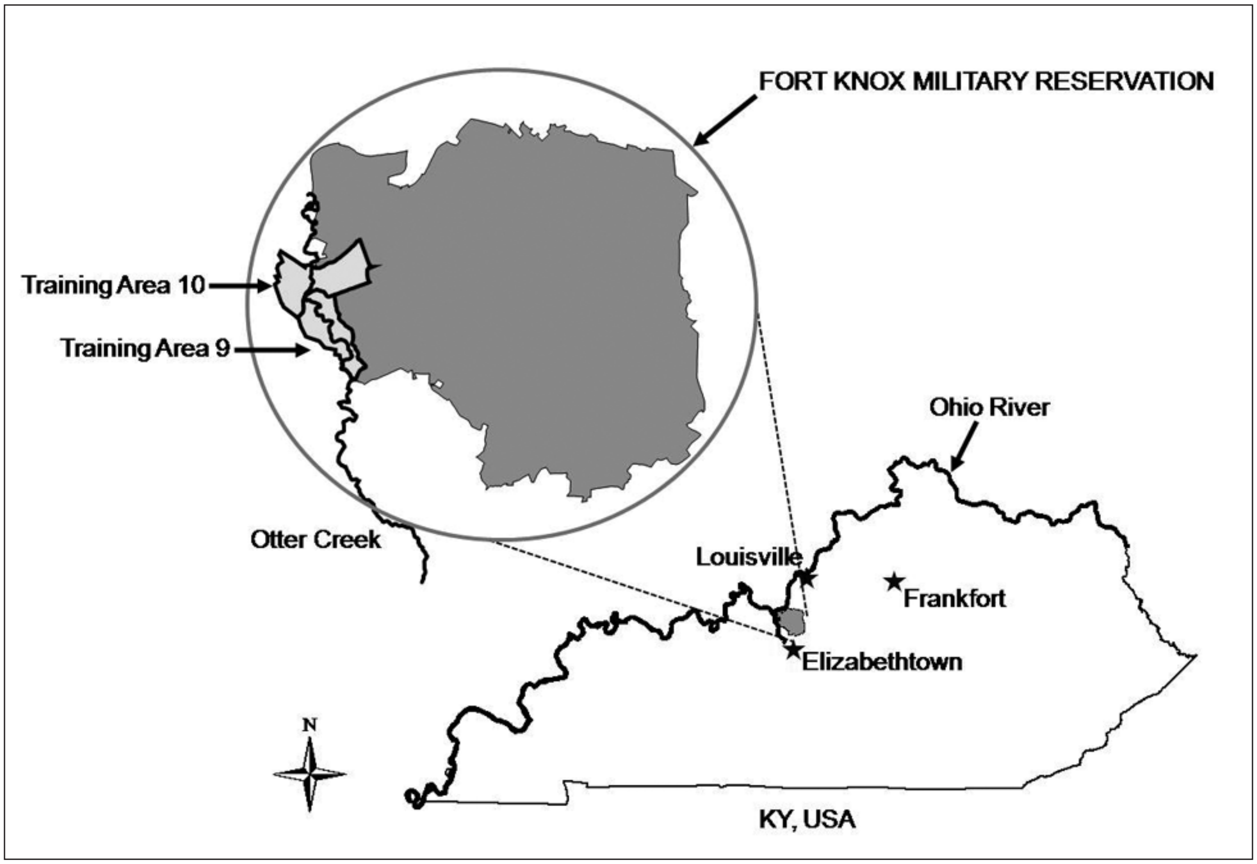

Figure 1.—Study area map of Ft. Knox Military Reservation, KY.

followed by silty clay loam (23-68 cm), extremely gravelly silty clay loam (68-102 cm), and clay (102-218 inches). Plot locations and areas of vehicle training all resided within Baxter or Hammack-Baxter complex soils. The heavily used portions of the TAs are characterized by expanses of exposed mineral soil.

The TAs are hydrologically connected, both through surface and subsurface drainage, to nearby Otter Creek. Otter Creek originates northwest of Elizabethtown, meanders north, and flows approximately 11 km through the reservation, where it then enters Otter Creek Park before draining into the Ohio River. Rills and large gullies exist throughout the TAs and are unstable and ever-changing as a result of continual training. Sediment resulting from severe erosion in the TAs is being transported off-site through surface runoff into the ephemeral streams and through the well developed underground karst drainage network via sinkholes. This area has sustained extensive tracked and wheeled vehicle training operations for more than 40 years. More than 20,000 soldiers utilize the area every year. Tracked vehicles cross the available land area at Ft. Knox at a rate of 20.78 km yr^{-1} ha^{-1} (Goran and others 1983). With the amount of bare area available for tracked vehicle usage in these watersheds and the assumption that vehicles are still using the area at this rate (tracked vehicle training has increased since this estimate was made, but no new numbers have been reported), tracked vehicles are crossing these watersheds approximately 91 to 357 km yr^{-1} (Table 1).

