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Influence of Catchment-Scale Military Land Use on Stream Physical and Organic Matter Variables in Small Southeastern Plains Catchments (USA)

KELLY O. MALONEY*
Department of Biological Sciences
Auburn University
331 Funchess Hall
Auburn, Alabama 36849-5407, USA

PATRICK J. MULHOLLAND
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831, USA

JACK W. FEMINELLA
Department of Biological Sciences
Auburn University
331 Funchess Hall
Auburn, Alabama 36849-5407, USA

ABSTRACT / We conducted a 3-year study designed to examine the relationship between disturbance from military land use and stream physical and organic matter variables within 12 small (<5.5 km^2) Southeastern Plains catchments at the Fort Benning Military Installation, Georgia, USA. Primary land-use categories were based on percentages of bare ground and road cover and nonforested land (grasslands, sparse vegetation, shrublands, fields) in catchments and natural catchments features, including soils (% sandy soils) and catchment size (area). We quantified stream flashiness (determined by slope of recession limbs of storm hydrographs), streambed instability (measured by relative changes in bed height over time), organic matter storage [coarse wood debris (CWD) relative abundance, benthic particulate organic matter (BPOM)] and stream-water dissolved organic carbon concentration (DOC). Stream flashiness was positively correlated with average storm magnitude and percent of the catchment with sandy soil, whereas streambed instability was related to percent of the catchment containing nonforested (disturbed) land. The proportions of in-stream CWD and sediment BPOM, and stream-water DOC were negatively related to the percent of bare ground and road cover in catchments. Collectively, our results suggest that the amount of catchment disturbance causing denuded vegetation and exposed, mobile soil is (1) a key terrestrial influence on stream geomorphology and hydrology and (2) a greater determinant of in-stream organic matter conditions than is natural geomorphic or topographic variation (catchment size, soil type) in these systems.

Stream ecosystems are tightly coupled with their catchments, historically being a product of natural geological and climatological attributes. However, in many geographic regions, dramatic human alteration of catchments from land-use practices has become a major source of landscape change (Hooke 1994, 1999). The effect of anthropogenic land use on stream systems is especially evident in the Southeastern Plains ecoregion of the United States (*sensu* Omernik 1987), where extensive agriculture, timber harvesting, and population growth have accelerated forestland conversion over the last 200 years (Hilliard 1984; USDOC 1990, Frost 1993). In addition, highly erodible sandy soils of this region (Griffith and others 2001) coupled with extensive land-use change might cause high upslope erosion and downslope sedimentation and, hence, sediment delivery to receiving streams.

Unlike that of the Southeastern Plains, effects of land use on streams in upland regions have been extensively studied (Harmon and others 1986; Herlihy and others 1998; Paul and Meyer 2001; Meador and Goldstein 2003). For example, in streams within nearby upland Piedmont and Blue Ridge ecoregions, discharge and flashiness (i.e., magnitude of hydrologic response to storms) often increase in response to catchment urbanization (Paul and Meyer 2001; Rose and Peters 2001) and forest harvest (Swank and others 2001), as does increase the export of dissolved organic

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*Author to whom correspondence should be addressed; *email:* malonko@auburn.edu

carbon (DOC) (Meyer and Tate 1983) and inorganic sediment loading from road construction (Swank and others 2001; King and Gonsier 1980; Reid and Dunne 1984). Unfortunately, extrapolation of changes in stream conditions associated with land use from stony, high-gradient systems to those of sandy, low-gradient Southeastern Plains streams, especially concerning sediment movement and bed stability, might not be applicable (Feminella 2000). If true, then the inherent difficulty in separating natural geomorphic influences from anthropogenic impacts on physicochemical and biotic variables within Southeastern Plains streams might be especially problematic (but see Morgan and Good 1988; Lenat and Crawford 1994; Dow and Zampella 2000).

Military installations occur throughout the United States and generally contain large tracts of land devoid of contemporary urban or agricultural land use. Streams draining military lands often are exposed to catchment disturbance from recurring training maneuvers ranging from light dismounted infantry and mechanized forces to munitions detonation and use of heavy (tracked) vehicles (Dale and others 2002). The spatial extent of training and associated disturbance ranges from localized to broad scale, where loss of vegetation, soil compaction, and sediment runoff can occur over several contiguous hectares (Goran and others 1983; Shaw and Diersing 1990, Milchunas and others 2000). Such large-scale disturbances are similar to forest land clearing for suburban, urban, and agricultural development, in terms of increased soil erosion and sedimentation in streams (Howarth and others 1991; Quist and others 2003). However, whereas physical disturbance to the soil surface from suburban, urban, and agricultural development could be short term (months to years), lasting only until denuded soils are stabilized by revegetation and/or physical remediation, disturbance from military training often is continuous (decades) from repeated training of military personnel. Thus, compared with other land uses, catchments within military installations might be subjected to prolonged, repeated surficial soil disturbance, which could have pervasive impacts on streams and their biota.

To date, the majority of stream studies conducted on military lands have been focused on developing bioassessment protocols (e.g., Tertuliani 1999; Gregory and others 2001) rather than explicitly addressing nutrient and sediment runoff into receiving streams associated with training. To our knowledge, only Quist and others (2003) addressed putative impacts of military training on stream abiotic factors, reporting increased sediment in stream pools and riffles and associated increases in silt-tolerant fauna, within high-use catchments. However, that study was done in mesic tallgrass prairie systems containing naturally steep-gradient streams with coarse substrate; virtually nothing is known about the degree to which landscape alteration from military training affects stream physical and organic matter variables in relatively low-gradient, sandy channels such as in the Southeastern Plains.

We investigated the relationships between military land use and physical and organic matter variables within small Southeastern Plains streams at the Fort Benning Military Installation, Georgia. Specifically, we tested whether stream hydrology (discharge, flashiness), geomorphology (streambed instability), and organic matter state (DOC, coarse woody debris, benthic particulate organic matter abundance) were better explained by variation in military land use at the catchment scale versus that of natural catchment features, including drainage area and predominant soil types.

