Response of soil organic carbon dynamics to disturbance from military training

W.F. DeBusk, B.L. Skulnick, J.P. Prenger, and K.R. Reddy

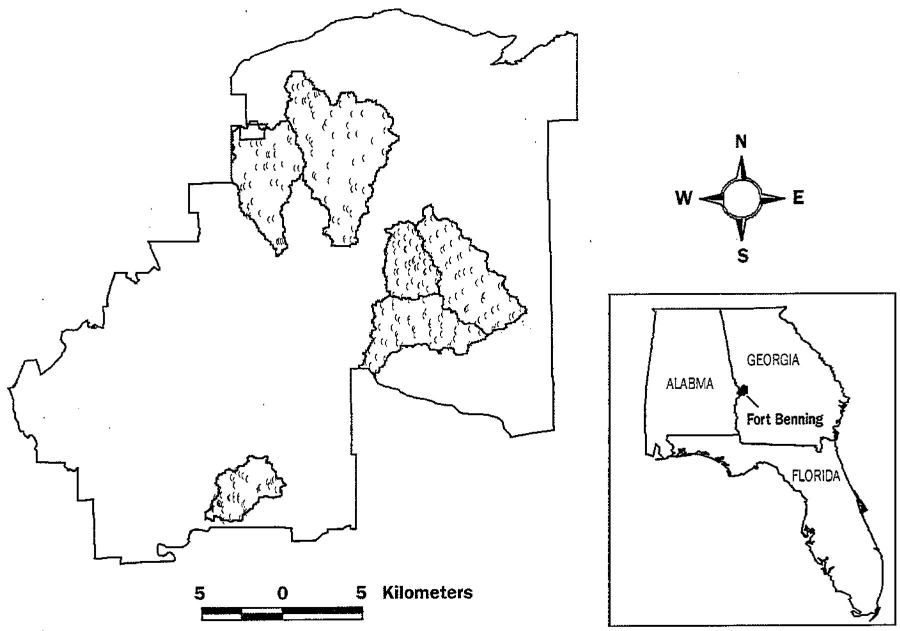
Abstract: A field study was conducted at Fort Benning, Georgia (USA) to evaluate changes in soil organic carbon storage and partitioning in response to site disturbance from ground-based military training. Our primary goal was to investigate the utility of selected soil biogeochemical parameters for monitoring and assessment of land condition in conjunction with restoration and other management activities. Soil was sampled at sites representing a wide range of intensity of land disturbance due to mechanized training, foot and light vehicle traffic, and related activities. Soil chemical and microbial analyses included total carbon (C), total nitrogen (N), dissolved organic C, microbial biomass C, and soil respiration. All of these, with the exception of dissolved organic C, showed relatively consistent decreasing trends (significant at $P \leq 0.05$) with increasing site disturbance, consistent with increased loss of topsoil in uplands and sedimentation in bottomlands. Concomitant increases in dissolved organic C:total C and microbial biomass C:total C appear to indicate that the relative bioavailability of soil C increased with soil disturbance despite a decrease in C storage.

Keywords: Microbial biomass, military lands, nitrogen, soil erosion, soil organic carbon

The long-term sustainability of ground-based (e.g., infantry) training programs at U.S. military installations is strongly dependent on the ecological sustainability of limited land resources. Accordingly, resource management goals for large military installations must incorporate the concepts of soil conservation and ecosystem management. In order to achieve resource management goals (i.e., desired future condition), monitoring and assessment of land condition for restoration or other management activities should provide some measure of ecological status and trends. Examination of soil biogeochemical properties, i.e., storage and cycling of soil organic carbon and related soil constituents, is a potentially expedient method for measuring ecological response to military training (as well as other land uses).

William F. DeBusk is an assistant research scientist at University of Florida in Milton, Florida. **Benjamin L. Skulnick** is a scientist with Jones, Edmunds, and Associates, Inc. in Gainesville, Florida. **Jospeh P. Prenger** is a scientist with Florida Fish and Wildlife Conservation Commission in Gainesville, Florida. **K. Ramesh Reddy** is a graduate research professor at the University of Florida in Gainesville, Florida.

Figure 1
Location of Fort Benning, Georgia study area (inset) and experimental watersheds. Phase 1 soil sampling locations are indicated by filled circles (•).



For example, total soil organic C, nutrient availability, microbial biomass, and soil respiration have been identified as potential indicators of soil quality (Nortcliff, 2002). Soil quality refers to the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran and Parkin, 1994).