Table 1.—Watershed area, sinkhole drainage area, bare area, and tracked vehicle use separated by watershed in Training Areas 9 and 10 at Ft. Knox Military Reservation, KY.

WS[a]	WS area (ha)	Sinkhole drainage area (ha)	Surface drainage area (ha)	Bare area (ha)	Tracked vehicle usage (km yr^{-1})
9-1	11.62	1.54	10.08	4.40	91.43
9-2	15.93	11.49	4.44	5.97	124.09
10-1	14.24	11.42	2.82	8.06	167.49
10-2	38.54	29.00	9.54	17.19	357.17

[a]WS refers to watershed. Tracked vehicle usage is based on an estimated usage at Ft. Knox of 20.78 km yr^{-1} ha^{-1} (Goran and others 1983). Bare area is based on on-screen digitized aerial photos (2002) and refers to any area devoid of vegetation.

METHODS

SITE CHARACTERIZATION

To gain a better understanding of the landscape, plots were chosen in each watershed for soil and vegetation assessments based on land cover, i.e., road, grass, early succession, and forest. Roads were defined as primary trails within the training area and were completely devoid of vegetation. Grass plots were not currently being used as part of the trail network and consisted of native and introduced species, primarily sericea lespedeza (*Lespedeza cuneata* [Dum. Cours.] G. Don.). Plots considered early succession were patches of open canopy stands and shrubs, while forested plots were closed canopy mature stands. Watersheds contained 37 to 57 percent bare area (no vegetation was present and the land could potentially be used as roads) while the remainder of the land was vegetated. Forested areas were common throughout the training areas and primarily surrounded sinkholes or resided on the uplands along Otter Creek. Early succession and grass areas were less common. Some grass areas changed seasonally as training was often transferred to grass areas that were not staked off during wet portions of the year.

Three fixed 1/10 hectare plots per land cover were established in each watershed for surface soil characterization in August 2007. These plots were randomly selected among all the potential sites within the watersheds. All plots were located on uplands and had similar soil types (Baxter and Hammack-Baxter soils). Within the plots, five subplots were randomly selected to characterize current surface soil conditions based on bulk density, infiltration rate, particle-size class, and penetration resistance. Using the bulk density core method (Culley 1993), we measured soil bulk density by taking a core from each subplot within the watersheds. Cores were oven-dried and weighed to determine weight per given volume and the average bulk density of each land cover was calculated for each watershed. Infiltration rates were determined for each subplot by pouring a known volume of water into a single ring infiltrometer and recording the time it takes the water to infiltrate the soil. The average water infiltration rate of each land cover was calculated for each watershed.

Using the hydrometer method (Sheldrick and Wang 1993), we determined the percent of sand, silt, and clay from a soil sample of each subplot. The average soil particle-size distribution of each land cover was calculated for each watershed, from which soil texture was determined. An Eijkelkamp penetrometer was used to record soil resistance to pressure for each subplot and the average penetration resistance of each land cover was calculated for each watershed (Eijkelkamp Agrisearch Equipment, the Netherlands). Significant differences in bulk density, infiltration rate, and penetration resistance between land covers were examined using PROC GLM and Tukey's multiple comparison test in SAS (SAS Institute, Cary, NC). Before testing for significant differences, we transformed infiltration data using the natural log to satisfy normality and equal variance assumptions of parametric statistics. All other soil data did not violate these assumptions based on normal probability plots and Levene's test in SAS. For the vegetation assessment, five 1-m^2 subplots were randomly chosen in each land cover plot and ground cover species were recorded. In addition to the five subplots, all trees greater than 5 cm diameter breast height (d.b.h.) were identified in the forest and early succession plots.

STREAM MORPHOLOGY

To determine any changes in channel morphology, cross-sections were established and surveyed in the four stream channels draining the training areas. Each cross-section was 10 to 20 m apart, depending on stream length. Rebar permanently marked the cross-sections for subsequent surveying. Using a Topcon total station (Topcon Positioning Systems, Livermore, CA), the cross-sections were surveyed in June 2008 and June 2009. Changes in channel morphology were determined by calculating the cross-sectional areas derived from elevation measurements and comparing the 2 years. To calculate the change in volume at each cross-section, the change in area was assumed to be uniform across a 1-m section of stream. An estimated change in total channel volume was calculated by multiplying the average cross-sectional area of the stream by total stream length. This calculation allowed for an overall estimation of deposition or scour within the stream channel.

STORM SAMPLING

In February 2008, stream gauging stations were established in the four watersheds to measure discharge and collect storm samples for total suspended solids determination. To continuously monitor stream stage levels, an OTT Thalimedes (OTT Hydrometry, Kempten, Germany) (a float and pulley system with integrated datalogger) was installed in a PVC pipe and set to monitor stage levels at 5-minute intervals. Rating curves were developed using Manning's Equation to estimate discharge from the continuous stage data (Gore 1996). Manning's Equation uses measurements of cross-sectional area, hydraulic radius, and slope, and an estimate of channel roughness, to calculate discharge at various stage levels. These rating curves allowed for estimation of sediment yields leaving the TAs through surface area drainage.