Methods

Study Site

We studied several streams and their catchments at the Fort Benning Military Installation (FBMI), within the Middle Chattahoochee River Drainage, in west-central Georgia (Figure 1). Catchments were within the Southeastern Plains ecoregion and the Sand Hills and Southern Hilly Gulf Coastal Plain subecoregions (Griffith and others 2001). Fort Benning comprises 735 km^2 and is possibly an important source of sedimentation in the Chattahoochee River Basin (NAPA 2001). Prior to military acquisition, the primary land use at FBMI was row crop agriculture and pasture (Kane and Keeton 1998; USAIC 2001). The US military purchased ~50% of the present-day area in 1918 and the remainder in 1941 and 1942. Since the 1940s, FBMI has been used for infantry and mechanized training with associated heavy equipment vehicles, including tanks, armored personnel carriers, and a variety of light- and heavy-wheeled vehicles (USAIC 2001).

At FBMI, military training dramatically alters the landscape by disrupting vegetative cover and the underlying surface soil layer (Dale and others 2002). Training maneuvers are localized and contained within compartments and differ in size and magnitude depending on compartment; thus, it was possible to investigate the effects of catchment-scale disturbance across a range of disturbance intensities. Additionally, forestry practices such as controlled burning and tim-

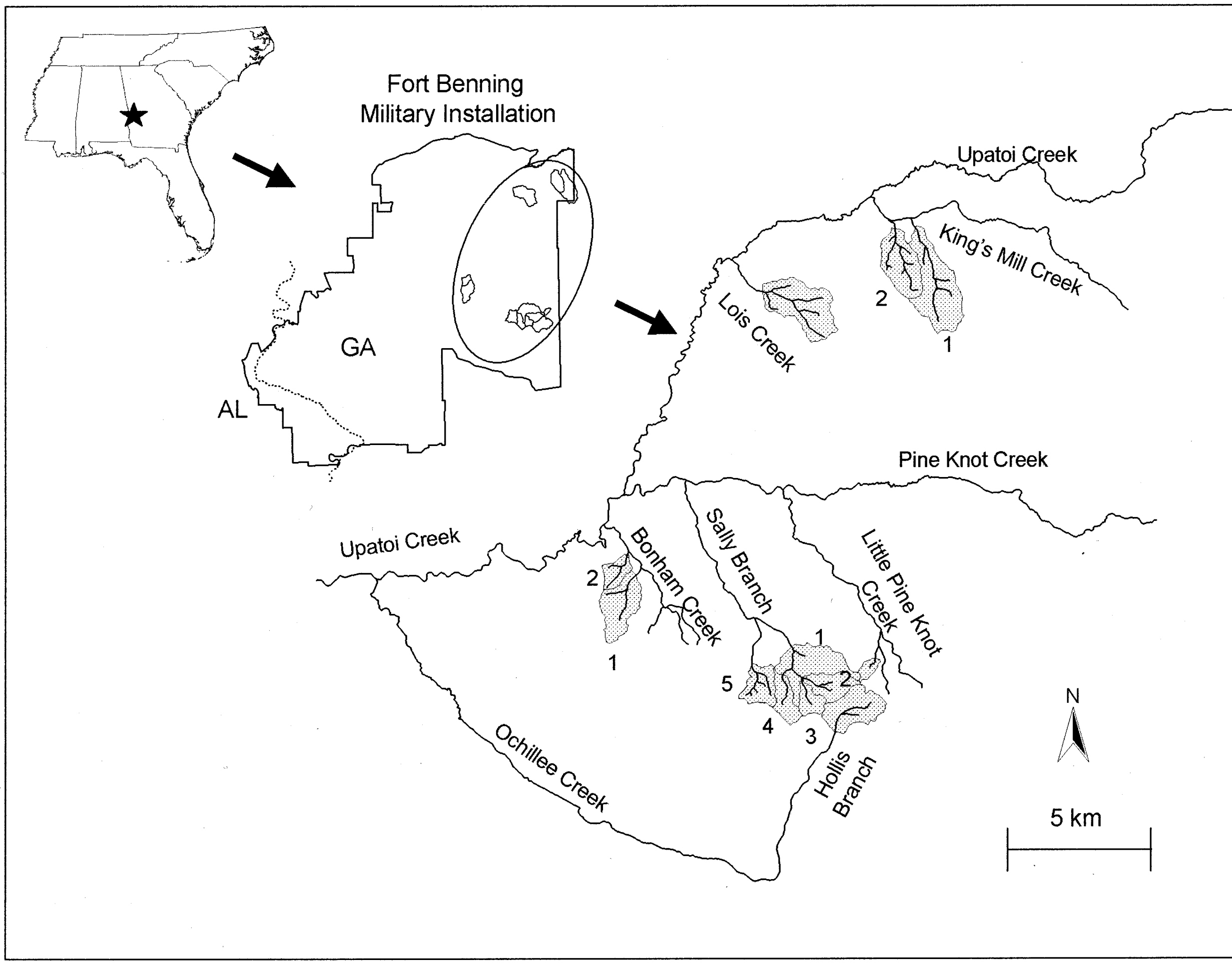

Figure 1. Locations of study catchments (depicted by polygons) within Fort Benning Military Installation, Georgia. Dotted line in the middle figure represents the Chattahoochee River, which separates Alabama (AL) and Georgia (GA). Numbers in the right figure identify watersheds on the same stream (e.g., 1 and 2 on the Bonham Creek represent Bonham Creek Tributaries 1 and 2, BC1 and BC2, respectively). Geographic coordinates and stream characteristics are given in Table 1.

ber harvesting frequently are used at FBMI (USAIC 2001), in large part relating to reestablishment of longleaf pine (*Pinus palustris*) forests and endemic red-cockaded woodpecker (*Picoides borealis*) populations (Dale and others 2002; see also Noss 1989).