Experimental data relating the impact of military training to soil biogeochemical characteristics is relatively scarce. While some work has been done on recovery of soils from encampments (Kade and Warren, 2002) and troop and mechanized training (Webb, 2002), these studies have involved desert ecosystems and focused primarily on alteration of soil physical properties. For example, a controlled study of mechanized military training activity in chalk grasslands (Hirst et al., 2003) showed significant changes in soil compaction but did not report changes in soil chemistry. Small but significant increases in soil bulk density and significant decreases in infiltration rate were associated with foot traffic from military training in Colorado (Whitecotton, et al., 2000). A recent study at Ft. Benning, Georgia by Garten et al. (2003) found increased soil bulk density, lower soil organic C concentrations, and less C and nitrogen (N) in particulate organic matter at moderate use, heavy use, and remediated sites relative to reference sites.

In this study we examined the relationship between military land use and soil biogeochemical properties, particularly in the context of soil quality and ecological condition. Our study was part of a broader interdisciplinary ecosystem management initiative to develop ecological metrics for use as diagnostic tools by resource management at military installations, primarily within the Coastal Plains region of the southeastern United States. The objectives of our study were to characterize soils under predominantly military land use by measuring a suite of biogeochemical parameters associated with C storage and cycling, and to evaluate these parameters as a function of land condition, or more specifically, physical site disturbance. Our overall goal was to investigate the potential applicability of soil biogeochemical parameters to the determination of ecological condition. We propose that monitoring of soil properties linked to storage and cycling of soil organic C can provide, either individually or in combination with other variables, a quantitative and reproducible measure of ecosystem recovery or degradation.

Methods and Materials

Site description. The study area was located on the Fort Benning military installation, near the city of Columbus in west-central Georgia (Figure 1). The installation covers 74,370 ha (183,772 ac) of land along the Chattahoochee River, with most of the land area located in Georgia, and the remainder located across the river in Alabama. Fort Benning lies within the Southern Mixed Forest Province (Bailey, 1995) along the Fall Line, which represents the transition between the Coastal Plain and Piedmont regions. The topography of the area is characterized by nearly level to gently sloping ridgetops, moderately steep and steep hillsides, and nearly level valleys along stream channels and other tributaries. Upland soils are primarily well- to excessively-drained Ultisols and Entisols, associated with longleaf pine sandhill communities and longleaf and loblolly pine plantations. Among the more commonly-occurring soil series in upland areas of Fort Benning are Troup (loamy, kaolinitic, thermic Grossarenic Kandiudults), Cowarts (fine-loamy, kaolinitic, thermic Typic Kanhapludults), Nankin (fine, kaolinitic, thermic Typic Kanhapludults), and Lakeland (thermic, coated Typic Quartzipsamments). Wetlands are generally restricted to riparian areas, where bottomland hardwood forests are common. Soils commonly associated with wetlands and other bottomland areas of Fort Benning include Bibb (coarse-loamy, siliceous, active, acid, thermic Typic Fluvaquents), and Pelham (loamy, siliceous, subactive, thermic Arenic Paleaquults) series. Climate in the study area is warm, humid and temperate. Monthly mean temperatures range from 7.7° C in January to 27.6° C in July, and average annual rainfall is 1321 mm.

Assessment of site condition. Fort Benning is the primary training facility for the U.S. Army Infantry. Ecological impact from military activities is highly variable and patchy. Severe impacts are concentrated in a few areas of the base, primarily along sandy ridge tops; many other areas experience low to moderate impacts from military training. Training-related impacts to natural communities range from low to moderate disturbance of understory vegetation and soils caused by foot and light vehicle traffic to severe localized vegetation clearing, soil compaction and erosion associated with site-intensive mechanized training (e.g., tracked vehicles). Common non-military impacts to vegetation and soil include prescribed burning and forestry activities such as cultivation, tree thinning and clear-cutting. Wildfires occur periodically, often resulting from ordnance detonation and other military training activities.

Evaluating the response of soil biogeochemical properties to anthropogenic

Table 1. Field observation criteria for classification of site impact for the Fort Benning study area.