At each gauging station, an Isco (Teledyne Isco, Inc., Lincoln, NE) automated sampler (Model 6712) was installed and connected to the Thalimedes. When the stream level exceeded a predetermined water level, a signal was sent from the Thalimedes to the Isco to initiate sampling. The Isco was programmed to take a water sample at 30-minute intervals until the stage fell back below the initiation level. Storm samples were collected and returned to the lab for TSS analyses using membrane vacuum filtration methods outlined by the Environmental Protection Agency (US EPA 1999). In addition to instantaneous samples, which provide the TSS concentration at a given time, the event mean concentration (EMC) of each storm event was calculated. The EMC represents the flow-weighted average TSS concentration during a storm event. The flow-weighted average is the sum of the TSS loads calculated for a series of storm samples divided by the sum of the discharges calculated for each of the storm samples.

Additionally, between March 2008 and December 2008, Otter Creek was sampled weekly where it enters and exits the TAs. Weekly sampling captured both baseflow and stormflow events. Samples were returned to the lab for TSS determination via vacuum filtration (US EPA 1999). Significant differences between TSS concentrations entering and exiting the TAs were analyzed using the Kruskal-Wallis test for nonparametric data in SAS.

RESULTS

SITE CHARACTERIZATION

Surface soil conditions were characterized based on bulk density, infiltration rate, particle-size class, and penetration resistance (Figs. 2-5). Road surface soils had the highest bulk density values in all watersheds, with a mean of 1.41 g cm^3 and a maximum of 1.81 g cm^3. Grass, early succession, and forest land covers averaged 1.25, 1.14, and 1.06 g cm^3, respectively. Surface soils on roads have been heavily compacted by military vehicles, decreasing pore space and thereby increasing bulk density. Roads had the lowest infiltration rates because of the high bulk densities, with a mean infiltration rate of 0.10 cm min^{-1}. Forest and early succession plots had the highest infiltration rates within the watersheds. Grass plots were similar to roads, with very low infiltration rates. This finding was expected, as the grass plots represented areas that received vehicle traffic for at least a portion of the year. Typically, this traffic occurred during the wet seasons of the year (winter, spring), when the vehicles spread out from the primary trail network. Additionally, roads in the TAs generally consisted of a higher clay percentage than did other land covers, likely from erosion of the surface horizon, leaving subsoils with higher clay content exposed. As expected, roads had the highest overall resistance to penetration, followed by grass, early succession, and forest land covers. Common ground cover species found within each plot and major overstory species identified within the forested plots are listed in Tables 2 and 3. *Sericea lespedeza*, introduced into the TAs to seed barren areas, was the primary ground cover species in disturbed areas. Seedling regeneration is limited in forested plots where sediment deposition is significant; Japanese honeysuckle (*Lonicera japonica* Thunb.), poison-ivy (*Toxicodendron radicans* (L.) Kuntze), and Allegheny blackberry (*Rubus allegheniensis* Porter) were the predominant ground cover species in forested areas.

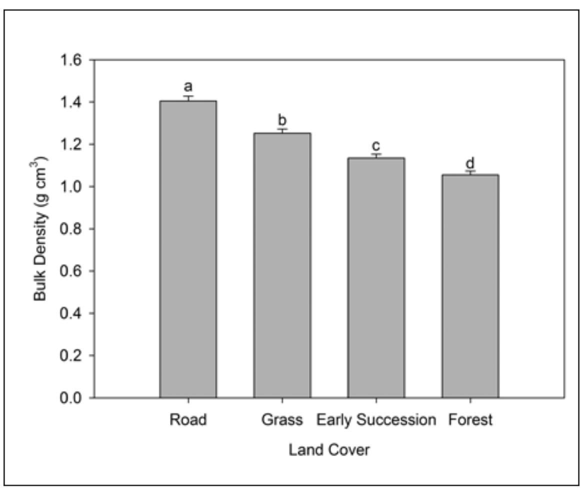

Figure 2.—Soil bulk density with standard errors by watershed and land cover in training areas 9 and 10 at Ft. Knox Military Reservation, KY. Different letters indicate a significant difference (α=0.05) in bulk density between land cover. Sample size equals 60 for each land cover.

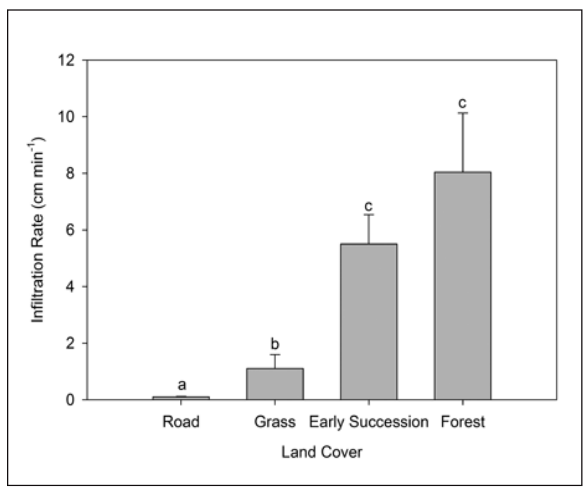

Figure 3.—Soil infiltration rates with standard errors by watershed and land cover in training areas 9 and 10 at Ft. Knox Military Reservation, KY. Different letters indicate a significant difference (α=0.05) in infiltration rate between land cover. Sample size equals 60 for each land cover.