We studied twelve second- and third-order stream catchments on the eastern part of FBMI (Figure 1). Vegetation was primarily oak-hickory-pine and southern mixed forest, with underlying sandy or sandy clay loams soils (Omernik 1987; Griffith and others 2001). Dominant soil series found within catchments were Troup, Lakeland, Nankin, and Cowarts soils. Troup soils are deep, excessively drained, moderately permeable loamy, kaolinitic, thermic Grossarenic Kandiudults. Lakeland soils are very deep, excessively drained, rapidly to very rapidly permeable, thermic coated Typic Quartzipsamments. Nankin soils are very deep, well-drained, moderately slowly permeable, fine, kaolinitic, thermic Typic Kanhapludults. Dominant hydric soils included Bibb and Chastain soils. Bibb soils are very deep, poorly drained, moderately permeable coarse-loamy, siliceous, active, acid, thermic Typic Fluvaquents. Chastain soils are very deep, poorly drained, fine, mixed, semiactive, acid, thermic Fluvaquentic Endoaquepts (Soil Survey Staff 2004). Geology is mainly Cusseta Sand (Lawton 1976). Study streams were low gradient (range = 0.8–5.1%, mean = 1.9%) with an intact riparian canopy (summer canopy cover range = 89–96%, mean = 94%, Table 1), typical of other sandy Southeastern Plains streams (Felley 1992; Griffith and others 2001). Dominate riparian vegetation included blackgum (*Nyssa syvlatica*), sweetgum

Table 1. Locations and characteristics of study streams at Fort Benning Military Installation, Georgia

Stream	Abbreviation	UTM	Military land use	Stream order	Drainage area (km^2)	Mean stream slope (%)	Average wetted width (m)	Average wetted depth (m)	Average bankfull depth (m)	% Canopy cover (summer)
Bonham Tributary	BC1	0710893N, 3588286E	Infantry/ ranger	2	2.10	1.67	1.34	0.16	0.45	94.19
Bonham Tributary	BC2	0710627N, 3588976E	Infantry/ ranger	2	0.75	2.67	0.99	0.10	0.41	94.59
Hollis Branch	HB	0717848N, 3583123E	Infantry/ ranger	2	2.15	2.00	1.98	0.12	0.43	91.86
Kings Mill Creek Tributary	KM1	0720701N, 3600036E	Infantry/ ranger	2	3.69	0.83	2.17	0.17	0.25	95.22
Kings Mill Creek Tributary	KM2	0719946N, 3599991E	Infantry/ ranger	3	2.31	1.00	1.66	0.19	0.36	94.34
Lois Creek	LC	0715377N, 3597908E	Infantry/ ranger/ impact	2	3.32	1.69	1.41	0.14	0.43	91.67
Little Pine Knot Tributary	LPK	0719223N, 3585421E	Heavy machinery	2	0.33	5.10	0.98	0.07	0.24	96.23
Sally Branch Tributary	SB1	0716349N, 3585850E	Heavy machinery	3	5.43	1.33	1.96	0.10	0.52	ND
Sally Branch Tributary	SB2	0716808N, 3584787E	Heavy machinery	2	1.23	2.31	1.58	0.09	0.39	93.33
Sally Branch Tributary	SB3	0716673N, 3584684E	Infantry/ ranger	1	0.72	1.00	1.03	0.07	0.31	95.04
Sally Branch Tributary	SB4	0716005N, 3584889E	Heavy machinery	1	1.00	1.33	1.26	0.07	0.21	88.50
Sally Branch Tributary	SB5	0714935N, 3585249E	Heavy machinery	2	1.27	1.67	1.04	0.06	0.43	95.16

Note: Infantry/ranger military land use primarily consists of foot traffic and associated personnel transport vehicles, which results in a low degree of disturbance; heavy machinery consists primarily of tracked vehicle training (tanks) and results in a high degree of disturbance, and impact military land use are areas where live and dud munitions detonate and results in a high degree of disturbance. ND = no data.

(*Liquidambar styraciflua*), and sweetbay [*Magnolia virginiana* (Cavalcanti 2004)].

Land-Use Classification

We quantified land use within study catchments using geographic information system (GIS) datasets (i.e., streams: 1:24,000, 1993 coverage; soils: 1:20,000, 1998; roads: 10-m resolution, 1995), digital orthophotographs (1:5,000, July 1999), digital elevation models (DEMs, 1:24,000, 10-m grid size, 1993) and Landsat imagery (28.5 m, July and December 1999). We processed datasets with catchment boundaries using ArcView© software (Environmental Systems Research Institute, Inc., Redlands, California). Landsat imagery, digital orthophotography, and DEMs were used to quantify the proportion of each catchment occurring in a particular land-use class on slopes >3%, using the ArcView extension Analytical Tools Interface for Landscape Assessments (ATtILA) (Ebert and Wade 2000). We used 3% slopes as our threshold value because examination of the relationship between the calculated universal soil loss equation and catchment slope indicated that slopes at or above this level showed the highest potential for increased annual soil loss in our study area (see GASWCC 2000).

Land-use and land-cover categories used in our analyses (Figure 2) were the proportion of bare ground and unpaved road cover (%BGRD) and the proportion of nonforested land in a catchment (%NF), whereas natural geomorphic categories included catchment size (Area) and the proportion of the catchment containing sandy, erodible soils (%Sand). The proportion of catchment on soils with >3% slopes and containing no vegetative cover was included in %BGRD (Figure 2A), which also included unpaved roads. We quantified road cover by multiplying road length by average width; the latter was estimated in the field for the two classes of unpaved road found in our catchments: class-6 roads (6-m wide, Figure 2B), and class-5 roads (20-m wide, Figure 2C). The proportion of catchment on soils with >3% slopes that were vegetated but without dense forests, including grasslands, sparse vegetation, shrublands, and fields, was incorporated into %NF (Figure 2D). Unfortunately, we were unable to separate forest harvesting practices from other types of nonforested land as a result of the low intensity of the selective cutting coupled with the resolution of land-use data (30 m). The proportion of catchment on Ailey loamy coarse sand and Lakeland sand soils was included in %Sand. Other soil types (sandy clay loams, loamy sands) were highly correlated with %Sand, so we excluded them from analysis. We defined Area as the catchment size (km^2) drained by the study stream upslope of our sampling location, determined using DEMs and ArcView. The proportion of forested land in catchments was highly negatively correlated with %NF ($r = -0.91$, $P < 0.0001$) and %BGRD ($r = -0.69$, $P = 0.006$), so we excluded this variable from analysis.