Site disturbance criteria	Site impact category: Low impact	Moderate impact	Severe impact
Overstory vegetation	No disturbance apparent	Minimal disturbance	Extensive tree removal or damage
Understory vegetation	No or minimal disturbance apparent	Moderate physical impact or removal	Cleared understory
Groundcover	No or minimal disturbance apparent	Moderate physical impact or patches of bare ground	Extensive bare ground
Soil	No disturbance apparent	Disturbance of O and A horizons, minimal erosion or other soil loss	Extensive soil disturbance, erosion and other soil loss, disruption of natural horizonation
Fire	Minimal (controlled burn, not recent)	Recent controlled burn or more severe burn in recent past	Not used as sole criteria for severe impact

disturbance entailed correlation of response variables with known levels of site disturbance. Since documentation of prior military training activity within the study area was poor with respect to frequency and duration of site disturbance, a set of site evaluation criteria was developed to classify the current level of soil and vegetation impact. Based on these criteria (Table 1), study sites were placed in one of three categories of ecological impact: low, moderate or severe. In general, low-impact sites represented areas of low military use, primarily foot traffic; moderate-impact sites represented areas of heavy foot traffic or light vehicular traffic (no tracked vehicles); and severe-impact sites were areas of heavy military training, including tracked vehicles, characterized by significant loss of vegetation and severe soil disturbance and/or erosion.

Sampling protocol. *Phase 1 sampling.* Soil sampling was conducted in two phases, during January to August 2000 (Phase 1) and December 2000 to June 2001 (Phase 2). Phase 1 sampling was conducted at a multi-watershed scale, and covered a significant portion of the Fort Benning installation, to capture the edaphic variability associated with landscape position, vegetation, hydrology and anthropogenic disturbance, both military and non-military. Soil sampling for Phase 1 was conducted within six, third and fourth order watersheds (Figure 1), which had been preselected for companion studies of watershed hydrologic processes. Sampling sites were distributed among three landscape positions, i.e., upland (hilltops and ridges), bottomland (wetlands and riparian zone), and the intermediate mid-slope areas, such that approximately equal numbers of sites were selected for each landscape position. The intent of the stratified sampling scheme was to account for variability in soil chemical properties due to landscape position. Sampling locations were based on transects orthogonal to the main stream of the watershed, with 0.5 to 1.0 km (0.3 to 0.6 mi) spacing between transects, depending on watershed size. Sites were located where transects intersected upland, mid-slope and bottomland areas. Exact site positioning was dependent on surrounding topographic and hydrologic features, as well as site accessibility.

Soil samples were obtained at approximately 50 locations in each watershed, for a total of 300 sites. Each sample point consisted of a 1 m^2 sq plot, within which five individual samples were taken in a diagonal pattern. The individual samples were then composited for analysis as a single sample. Soil was sampled to a depth of 20 cm (8 in), using a soil push probe with an inside diameter of 1 inch. Each sampling site was assessed using criteria in Table 1, and classified according to the corresponding level of impact (site disturbance), i.e., low, moderate or severe.

Phase 2 sampling. Phase 2 sampling was conducted at 13 study sites located within the Phase 1 sampling domain. While Phase 1 sites represented a collection of point measurements across a heterogeneous landscape, Phase 2 sites consisted of small (typically less than 5 ha or 12 ac) parcels of relatively uniform soil type, landscape position and level of anthropogenic impact. Upland sites were underlain by Troup loamy sands, while bottomland (wetland) sites were associated with Bibb sandy loams. Phase 2 sampling was intended to supplement Phase 1 by providing more information on within-site variability of soil biogeochemical properties, and to allow comparisons among individual sites.

Sampling points within each upland site were distributed along a single transect ranging in length from 80 to 400 m (263 to 1,312 ft), depending on the total area of the site. Each transect contained sampling points spaced at 20 m (66 ft) intervals, resulting in a range of five to 21 sampling points per transect. Multiple transects spanning the riparian zone (orthogonal to stream, typically 25 m or 82 ft in length), were established for sampling bottomland sites. Sampling protocol for Phase 2 sites was identical to that used for Phase 1 sites, except that bottomland soils were sampled to a depth of 5 cm, using a 6.5 cm diameter polycarbonate corer, to emphasize the biologically active soil surface and detrital layer.

Analytical methods. All soil samples were analyzed for total C, total N, dissolved organic C, microbial biomass C, and pH. In addition, soil respiration rate was determined for Phase 2 samples. Prior to analysis, upland (dry) soil samples were screened through a 10 mesh (2 mm) sieve to remove gravel, leaves and large roots, while wetland soil samples were hand-picked to remove large plant parts and live roots.