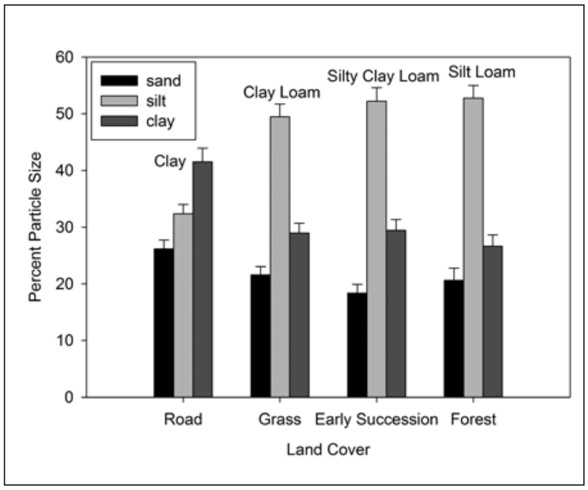

Figure 4.—Soil texture with standard errors by watershed and land cover in training areas 9 and 10 at Ft. Knox Military Reservation, KY.

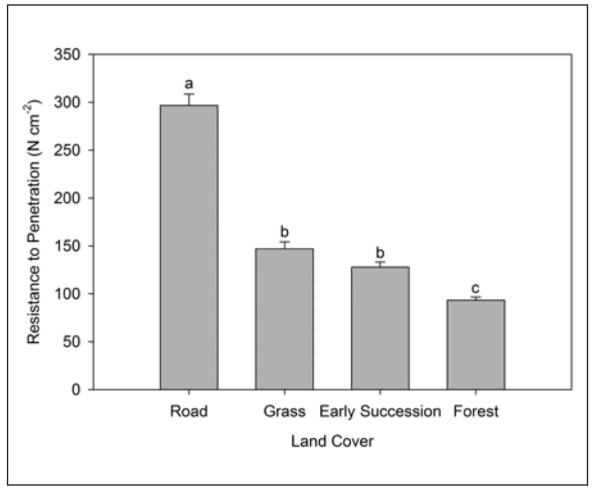

Figure 5.—Mean soil resistance to penetration with standard errors by land cover in training areas 9 and 10 at Ft. Knox Military Reservation, KY. Different letters indicate a significant difference (α=0.05) in penetration resistance between land cover. Sample size equals 60 for each land cover.

Table 2.—Common ground cover species in land cover plots (five 1-m² subplots within each land cover) in training areas 9 and 10 at Ft. Knox Military Reservation, KY.

Common name	Scientific name	Native or introduced	Main plot type(s)[a]
Annual marsh elder	*Iva annua* L.	Native	G
Black medick	*Medicago lupulina* L.	Introduced	E
Blackberry	*Rubus allegheniensis* Porter	Native	E, F
Coralberry	*Symphoricarpos orbiculatus* Moench.	Native	F
Crabgrass	*Digitaria* spp.	Introduced	F
Dallisgrass	*Paspalum dilatatum* Poir.	Introduced	E
Eastern poison-ivy	*Toxicodendron radicans* (L.) Kuntze	Native	E, F
Fall panicgrass	*Panicum dichotomiflorum* Michx.	Native	G
Giant foxtail	*Setaria faberi* Herrm.	Introduced	E
Goldenrod	*Solidago missouriensis* Nutt.	Native	G, E
Japanese honeysuckle	*Lonicera japonica* Thunb.	Introduced	E, F
Periwinkle	*Vinca minor* L.	Introduced	F
Sericea lespedeza	*Lespedeza cuneata* (Dum. Cours.) G. Don.	Introduced	G, E
White heath aster	*Symphyotrichum ericoides* (L.) G.L. Nesom.	Native	G, E, F
White snake root	*Ageratina altissima* (L.) King & H. Rob.	Native	F
Woodland sunflower	*Helianthus divaricatus* L.	Native	E
Yellow foxtail	*Setaria pumila* (Poir.) Roem. & Schult.	Introduced	G, E

[a]G refers to grass; E refers to early succession; F refers to forest.

Table 3.—Major overstory species (> 5 cm diameter breast height) in forested plots (1/10 ha) in training areas 9 and 10 at Ft. Knox Military Reservation, KY. All species are native to the area.