Figure 2. Photographs illustrating typical heavy-machinery training areas (A), trails (B), unpaved roads cover (C), and nonforested land (D) at the Fort Benning Military Installation, Georgia. Note the unstable, vegetation-poor soils in A and C, the poorly defined road cover in C, and the exposed (unvegetated) soil in D.

Physical and Organic Matter Variables

Streambed instability. We estimated streambed instability by quantifying sediment movement using a modified transect method (Ray and Megahan 1979). We established cross-stream transects (n = 5 per stream) by staking pairs of rebar on opposite banks of the channel perpendicular to flow. We leveled each transect (using a line level) and marked leveled heights on rebar pieces with cable ties. We quantified streambed height along fixed points of transects (20-cm intervals) by measuring vertical distance between the stream bottom and a fiberglass tape stretched across the channel; measures were made initially in January 2003 and then in July 2003 (~7-month interval). Several storm events occurred during this sampling interval (K. O. Maloney, unpublished data), so we considered this period sufficient to characterize relative changes in bed height among streams. We calculated streambed instability as the average absolute difference in height for each transect over the sampling period.

Stream flashiness. Storm hydrograph recessions integrate numerous sources of inflow (e.g., overland flow, interflow) and have been used by others to indicate stream flashiness (Rose and Peters 2001). Therefore, we quantified the rate of descent of the falling limb of several storm hydrographs in each stream as a relative measure of hydrologic flashiness. We estimated discharge from measurements of channel width and thewater velocity and depth measured by an ISCO ultrasonic flow module (model 750) and series portable sampler (model 6700); depth and velocity were recorded every 30 min to 1 h. We computed recession constants for the initial portion of the hydrograph recession curves for each storm hydrograph as the slope of the natural logarithm of discharge over time during the first 4 h following peak discharge (see Rose and Peters 2001). If the recession limb showed an obvious break in slope in <4 h, then we used data only prior to the break point to calculate recession constants. As a measure of storm magnitude, we calculated the ratio of maximum discharge to prior base flow discharge for each storm event [$\max(Q/Q_{\text{base}})$]. We only included storms with $\max(Q/Q_{\text{base}}) > 4$ because smaller storms did not have well-defined storm hydrographs (KOM, unpublished data). For three study catchments (LPK, SB1, SB5), we collected data for less than three storms, so we excluded these sites from analyses.

BPOM, particle size, and coarse woody debris. We used sediment cores (PVC pipe, area = 2.01 cm^2, 10-cm depth) to quantify proportion of benthic particulate organic matter (BPOM) and streambed particle size. We considered BPOM all organic matter material ≤ 1.6 cm in diameter, and quantified BPOM at three sites per stream every 2 months (August 2001 to May 2003) and streambed particle size every 4 months (September 2001 to May 2002). For BPOM analysis, we took three cores from the stream thalweg, oven-dried each sample at 80°C for 24–48 h, and then weighed them. Samples were then ashed in a muffle furnace at 550°C for 3 h, cooled in a desiccator, and reweighed; the %BPOM was determined as the difference between dry and ashed masses divided by total dry mass. For particle size analysis, we collected two cores per site: one in the thalweg and one near the stream margin. We combined cores within each site (n = 3), removed organic matter, and dispersed particles following the pipette method from a 10-g subsample (Gee and Bauder 1986). Particle sizes were then separated by dry sieving (2.0-, 1.0-, 0.5-, 0.250-, 0.125-, 0.063, and <0.053-cm fractions), and the mean weighted particle size for each stream was estimated by multiplying the mass of each fraction by the midpoint between sieve fractions and then dividing by the total sample weight. Particles >2 mm were removed prior to the dispersing process (see Gee and Bauder 1986). However, we estimated the percent of the entire sample that was >2 mm prior to dispersion and used this value to estimate the percent of sample that would have been >2 mm in the 10-g subsample. For particle sizes occurring between 2 and 5 mm in diameter (<10% of total particles) (KOM, unpublished data), we assigned a midpoint size of 3.5 mm and included them in mean weighted particle size calculations.

We quantified the relative abundance of coarse woody debris (CWD) in each stream during April 2002 and March 2003 using a modified transect method (see Wallace and Benke 1984). We quantified all submerged CWD >2.5 cm in diameter and all CWD buried within the upper 10 cm of the substrate along 15 cross-stream transects per stream; individual transects were 1 m wide with adjacent transects being spaced longitudinally 5 m apart. Live woody material (i.e., roots) was abundant in our study streams and appeared to be an important influence on channel structure (KOM, personal observations), so we also included all live material in CWD measurements. CWD data were converted to planar area (m^2 of CWD per m^2 of stream bed) by multiplying the CWD diameter by length and then dividing this value by the area sampled within each transect.

Dissolved organic carbon. We measured stream-water DOC on one date every 2 months from November 2001 to September 2002, with one grab sample collected per stream per date using a 60-mL syringe. The syringe was fitted with a 0.45-μm high-performance liquid chromatographic (HPLC) Gelman Acrodisc® syringe filter and ~30 mL was filtered into a pre-acid-washed polycarbonate bottle. We then shipped samples on ice to the Oak Ridge National Laboratory, Oak Ridge, Tennessee, where DOC was measured by high-temperature combustion using a Shimadzu Model 5000 TOC analyzer after acidification and purging to remove inorganic C.

Data Analysis

Preliminary analyses using a repeated-measures analysis of variance (ANOVA) to examine seasonal variation (spring, summer, winter) revealed no seasonal effect for any of the parameters measured (KOM, unpublished data). Therefore, we used average seasonal values in the analyses. Preliminary analysis using a simple correlation revealed no significant relationship between selected land-cover/land-use variables. However, many physical and organic matter variables were interrelated (i.e., one variable potentially affecting another), so we used a simple linear correlation to detect bivariate relationships between dependent variables. We used multiple regression to determine pre-