Soil pH was measured in a 1:1 (mass basis) soil-water slurry, using deionized water and field-moist soil. Total C and total N were measured by combustion using a Carlo-Erba NA-1500 CNS analyzer (Haak-Buchler Instruments, Saddlebrook, New Jersey). Samples were oven-dried at 40° C for 72 hours, and ground to pass a 20 mesh (850 μm) sieve; approximately 20 to 40 mg of sample were used for analysis.

Water dissolved organic C was determined by extracting approximately 6 g (0.2 oz) of field-moist soil with 30 mL of de-ionized water on a reciprocal shaker for one hour. Samples were then centrifuged and the supernatant decanted and filtered through a 0.45-μm membrane filter. The resulting solution was analyzed for total C using a Dorman DC-190 TOC analyzer (Rosemount Analytical Inc., Santa Clara, California).

Microbial biomass C was determined using

Table 2. Summary statistics for Phase 1 soil characterization for bottomland (n=98) and upland (n=203) sites at Fort Benning. (pct = percentile).

	Bottomland			Upland		
	Mean	10th pct	90th pct	Mean	10th pct	90th pct
pH	4.99	4.19	5.85	5.28	4.73	5.77
Total C (g kg^{-1})	38.3	7.0	100.6	10.9	4.6	18.4
DOC* (mg kg^{-1})	121.3	21.3	272.7	65.5	18.8	141.0
MBC** (mg kg^{-1})	561.2	122.0	1435.0	218.9	76.4	400.0
Total N (g kg^{-1})	2.03	0.33	4.92	0.42	0.20	0.74
C:N ratio	18.9	14.6	23.8	26.8	18.7	34.7

* Dissolved organic carbon.

** Microbial biomass C

a modification of the chloroform fumigation-extraction procedure of Horwath and Paul (1994). Ethanol-free chloroform was added directly to approximately 5 g of field-moist soil to enhance distribution of chloroform within the sample (Ocio and Brookes, 1990) prior to incubation of samples under a chloroform atmosphere in a vacuum dessicator. After incubation in darkness for a 24 hour period, chloroform was removed from the samples by repeatedly purging the dessicator, then the labile organic C in the soil samples was extracted with 0.5 M potassium sulfate. Extracted samples were centrifuged, supernatant decanted, and filtered through Whatman No. 41 filter paper to remove particulate material. The sample solution was analyzed for total C using a Dorman DC-190 total organic C analyzer. A parallel set of samples was extracted with potassium sulfate in the same manner, without prior chloroform fumigation; microbial biomass C was calculated as the difference between labile organic C content of the fumigated and non-fumigated samples.

Soil microbial respiration was determined under controlled conditions in laboratory incubations, providing a normalized (among sites) measure of potential organic C mineralization rate. For each sample, approximately 5 g of field-moist soil and 50 mL distilled water were placed in a 150 ml glass serum bottle and sealed with a butyl rubber septum. Samples were placed in an incubator in the dark at 25° C with continuous shaking. Headspace samples were taken every 12 hours for a period of seven days, and analyzed immediately for CO_2 using a Shimadzu gas chromatograph (GC) equipped with a Poropak N (Supelco, Bellefonte, PA) column and thermal-conductivity detector (TCD). Soil respiration rate was determined from linear increase in headspace CO_2 over time. In addition, the metabolic quotient (qCO_2), or specific respiration rate, was calculated as the ratio of soil microbial respiration to microbial biomass C concentration (Anderson and Domsch, 1990).

Statistical analysis. Statistical analyses were performed using the JMP statistical package (SAS Institute, Cary, North Carolina). Analysis of variance and mean comparisons were determined for P greater than or equal to 0.05. Data sets with non-normal distributions were transformed to normal distributions using a natural log transformation procedure prior to statistical analysis.

Results

Phase 1 sampling. Soil chemical properties for Phase 1 sites (n=301) are summarized in Table 2 by landscape position. There were no significant differences in mean values between mid-slope and hilltop/ridge sites for the parameters listed in Table 2; therefore, for subsequent analyses and discussion all upland sites were combined into a single category ("upland"). In contrast, for all parameters, mean values for bottomland sites were significantly different from means for upland sites. Total C, dissolved organic C , microbial biomass C, and total N concentrations were all greater in bottomland soils than in upland soils, as expected, given the elevated soil organic matter content that is characteristic of wetlands and other riparian areas.