Common name	Scientific name
American elm	*Ulmus Americana* L.
[a]American sycamore	*Platanus occidentalis* L.
Black cherry	*Prunus serotina* Ehrh.
Black locust	*Robinia pseudoacacia* L.
Black willow	*Salix nigra* Marsh.
Blackjack oak	*Quercus marilandica* Munchh.
Boxelder	*Acer negundo* L.
Common persimmon	*Diospyros virginiana* L.
[a]Eastern cottonwood	*Populus deltoids* Bartram ex Marsh.
Eastern redcedar	*Juniperus virginiana* L.
Flowering dogwood	*Cornus florida* L.
Kentucky coffeetree	*Gymnocladus dioicus* (L.) K. Koch
Pin oak	*Quercus palustris* Munchh.
Red maple	*Acer rubrum* L.
[a]Sassafras	*Sassafras albidum* (Nutt.) Nees
Shingle oak	*Quercus imbricaria* Michx.
Swamp white oak	*Quercus bicolor* Willd.

[a]Three most common species.

STREAM MORPHOLOGY

Forty-two cross-sections were surveyed. A cross-section example from watershed 9-1 is provided (Fig. 6). Each cross-section underwent scour or deposition, or was unchanged. The average cross-sectional volume change and the estimated change in total stream channel volume are provided for each watershed (Table 4). While all streams experienced a net change of scour, losing between 0.31 and 44.45 m^3 of sediment over the year, each stream had cross-sections that underwent sediment deposition. The largest changes in cross-sectional volumes resided in watershed 9-1, ranging from a loss of 1.77 m^3 to a gain of 0.72 m^3 over a 1-m section of stream. This stream had areas of deep incision and widening, compared to the other watersheds. Watershed 10-2 experienced the smallest range in volume change (-0.16 m^3 to 0.16 m^3). Much of the stream channel in this watershed is bedrock, with some cross-sections remaining unchanged between the 2 years.

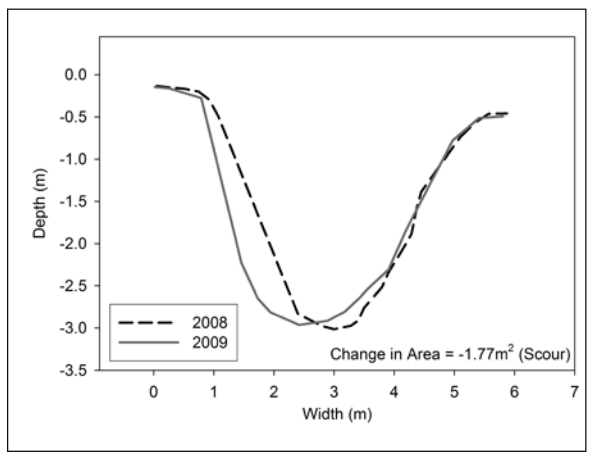

Figure 6.—Example of a stream cross-section in watershed 9-1 comparing the 2008 and 2009 morphology survey in training areas 9 and 10 at Ft. Knox Military Reservation, KY.

Table 4.—Changes in stream channel morphology in training areas 9 and 10 at Ft. Knox Military Reservation, KY.

Stream	Mean change in cross-section volume (m^3 yr^{-1})	Total change in channel volume (m^3 yr^{-1})	Net stream channel change
9-1	-0.17 ± 0.26	-27.80	Scour
9-2	-0.37 ± 0.26	-14.81	Scour
10-1	0.01 ± 0.03	-0.31	Scour
10-2	-0.11 ± 0.07	-44.45	Scour

STORM SAMPLING

Watersheds

Twenty-six storm events were captured in the four watersheds combined. An example hydrograph of a storm event in watershed 10-2 and the associated TSS samples are provided (Fig. 7). Mean TSS concentrations of each watershed (based on instantaneous samples) ranged from 314 to 6,413 mg L^{-1} (Table 5). TSS EMCs of each watershed (based on flow-weighted samples) ranged from 640 to 10,521 mg L^{-1} (Table 5). Using the rating curves developed from continuous stage data, sediment yields were calculated on a per-area basis. Mean TSS yields ranged from 6 to 127 metric ton yr^{-1} ha^{-1} (Table 5). It is estimated that TAs 9 and 10 are exporting 27 and 40 metric ton yr^{-1} ha^{-1}, respectively, through surface water drainage.

Otter Creek

Forty-three samples (31 baseflow and 12 stormflow) were taken. Mean TSS concentrations were higher exiting than entering the TAs during baseflow, stormflow, and combined flows (Fig. 8). Additionally, 74 percent of combined flow samples, 63 percent of baseflow samples, and 100 percent of stormflow samples had higher values exiting versus entering the TAs.

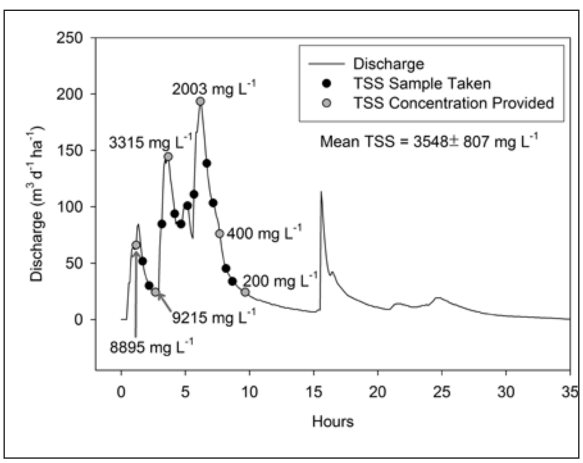

Figure 7.—Example of a sampled storm event in training areas 9 and 10 at Ft. Knox Military Reservation, KY: Watershed 10-2, April 19, 2009, 3.12 cm rainfall. Total suspended solids (TSS) concentrations measured at 30 minute intervals along the hydrograph.