Table 2. Results of land-use classification

Stream	% of catchment as bare ground on slopes >3%	% of catchment as unpaved roads	% of catchment as trails	% of catchment as bare ground and roads	% of catchment as nonforests	% of catchment with sandy soils	No. of stream and road crossings above sampling site
BC1	7.1	2.7	0.6	10.5	12.6	3.2	2
BC2	0.3	1.5	1.3	3.1	6.1	1.8	1
HB	4.6	0.8	1.3	6.6	26.6	54.1	3
KM1	1.5	1.4	1.7	4.6	14.4	35.7	0
KM2	0.1	0.7	0.9	1.8	13.1	17.8	0
LC	2.8	0.0	0.9	3.7	22.3	23.5	0
LPK	9.7	0.0	1.6	11.3	29.2	9.0	0
SB1	5.8	1.1	1.5	8.4	22.4	31.0	4
SB2	4.8	1.8	1.6	8.1	37.7	28.3	0
SB3	9.1	0.8	0.6	10.5	32.2	97.2	0
SB4	10.6	1.7	1.4	13.6	22.2	35.2	1
SB5	10.4	2.9	1.3	14.7	20.2	5.3	0

Note: Stream abbreviations defined in Table 1.

dictive relationships between physical and organic matter and land-use and natural landscape variables. We used Akaike's Information Criteria adjusted for sample size (AIC_c) and adjusted coefficients of determination (R^2_{adj}) for model selection. The regression model with the smallest AIC_c value was considered the best model of the measured variation in the data; however, we also considered all models with <2 AIC_c units of the overall best model (ΔAIC_c <2) to have substantial support (Burnham and Anderson 2002). Analysis of multicollinearity using variation inflation factors (VIFs) revealed no highly multicollinear land cover/use variables (i.e. all VIFs < 10) (Myers 1990). We transformed %CWD and %BPOM (arcsine square root) and particle size data ($\log_{10}$) prior to analysis to satisfy normality. All remaining variables were normally distributed and, therefore, received no transformation.

Results

The proportion of bare ground and road cover in study catchments (%BGRD) ranged from ~2% to 15% (mean = 8%), whereas the proportion of nonforested land (%NF) ranged from ~6% in BC2 to 38% in SB2 (mean = 22%, Table 2). The percent of the catchment containing sandy soils (%Sand) ranged from ~2% in BC2 to almost 100% in SB3 (mean = 29%). In general, catchments within military compartments associated with heavy-tracked vehicular training showed higher %BGRD and %NF (LPK, SB1, SB2, SB4, SB5) than compartments without such mechanized training (BC1, BC2, HB, KM1, KM2, SB3; Tables 1 and 2).

Not surprisingly, stream physical and organic matter variables often were intercorrelated (Table 3). For correlations involving percent submerged CWD and %BPOM, we removed one stream (BC1) from the analysis following preliminary diagnostics. This catchment showed an atypical flood plain (see below). The percent of submerged CWD was negatively correlated with flashiness. DOC and %BPOM were positively correlated with pecent submerged CWD (Table 3). Streambed instability was negatively correlated with mean particle size (Table 3). Particle size also was negatively correlated with flashiness but positively so with percent submerged CWD (Table 3).

Analysis of relationships between land-use and stream variables indicated that %BGRD was the best single predictor for many physical and organic matter parameters (Table 4). Streambed instability was positively correlated with %NF ($\beta_0 = 1.87$, $\beta_{\%NF} = 0.08$, $R^2_{adj} = 0.43$; Figure 3), whereas stream flashiness was negatively correlated with storm magnitude (as $\max[Q/Q_{base}]$) and %Sand ($\beta_0 = -0.041$, $\beta_{\max(Q/Q_{base})} = 0.010$, $\beta_{\%Sand} = 0.003$, $R^2_{adj} = 0.74$, Table 4). However, the univariate model containing %BGRD also explained a high amount of variation in stream flashiness and thus had support ($\beta_0 = 0.067$, $\beta_{\%BGRD} = 0.020$, $R^2_{adj} = 0.54$; Figure 4A). Sally Branch 4 (SB4) was the only stream with an undefined channel and thus could have been considered an outlier (i.e., >2 SD from mean recession constants for other streams). When we removed SB4 from the analysis, the best two-factor model for stream flashiness consisted of %BGRD and %NF ($\beta_0 = -0.049$, $\beta_{\%BGRD} = -0.037$, $\beta_{\%NF} = 0.003$, $R^2_{adj} = 0.94$). However, the univariate model containing %BGRD also explained a large amount of variation in flashiness with the removal of SB4 from the analysis ($\beta_0 = -0.014$, $\beta_{\%BGRD} = -0.031$,

Table 3. Summary of univariate Pearson correlations among stream physical and organic matter variables observed within the 12 study streams

	DOC	%BPOM	Streambed instability	Mean particle size	% Submerged CWD	% Buried CWD	Stream flashiness
DOC	1.00	0.66**[a]	−0.52	−0.81**[a]	0.59*[a]	−0.46	−0.56
% BPOM		1.00	−0.48[a]	0.76**[a]	0.76**[a]	−0.05[a]	−0.60[a]
Streambed instability			1.00	−0.82**[a]	−0.23[a]	0.51	0.18
Mean particle size				1.00	0.67*[a]	−0.24[a]	−0.65*[a]
% Submerged CWD					1.00	−0.25[a]	−0.81**[a]
% Buried CWD						1.00	0.34
Stream flashiness							1.00

Abbreviations: DOC = stream-water dissolved organic C concentration; %BPOM = proportion of substrate as benthic particulate organic matter; %CWD = proportion of stream bottom as coarse woody debris.
*$P \leq 0.10$.
**$P \leq 0.05$.
[a]Correlations excluding stream BC1 (see text).