In general, Phase 1 soil chemistry data were consistent with the low-fertility and poorly-buffered soils of the region. Concentrations of TC and TN in the topsoil (surface 20 cm) reflected the relatively low organic matter content of both upland and bottomland soils at Fort Benning. Organic matter accumulation in the upland soils was generally restricted to the shallow A horizon (typically about 5 to 10 cm thick for Troup soil series), although an organic (O) surface horizon was observed in a few minimally-disturbed forested upland areas. Bottomland soils showed extensive variation in organic matter content relative to surrounding upland soils (inter-decile range for total C of 7.0 to 100.6 g kg^{-1}). Accordingly, our field observations indicated that frequency and duration of flooding varied widely among the bottomland sampling sites. Although soils at several bottomland sites had noticeably elevated organic matter contents, no significant accumulation of muck or peat was found at any sampling site. Increases in soil dissolved organic C , microbial biomass C and total N concentrations between upland and bottomland sites were roughly proportional to the increase observed in total C, although mean C:N ratio differed significantly between upland and bottomland sites. The mean C:N ratio of 26.8 for upland sites reflected the low fertility of these soils; in contrast the mean C:N ratio for bottomland soils was somewhat lower at 18.9.

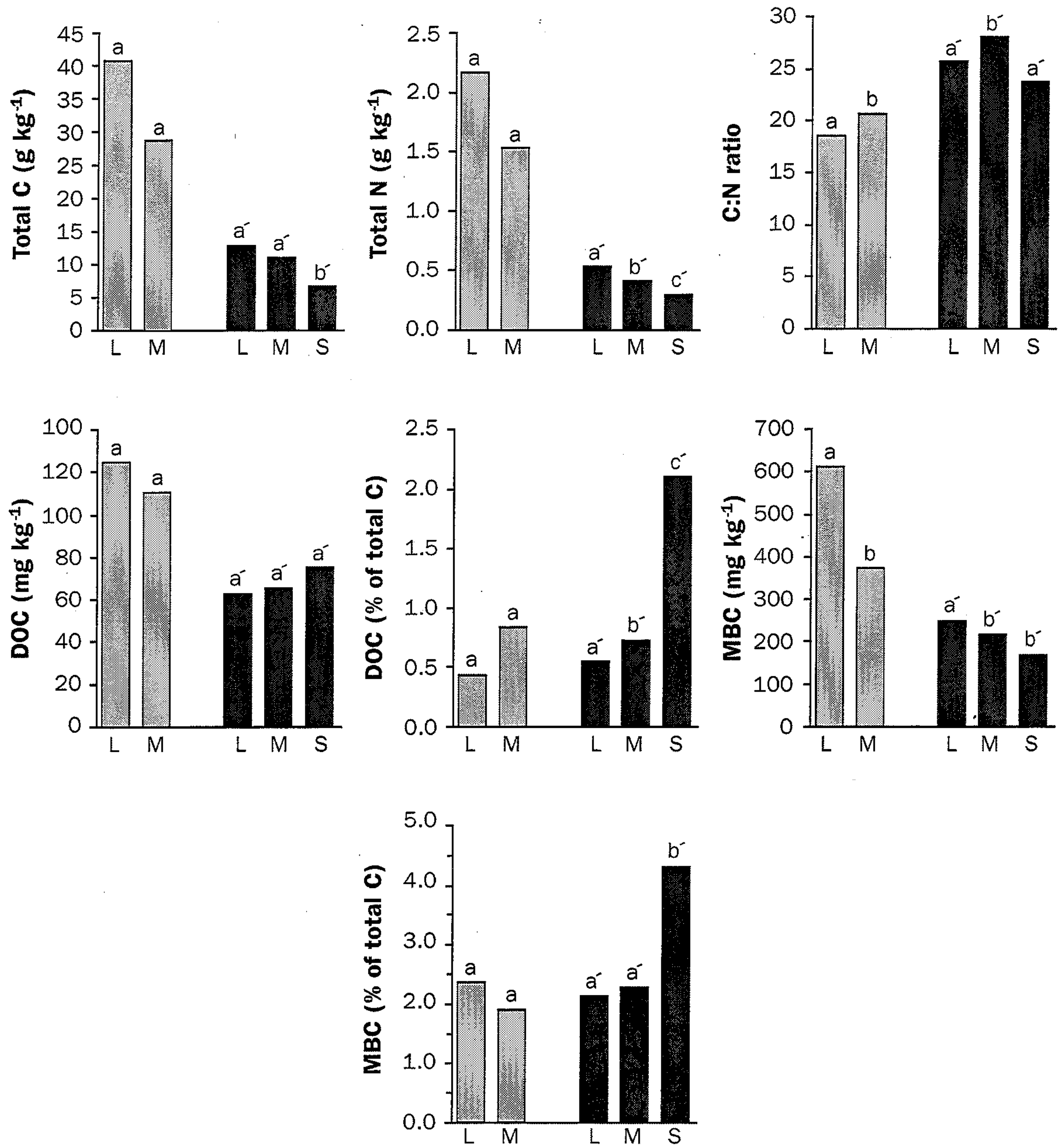
The primary disturbance-related trend for soil total C and total N among upland and bottomland Phase 1 sites was a decrease in concentration with increasing level of impact (Figure 2). A significant decrease in total C and total N with increasing level of impact was observed for upland sites; decreasing total C and total N was also observed for bottomland sites, but was not significant. Soil C:N ratio increased slightly, but significantly, with level of impact in bottomland sites. In upland areas, C:N ratio was significantly greater for moderate-impact sites than in low- or severe-impact sites. Microbial biomass C concentration showed a similar trend to total C and total N, decreasing significantly with increasing impact in both upland and bottomland sites. Dissolved organic C concentration did not vary significantly with level of impact in bottomland or upland areas.