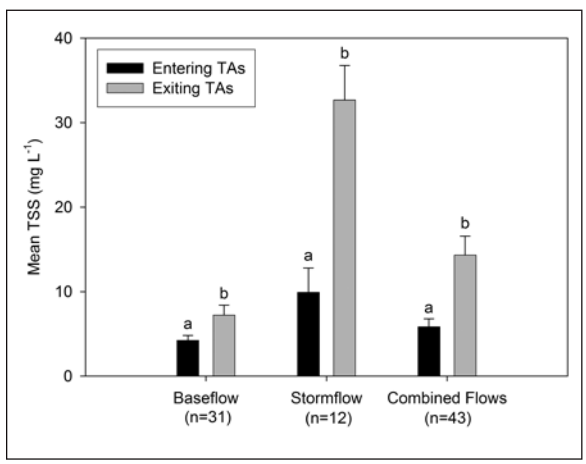

Figure 8.—Total suspended solids (TSS) concentrations with standard errors during baseflow and stormflow sampling of Otter Creek, the receiving stream of training areas 9 and 10 at Ft. Knox Military Reservation, KY. Different letters indicate a significant difference (α=0.05) in TSS within flow categories. 'TA' refers to training area.

Table 5.—Mean watershed discharge and total suspended solids concentrations and loads during storm events in training areas 9 and 10 at Ft. Knox Military Reservation, KY.

WS[a]	TSS EMC (mg L^{-1})	TSS (mg L^{-1})	TSS (metric ton yr^{-1} ha^{-1})	Discharge during sampling (m^3 d^{-1} ha^{-1})
9-1	741 ± 56	591 ± 62	33 ± 6	127 ± 15
9-2	10,521 ± 6,040	6,412 ± 1,288	23 ± 19	6 ± 2
10-1	640 ± 294	314 ± 80	26 ± 6	114 ± 17
10-2	3,666 ± 1,761	2,443 ± 420	43 ± 10	40 ± 3
TA 9	7,727 ± 4,541	4,084 ± 817	27 ± 12	49 ± 8
TA 10	3,018 ± 1,413	1,817 ± 307	39 ± 8	55 ± 5
Overall	4,587 ± 1,781	2,765 ± 391	33 ± 7	52 ± 5

[a]WS refers to watershed; TSS refers to total suspended solids; EMC refers to event mean concentration; TA refers to training area.

DISCUSSION

The soil and vegetation disturbance from training activities has resulted in bare ground, significant surface compaction, and erosion down to the subsoils in many areas. These effects are damaging the water quality of the subsurface drainage network since much of the eroded soil is transported into sinkholes through flowpaths and gullies in the TAs. Groundwater tracer tests were performed on nearby sinkholes and sinking streams (injection sites were not within the boundaries of TAs 9 and 10) to determine groundwater flowpaths and identify the potential for contamination of McCraken Springs, a source of public water supply located on TA 9 (Taylor and McCombs 1998). Contaminants, such as increased sediment, could be expected to resurface at McCraken Springs within 1 to 5 days, depending on distance of the entry point and hydrologic flow conditions (Taylor and McCombs 1998). Additionally, soil from the TAs is deposited directly into the ephemeral stream networks via overland flow. The subsurface and surface drainage network combine to create an extensive network of flowpaths that are collecting and transporting sediment into Otter Creek, the final receiving stream of these TAs.

The effects of both catchment and localized disturbances such as military training, forest clearing, agricultural practices, and urban development can be particularly strong during storm events. Houser and others (2006) found mean storm event TSS concentrations ranging from 847 to 1,881 mg L^{-1} in watersheds with high disturbance at Ft. Benning Military Installation in Georgia. Lenat and Crawford (1994) revealed higher TSS concentrations during storm events in urban watersheds (440 mg L^{-1}) followed by agricultural (267 mg L^{-1}) and forested (198 mg L^{-1}) watersheds in North Carolina; they estimated sediment yields in urban watersheds to be 1.32 metric ton yr^{-1} ha^{-1} compared to 0.291 metric ton yr^{-1} ha^{-1} in the forested watershed. Comparatively, this study found elevated mean TSS concentrations exiting the training areas during storm events (314 to 6,413 mg L^{-1}) and much greater yields of sediment leaving the TAs per yr (23 to 43 metric ton yr^{-1} ha^{-1}) than with urban or agricultural disturbance. Additionally, mean watershed TSS EMCs (640 to 10,521 mg L^{-1}) in this study were much greater than that of a 90th-percentile urban site (300 mg L^{-1}) sampled as part of the U.S. Environmental Protection Agency's Nationwide Urban Runoff Program (US EPA 1983).