Table 4. Selected results of multiple regression analyses to describe the relationship among land use and hydrological variables and stream response variables

Parameter	Parameters in model	No. of parameters in model	AIC_c	ΔAIC_c	SSE	Adjusted R^2	P
Stream flashiness (all streams)	%BGRD	2	−44.21	1.73	0.034	0.54	0.014
	$\max(Q/Q_{base})$, %Sand	3	−45.94	0.00	0.016	0.74	0.007
	$\max(Q/Q_{base})$, %NF, %Sand	4	−44.83	1.11	0.008	0.84	0.006
Stream flashiness (without BC1)	%BGRD	2	−46.44	3.39*	0.011	0.85	0.001
	%BGRD, %NF	3	−49.83	0.00	0.004	0.94	0.000
Streambed instability	%NF	2	1.24	0.00	5.3	0.43	0.033
	%NF, %Sand	3	2.18	0.93	3.5	0.57	0.035
Substrate size	%BGRD	2	−56.30	0.00	0.040	0.45	0.014
% Submerged CWD	%BGRD	2	−74.74	0.00	0.007	0.79	0.000
	%BGRD, %Sand	3	−73.15	1.59	0.006	0.81	0.001
% Buried CWD	%NF	2	−114.54	0.08	0.001	0.19	0.086
	%NF, %Sand	3	−114.62	0.00	0.000	0.34	0.061
%BPOM	%BGRD	2	−79.98	0.00	0.005	0.62	0.002
DOC	%BGRD	2	−4.33	0.00	5.364	0.32	0.031
	%BGRD, % Sand	3	−4.26	0.07	3.976	0.44	0.029

Note: Models for each variable are listed in increasing complexity. The regression with the lowest adjusted Akaike's Information Criterion (AIC_c) was considered the best model, although models with a slight difference from the best model (ΔAIC_c <2) also had substantial support (Burnham and Anderson 2002). $\max(Q/Q_{base})$ was the maximum increase in discharge over base flow during a storm event, %BGRD, %NF, and %Sand were percentages of the catchment occurring as bare ground and road cover, nonforested, and sandy soil, respectively. BC1= outlier stream, SSE = model sum of squares error, CWD = coarse woody debris, DOC = dissolved organic C concentration, %BPOM = percentage of benthic particulate organic matter in the stream bed. n = 12 for buried CWD and DOC, n = 11 for particle size, submerged CWD, and %BPOM, and n = 9 for stream instability and flashiness. The asterisk indicates the model with ΔAIC_c >2, but had high amount of variation explained by the simple model.

$R^2_{adj} = 0.85$; Table 4). The mean substrate particle size was negatively correlated with %BGRD ($\beta_0 = -0.054$, $\beta_{\%BGRD} = -0.015$, $R^2_{adj} = 0.45$; Figure 4B).

All three stream organic matter variables (CWD, BPOM, DOC) were inversely correlated with %BGRD (Figure 5). For submerged CWD and %BPOM, one catchment (BC1) showed %BPOM and CWD amounts that were >2 SD of the mean, which prompted us to exclude this site from regressions. This catchment had an unusually broad floodplain and a high riparian stand density, both of which likely increased streambed organic matter retention. The proportion of bare

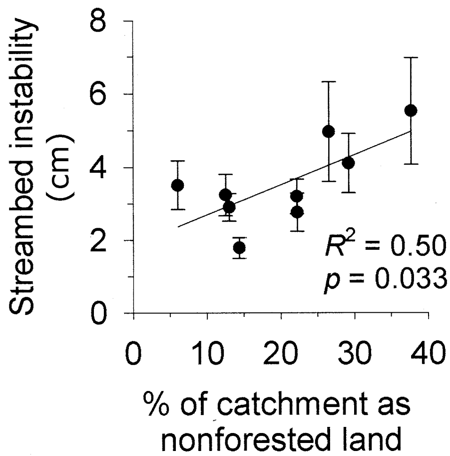

Figure 3. Relationship between streambed instability, calculated as the mean absolute change in bed height from January to July 2003, and the percent of nonforested land in the catchment (mean ± 1 SE).

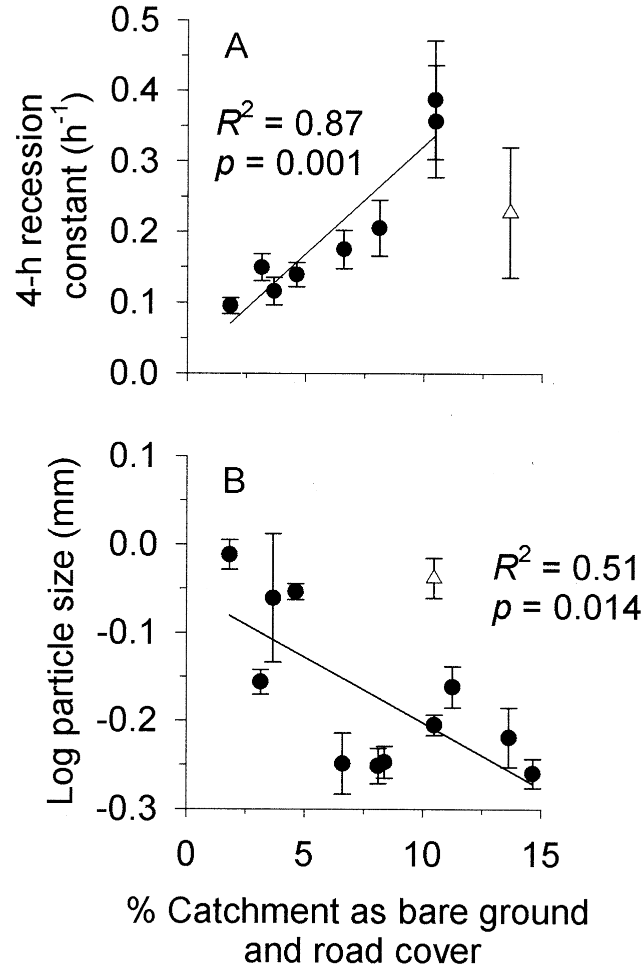

Figure 4. Stream flashiness (4-h recession constants) calculated as the regression slope of the LN(flow) for 4 h following peak flow as a function of the percent of bare ground in a catchment (A) and mean stream substrate particle size (B) plotted against the percent of bare ground and road cover in a catchment. Triangle indicates outlier catchments (>2 SD below the mean), SB4 for recession constant, and BC1 for particle size and pH, which were excluded from analyses (mean ± SE).

ground and unpaved road cover best explained percent submerged CWD (β_0 = 0.358, $\beta_{\%BGRD}$ = −0.013, R^2_{adj} = 0.79; Figure 5A), %BPOM (β_0 = 0.171, $\beta_{\%BGRD}$ = −0.007, R^2_{adj} = 0.62; Figure 5B), and DOC (β_0 = 4.04, $\beta_{\%BGRD}$ = −0.132, R^2_{adj} = 0.32; Figure 5C). A two-variable model including %NF (negative correlation) and %Sand (positive) best explained the percent of buried CWD (β_0 = 0.015, $\beta_{\%NF}$ = 0.0007, $\beta_{\%sand}$ = −0.0002, R^2_{adj} = 0.34; Table 4).