In contrast to the response of soil dissolved organic C and microbial biomass C concentration to site impact, the relative proportion of dissolved organic C and microbial biomass C in the total soil C pool (i.e., dissolved organic C:total C and microbial biomass C:total C) increased significantly with level of impact in upland sites. The ratio of microbial biomass C to soil organic C, a.k.a. microbial quotient, has been related to soil C availability and the tendency for a soil to accumulate organic matter (Anderson and Domsch, 1989; Sparling, 1992).

Among the parameters investigated during Phase 1 of this study, soil total C, total N, dissolved organic C and microbial biomass C all exhibited a similar response to site disturbance, consistent with observed differ-

Figure 2

Summary results for the Fort Benning Phase 1 soil characterization study. Data points represent mean values for each level of site impact (L = low, M = moderate, S = severe) for bottomland (hatched bars) and upland (solid bars) sites. Bars labeled with the same letter are not significantly different (P<=0.05); separate means comparisons were performed for bottomland and upland sites. Severe-impact sites were not represented in bottom land areas for Phase 1.



ences in soil organic matter content. However, only total N and dissolved organic C:total C varied significantly and consistently among all levels of site impact in upland sites, and only microbial biomass C and C:N ratio showed significant responses to impact level in bottomland sites.

Phase 2 sampling. Analytical results for Phase 2 (Table 3) indicated significant differences in soil total C and total N concentration among sites with different levels of impact. For some parameters, in particular dissolved organic C, microbial biomass C and respiration, significant differences were found among sites with the same *a priori* designation of impact level. Although any number of observed or unknown site characteristics may account for differences in soil chemistry among similar sites, it is likely that prior land use and management exerted a significant influence on present-day soil properties, particularly those related to soil organic matter storage and turnover. Although historical land use and disturbance regime are poorly documented for specific sites within the study area, it is known that much of the study area was under cultivation for a substantial period of time prior to World War II. Significant long-term (up to 100 yrs) effects of prior cultivation on soil organic matter properties,

Table 3. Mean values for biogeochemical parameters analyzed for Phase 2 sampling at Fort Benning. Means followed by the same letter are not significantly different (P<=0.05); separate means comparisons were performed for bottomland and upland sites.

Landscape position	Site name	Site impact	Total C	Total N	C:N ratio	Dissolved organic C	microbial biomass C	Soil respiration
			g kg⁻¹	*g kg⁻¹*		*mg kg⁻¹*	*mg kg⁻¹*	*µg C g⁻¹ h⁻¹*
Bottomland sites	BW1	Low	155.0 a	8.62 a	18.2 a	433.7 a	2705 a	12.79 a
	LW	Low	111.4 bc	4.99 b	21.9 b	170.1 b	762 b	6.78 b
	BW2	Moderate	129.2 ab	5.61 b	23.0 b	393.7 a	1148 c	9.12 b
	OW	Moderate	70.1 c	3.9 b	17.7 a	132.9 b	1099 c	6.71 b
	HW	Severe	11.30 d	0.46 c	26.5 c	25.9 c	178 d	1.17 c
Upland sites	BU1	Low	9.6 a'	0.24 a'	40.1 a'	74.4 a'	128 a'	0.36 a'
	HU1	Low	10.5 a'b'	0.34 a'b'	32.7 a'b'	16.4 b'	138 a'b'	1.14 b'
	LU	Low	10.1 av	0.27 a'b'	38.8 a'	27.4 c'	170 b'	0.81 c'
	HU2	Moderate	9.7 a'	0.44 a'b'	31.4 a'b'c'	15.9 b'	144 a'b'	0.77 c'
	OU1	Moderate	12.9 b'	0.43 b'	31.8 b'	132.0 d'	273 c'	0.78 c'
	OU2	Moderate	9.8 a'	0.39 b'	28.0 b'c'	96.1 a'd'	202 b'	0.46 a'
	HU3	Severe	2.1 c'	0.10 c'	23.0 c'	8.9 e'	101 a'	0.12 d'
	RH	Severe	2.6 c'	0.10 c'	26.9 b'c'	72.6 a'	199 b'	0.14 d'