Soil texture is related to soil bulk density and is an indicator of a soil's susceptibility to compaction. Fine-textured loamy and clayey soils are generally considered more vulnerable to compaction and therefore are more susceptible to impacts of heavy loads (Milchunas and others 1999). Bulk densities are generally higher deeper in the soil profile, where the organic matter content is low, fewer roots exists, and the overlying weight of the soil profile has increased compaction. Roads in the TAs have been eroded of upper soil horizons as a result of training exercises and consequently have high bulk densities compared to forested areas, where the topsoil is still intact. High bulk densities and decreased vegetative cover have reduced infiltration into the soil. Thurow and others (1993) found an increase in bulk density on wet-tracked sites at Ft. Hood, TX, with a bulk density of 1.13 g cm^3 in the control and 1.33 g cm^3 after 10 passes of an M2 Bradley Infantry Fighting Vehicle; infiltration rates also declined as the number of passes over wet soils increased. Comparatively, Whitecotton and others (2000) characterized surface soils after 2 years of intensive training via foot traffic at the U.S. Air Force Academy in Colorado. They found a mean bulk density and infiltration rate of 1.37 g cm^3 and 0.63 cm min^{-1} in high-use training sites versus 1.04 g cm^3 and 3.83 cm min^{-1} in reference sites with little to no training. Both Whitecotton and others (2000) and this study revealed significantly higher soil bulk density and significantly lower infiltration rates in the heavily used areas compared to the reference and forest areas. Reduced infiltration generates more surface runoff into the sinkholes and ephemeral streams of TAs 9 and 10, resulting in continued erosion. Sediment transported off-site is impairing the water quality of Otter Creek, as evidenced by higher TSS concentrations exiting the TAs than entering the TAs.

MANAGEMENT IMPLICATIONS

Without restorative measures, erosion will continue along with the resulting impacts on water quality in the subsurface system and Otter Creek. Erosion causes loss of soil fertility, impacting the success of terrestrial restoration activities even after disturbance has ceased. In much of the TAs, topsoil has been removed, leaving compacted soils deeper in the profile exposed and thereby increasing the difficulty of vegetation regeneration. Though natural weathering processes such as freezing and thawing and renewed root growth can eventually restore the structure of the compacted soil (spanning 1,000 years or more), continued use of the area keeps the surface soils in a compacted state (Goran and others 1983). U.S. Department of Defense leadership and land managers at the Ft. Knox Military Reservation are concerned about the environmental impacts of training activities and are directing the implementation of best management practices to reduce the amount of sediment entering the sinkholes and ultimately Otter Creek.

TAs 9 and 10 at Ft. Knox have undergone continued repeated training for more than 40 years. Areas that receive constant, intense use, such as these TAs, may have degraded beyond the point of restoring the ecological integrity of the landscape, but active management could allow continued use for training and reduce off-site sediment transport.

It is difficult to assess the success of vegetation recovery in this area because training was so widely dispersed throughout the site. However, vegetated buffer zones have been a long-standing means of protecting streams from anthropogenic disturbances. These buffer zones have been incorporated into best management practices in forestry, agriculture, and engineering, with varying degrees of success for intercepting sediment inputs. Grass cover is considered one of the most effective agents in filtering and depositing sediment from surface runoff because of the extensive dense ground cover (Wischmeier and Smith 1978). Grass buffers should be extended and maintained along the primary connected concentrated flow paths to promote sustained herbaceous cover. Additionally, tank trails within sinkhole buffers should be cyber-staked (a marking methodology that informs troops of areas of restricted use) and replanted to reduce sediment transport into the sinkholes.

Gully stabilization would also reduce soil erosion and help maintain the areas for future training. Depending on the severity of gully incision and widening, appropriately sized check dams could be installed to stabilize the channel and limit further incision and widening. Similarly, stabilization of the ephemeral streams draining the watersheds would likely reduce the scouring evident in this study.

CONCLUSIONS

Disturbance over the past decades in the military vehicle training areas has caused significant soil compaction and soil loss by erosion, leaving subsoils exposed. Altering the soil in this way can have detrimental effects on vegetation growth and sustainability. With continued loss of vegetation, realistic training efforts may be difficult as there are fewer places for soldiers and vehicles to take cover in training exercises. In addition to the training challenges, ecosystems linked to the TAs are being degraded, impacting water quality in the underground karst network and Otter Creek. The U.S. Department of Defense is taking a proactive approach in addressing the environmental impacts of training activities by implementing best management practices, such as vegetated buffer zones, to reduce the amount of sediment entering sinkholes and streams.

ACKNOWLEDGMENTS

The authors thank Scot Serafin, Integrated Training Area Management Coordinator at Ft. Knox, and Rick Tibbitts of ICI Services for their assistance with project logistics and administration. Christine Goldstein, Kevin Bold, Klairoong Pattumma, J.P. Hetterich, Emma Bialecki, Andrew Somor, Michael Hatfield, and Nicholas Zaczek are acknowledged for their assistance with field data collection. This research was supported by funding from the U.S. Department of Defense.