Discussion

Military installations often have repeated and high-magnitude, but localized perturbations associated with training, causing soil disturbance, increased erosion, and sedimentation in streams. At FBMI, heavy-tracked vehicle training (i.e., tank maneuvers), munitions impact areas, unpaved roads, controlled burning, and timber harvesting all contributed to terrestrial disturbance (USAIC 2001). Although our study was correlative and thus could not determine specific causal mechanisms of landscape change, our results suggest that the proportion of a catchment denuded of vegetation and with exposed and constantly disturbed soil (%BGRD) was a key terrestrial influence on stream geomorphology, hydrology, and organic matter state. In general, land-use variables (e.g., proportion of bare ground and road cover, nonforested land) were far better predictors of in-stream physical and organic matter conditions than were natural geomorphic or topographic attributes (catchment size and soil type).

Influence of Military Land Use on Stream Geomorphology and Hydrology

Land-use practices such as urbanization, agriculture, and forest harvest often deliver eroded soil to stream channels (Ryan 1991; Waters 1995, Sutherland and others 2002). Increased sedimentation might increase streambed instability (i.e., increase threshold entrainment per unit discharge; Lorang and Hauer 2003) because of reduced shear resistance associated with recent deposition of unstable particles (Jain and Park 1989; Krone 1999). Our results at FBMI are consistent

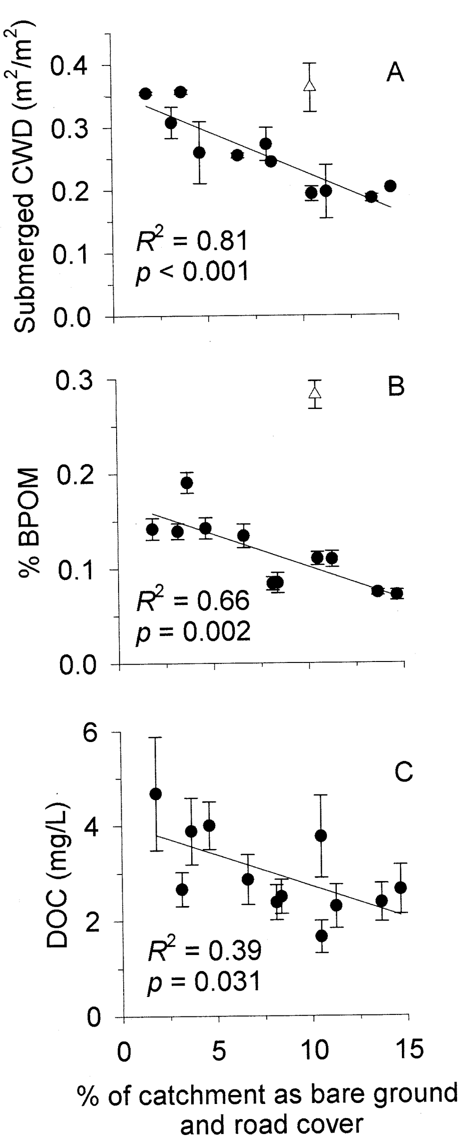

Figure 5. Relationship between percent of catchment as bare ground and road cover and average submerged coarse woody debris (CWD) (A), benthic particulate organic matter (BPOM) (B), and base flow streamwater dissolved organic carbon (DOC) concentration (C). The triangle indicates an outlier catchment BC1 (> 2 SD) that was excluded from analyses. CWD and BPOM are the arcsine square root transformed data. Plotted points are individual streams. (Mean ± 1 SE.)

with these findings, in that streambeds draining catchments with a higher proportion of nonforested land were less stable than those draining less disturbed, forested catchments. It must be noted, however, that grassland and shrubland in our nonforested category (%NF, Figure 2D) probably represented land recovering from not only contemporary military training and silviculture but also from historical agriculture, a likely additional sediment source for streams (Trimble 1981, 1999). The FBMI landscape consisted of extensive agriculture prior to military purchase in the early 1940s (Kane and Keeton 1998; USAIC 2001), so a "legacy" effect (*sensu* Harding and others 1998) of sediment input from historical agriculture is plausible, with sediments eroded during the agricultural period continuing to migrate through ephemeral channels and into perennial streams. As with agriculture, use of heavy-tracked vehicles for military training is generally limited to low to moderate slopes of the installation, although in most catchments, active sediment entry into streams from upland sources appears to occur mainly from contemporary land use, especially from active roads or bare ground used for training (Figures 2A and 2C). However, the presence of active sediment movement in some stream channels at FBMI with no apparent upland source in the catchment (KOM, personal observations) would suggest that streambed instability and substrate composition might result from a combination of contemporary military/forestry and historical agriculture land use.

Stream flashiness increased as a function of increasing proportion of bare ground and road cover in catchments. One likely explanation for this pattern was that low vegetative cover in highly disturbed catchments caused higher and more temporally variable runoff. In addition, bare ground might amplify sealing of soil surfaces (Assouline and Mualem 2002) and use of heavy-tracked vehicles at FBMI are known to compact soil and decrease rainfall infiltration (Goran and others 1983; Garten and others 2003). Taken together, the combination of increased soil sealing and reduced evapotranspiration and infiltration likely contributed to increased overland flow in high-%BGRD catchments, thus increasing the magnitude of short-term variation in stream hydrographs during storm events (Rose and Peters 2001).