including decreased C content and lower C:N ratio, have been documented for forest soils (Compton and Boone, 2000; Compton et al., 1998).

Mean total C and total N concentration in bottomland soils were roughly three times higher for Phase 2 sites than for the more spatially distributed Phase 1 data set. This discrepancy resulted from the fact that the comprehensive set of bottomland sites sampled in Phase 1 included many infrequently flooded wetlands and riparian zones of intermittent streams, with characteristically low accumulation of soil organic matter. The Phase 2 bottomland sites, on the other hand, were true wetlands, as evidenced by the hydrophytic vegetation and flooded or saturated soils noted during numerous field visits.

Aside from the difference in magnitude of total C and total N between Phase 1 and 2 sampling events, the general trends of C and N related parameters with respect to site impact were similar for Phase 1 and 2 (Figure 3). Total C showed an overall decrease with increasing level of impact, in both bottomland and upland areas, although mean total C concentrations for low and moderate levels of impact were not significantly different. Total N concentration followed a similar trend to total C in bottomlands; however, for upland areas the highest total N values were associated with moderate site impact rather than low site impact. Soil C:N ratio was significantly higher in severely-impacted bottomland sites than in low to moderate impact bottomlands. In contrast, C:N ratio decreased significantly with increasing level of site impact in upland areas. Dissolved organic C and microbial biomass C decreased significantly with increasing impact in bottomlands, but were highest at the moderate level of impact in uplands. As observed for Phase 1 sites, dissolved organic C:total C and microbial biomass C:total C increased significantly with level of impact in upland sites and, in contrast to Phase 1 results, showed a significant increase with site impact for bottomland areas.

Soil respiration decreased significantly with increasing level of impact for both bottomland and upland sites (Figure 3), although differences between low- and moderate-impact sites were not significant. Since soil respiration was determined by laboratory incubation of soil samples at a constant temperature, the measured rates represented (1) primarily microbial respiration rather than root respiration, and (2) potential respiration rates rather than actual *in situ* rates at the time of sampling. Although this approach does not capture the true magnitude (i.e., CO_2 evolved per unit area) or temporal variability of soil respiration under field conditions, it is a useful method for inter-site comparison of soil microbial activity.

Soil respiration rate was roughly correlated with total C concentration, as would be expected since organic C provides the metabolic substrate for soil microorganisms. However, metabolic quotient (qCO_2), or specific respiration rate (normalized to microbial biomass C), showed a significant decrease with increasing level of impact (Figure 3). Conceptually, qCO_2 is a measure of microbial efficiency in the conversion of substrate C to microbial biomass C, and elevated qCO_2 is often viewed as an indicator of increased environmental stress or disturbance (Wardle and Ghani, 1995). Increased qCO_2 has also been associated with soils in early successional ecosystems, under the premise that microbial efficiency is lower in these high resource systems with open cycling (Insam and Haselwandter, 1989; Wardle, 1993). However, Wardle and Ghani (1995) concluded that qCO_2 response is not always predictable, citing, for example, experimental evidence that this parameter may increase during the course of ecological succession. In this case, it is likely that decreasing qCO_2 with increasing site impact was related to substrate bioavailability, and was not a response to environmental (external) stress.