LITERATURE CITED

Connair, D.P.; Murray, B.S. 2002. **Karst groundwater basin delineation, Fort Knox, Kentucky.** Engineering Geology. 65: 125-131.

Croke, J.; Hairsine, P.; Fogary, P. 1999. **Sediment transport, redistribution and storage on logged forest hillslopes in south-eastern Australia.** Hydrological Processes. 13: 2705-2720.

Culley, J.L.B. 1993. **Density and compressibility. 50.2 Bulk Density.** In: Soil sampling and methods of analysis. Boca Raton, FL: CRC Press. 529-532.

Diersing, V.E.; Courson, J.A.; Warren, S.D.; Tazik, D.J.; Shaw, R.B.; Novak, E.W. 1990. **A climatic basis for planning military training operations and land maintenance activities.** Technical Report N-90/13. Champaign, IL: U.S. Army Corps of Engineers. 24 p.

Fuchs, E.H.; Wood, M.K.; Jones, T.L.; Racher, B. 2003. **Impacts of tracked vehicles on sediment from a desert soil.** Journal of Range Management. 56(4): 342-352.

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.** Tech. Rep. N-142. Champaign, IL: U.S. Army Corps of Engineers. 79 p.

Gore, J.A. 1996. **Discharge measurements and streamflow analysis.** In: Methods in stream ecology. San Diego, CA: Academic Press. 53-74.

Houser, J.N.; Mulholland, P.J.; Maloney, K.O. 2006. **Upland disturbance affects headwater stream nutrients and suspended sediments during baseflow and stormflow.** Journal of Environmental Quality. 35: 352-365.

Howarth, R.W.; Fruci, J.R.; Sherman, D. 1991. **Inputs of sediment and carbon to an estuarine ecosystem: Influence of land use.** Ecological Applications. 1(1): 27-39.

Lenat, D.R.; Crawford, J.K. 1994. **Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams.** Hydrobiologia. 294: 185-199.

Maloney, K.O.; Mulholland, P.J.; Feminella, J.W. 2005. **Influence of catchment-scale military land use on stream physical and organic matter variables in small southeastern plains catchments (USA).** Environmental Management. 35(5): 677-691.

Milchunas, D.G.; Schultz, K.A.; Shaw, R.B. 1999. **Plant community response to disturbance by mechanized military maneuvers.** Journal of Environmental Quality. 28: 1533-1547.

Quist, M.C.; Fay, P.A.; Guy, C.S.; Knapp, A.K.; Rubenstein, B.N. 2003. **Military training effects on terrestrial and aquatic communities on a grassland military installation.** Ecological Applications. 13(2): 432-442.

Sheldrick, B.H.; Wang, C. 1993. **Particle size distribution. 47.3 Hydrometer Method.** In: Soil sampling and methods of analysis. Boca Raton, FL: CRC Press. 507-507.

Taylor, C.J.; McCombs, G.K. 1998. **Recharge-area delineation and hydrology, McCraken Springs, Fort Knox Military Reservation, Meade County, Kentucky.** Water-Resources Investigations Report 98-4196. Louisville, KY: U.S. Geological Survey. 12 p.

Thurow, T.L.; Warren, S.D.; Carlson, D.H. 1993. **Tracked vehicle traffic effects on the hydrologic characteristics of central Texas rangeland.** Transactions of the American Society of Agricultural Engineers. 36(6): 1645-1650.

U.S. Environmental Protection Agency. 1983. **Results of the nationwide urban runoff program, vol. 1.** Final Report, NTIS PB84-185552. Washington, DC: U.S. Environmental Protection Agency. 200 p.

U.S. Environmental Protection Agency. 1999. **Standard operating procedure for the analysis of residue, non-filterable (suspended solids) water.** Method 160.2 NS. Chicago, IL: U.S. Environmental Protection Agency Region 5 Central Regional Laboratory.

Vannote, R.L.; Minshall, G.W.; Cummins, K.W.; Sedell, J.R.; Cushing, C.E. 1980. **The river continuum concept.** Canadian Journal of Fisheries and Aquatic Sciences. 37: 130-137.

Whitecotton, R.C.A.; David, M.B.; Darmody, R.G.; Price, D.L. 2000. **Impact of foot traffic from military training on soil and vegetation properties.** Environmental Management. 26(6): 697-706.

Wigmosta, M.S.; Lane, L.J.; Tagestad, J.D.; Coleman, A.M. 2009. **Hydrologic and erosion models to assess land use and management practices affecting soil erosion.** Journal of Hydrologic Engineering. 14(1): 27-41.

Wischmeier, W.H.; Smith, D.D. 1978. **Predicting rainfall erosion losses: A guide to conservation planning.** USDA Agriculture Handbook 537. Washington, DC: U.S. Department of Agriculture, Science and Education Administration. 69 p.