Average streambed particle size often decreases with increasing agriculture, silviculture, or urbanization within catchments (Nerbonne and Vondracek 2001; Walters and others 2003), usually because eroded particles entering streams are disproportionately fine grained (Bilby and others 1989). We observed a similar pattern at FBMI, where catchments with a higher proportion of %BGRD had smaller streambed particle sizes than less disturbed catchments. Moreover, average particle size was negatively related to streambed instability and flashiness (Table 3), with both hydrologic variables being higher in highly disturbed streams (Table 4). Disturbed streams generally contained a higher proportion of active channel incision and bank erosion (KOM, personal observations), which probably supplied substantial fine-grained sediment to the stream bottom. Further, input of eroded sediment from incised ephemeral channels as a result of historical agriculture (pre-1940 s) likely also contributed sediment to perennial streambeds. Collectively, our results suggest that disturbance from land use at FBMI alters particle size distributions in the stream bed, apparently from a combination of erosional (i.e., a disproportionate terrestrial input of fines) and hydrologic (i.e., increased bank erosion from high flashiness) influences, resulting in disproportionately high input of fine particles in disturbed catchments.

Influence of Military Land Use on Stream Organic Matter

Low in-stream CWD in disturbed (high %BGRD and %NF) catchments (Table 4) was consistent with studies of CWD relationships with other land-use practices, including timber harvest (Harmon and others 1986; Webster and others 1992). In this context, military and silvicultural land uses are similar in that both remove or reduce vegetation, decrease the amount of organic matter within the catchment, and hence potentially reduce detrital inputs to streams. In addition to lower organic matter inputs however, flashier streams with less stable beds in more highly disturbed catchments might increase burial and/or export of CWD, which in tandem might reduce CWD abundance in the surficial substrate. However, the high correlation between percent of buried CWD and %NF in our streams (albeit not with %BGRD, Table 4) suggests that CWD burial might be coincident with increased CWD transport from disturbed stream reaches (see Bilby and Bison 1998). Transport of CWD is a function of CWD size with respect to the wetted and bankfull channel width and discharge (Harmon and others 1986; Bilby and Bison 1998). Coarse woody debris pieces within our streams were much smaller (median diameter = 5 cm, length = 35 cm) than both average wetted and bankfull stream width (median = 170 cm and 235 cm, respectively), so it is possible that considerable CWD export occurred from study reaches during storms. Further, live roots were important components of the CWD measure composing ~23% of CWD abundance in study streams (range 0–50%), and abundance of live roots also were significantly higher in the five least disturbed compared with the five most disturbed streams (two-tailed *t*-test, $P = 0.005$). Live roots are typically stable and could also accumulate debris (Smock and others 1989), which likely increased CWD in low-disturbance streams. Historic removal of CWD (''stream cleaning'') in agricultural catchments also might have influenced abundance of contemporary in-stream CWD. However, the majority of study catchments experienced high historic disturbance from agriculture [range = 22–54%, mean = 39% of catchment was historic (1944) bare ground and field cover (KOM unpublished data)], so it is likely all catchments experienced a relatively similar historic cleaning of CWD within channels.

Organic matter in small temperate-deciduous streams is derived primarily from allochthonous inputs (Cummins 1974; Mulholland 1997). Forested streams generally show higher BPOM than disturbed nonforested streams (Golladay 1997), mainly because reduced riparian vegetation might directly decrease BPOM. At FBMI, most streams have intact riparian vegetation and high canopy cover (>90%; KOM unpublished data), so low BPOM in disturbed stream beds was not likely produced from lower allochthonous inputs. A more plausible reason for lower BPOM in disturbed catchments was because of lower in-stream BPOM-retention structures, particularly that of low CWD in the stream channel (Bilby 1981; Smock and others 1989, Wallace and others 1995). In our study, relative abundance of submerged CWD decreased with increasing %BGRD (Table 4) and CWD and %BPOM were highly correlated (Table 3), suggesting that land use might directly reduce in-stream CWD, which, in turn, reduces BPOM. Furthermore, higher stream flashiness in more disturbed catchments (high %NF and %BGRD) might have exacerbated effects of low CWD on BPOM by increased BPOM transport during storms (see Smock 1990, 1997).

We also found lower stream-water DOC concentrations in highly disturbed (high %BGRD) catchments. This result is consistent with patterns observed in clearcut catchments, where deforestation reduces subsurface, litter leachate, throughfall, and in-stream DOC inputs (Meyer and Tate 1983). Primary sources of stream-water DOC either are allochthonous, including C from terrestrial organic matter, precipitation, and throughfall (McDowell and Likens 1988; Qualls and others 1991; Michalzik and others 2001), or autochthonous, such as from algal or cyanobacterial exudates (Kaplan and Newbold 1982; Meyer and Tate 1983, Mulholland and Hill 1997). At FBMI, exposed soil in our %BGRD category generally contains low levels of labile organic matter (Garten and others 2003); hence, reduction of this C source from soil might have lowered stream-water DOC inputs. In addition, streams in highly disturbed catchments typically showed much lower benthic algal biomass (as chlorophyll-*a*) than low-disturbance streams (~2 versus ~6 μg/L in disturbed versus undisturbed streams, respectively; Stephanie A. Miller, Auburn University, unpublished data), which also might have contributed to lower DOC concentrations in disturbed streams.

Implications of Military Land Use to Stream Ecology

Dramatic modification of stream geomorphological and hydrological conditions and organic matter states attributable to military land use at FBMI might cause severe impairment to biotic communities. In particular, decreased streambed stability, increased stream flashiness, and decreased CWD might all impact stream communities by affecting habitat stability, persistence, and abundance, especially for benthic algae (Tett and others 1978; Yamada and Nakamura 2002) and macroinvertebrates (Benke and others 1984; Angradi 1999). Moreover, streams with low CWD often show smaller, shallower pools and less cover for fish (Angermeier and Karr 1984; Inoue and Nakano 1998).

The US Department of Defense (DoD) manages ~30 million acres of land at ~6000 locations (USDoD 2004), which can provide fruitful areas for long-term ecological research involving landscape disturbance on stream structure and function. There are several other military bases in the southeastern United States (Fort Stewart, Fort Mitchell, Fort Polk) for which our results might be directly applicable; however, our results also might apply to nonmilitary lands in the region where sediment is the main stressor to streams. Moreover, apart from the need to characterize long-neglected impacts of landscape disturbance on in-stream processes on military lands, perhaps the greatest values of these installations is (1) the vast amount of supporting data available and (2) the consistent, well-documented patterns of land use attributable to military training. Long-term studies can thus be conducted at installations to increase our understanding of the contemporary and historical influences on receiving streams.

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