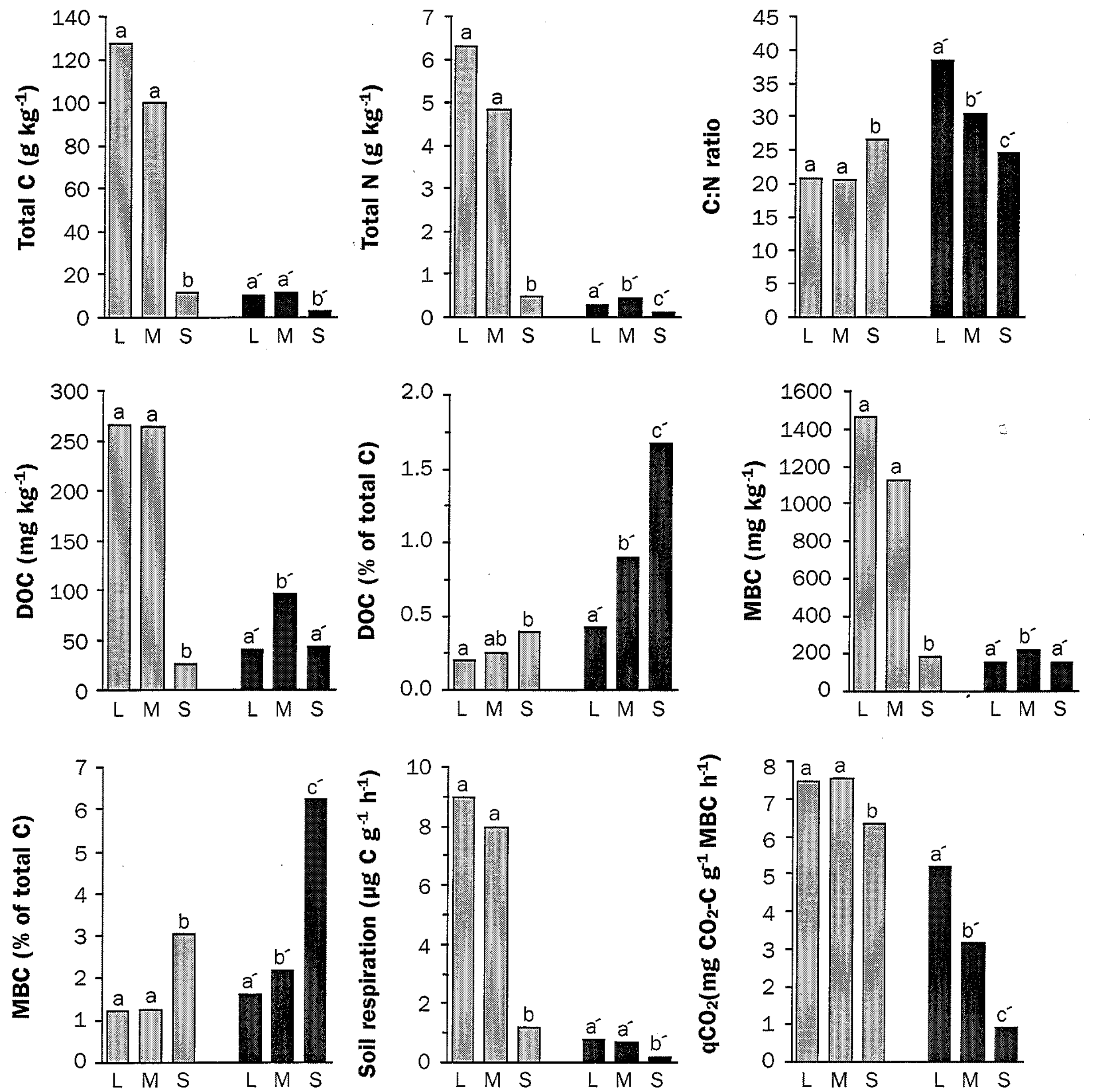
Discussion

The nature of physical impacts to upland sites ranged from partial to total loss of vegetative ground cover; minor sheet or rill erosion to severe gully erosion; and disturbance of O and A horizons by foot or vehicular traffic to complete loss of topsoil through mechanized training and erosion. Elevated soil bulk density and decreased infiltration rate have been documented in areas of moderate to high foot traffic associated with military training, at Fort Benning and elsewhere (Garten et al., 2003; Whitecotton et al., 2000). Based on site observations, it was apparent that moderate to severe disturbance (e.g., training exercises) tended to disrupt the integrity of the topsoil, primarily the A horizon, where ground cover had been reduced by disturbance or was naturally sparse. Furthermore, it is likely that ground cover impacts from training were magnified because of the loose structure and sandy texture of the A horizon.

Ecological impacts to bottomland sites were generally the result of soil disturbance in

Figure 3

Summary results for the Fort Benning Phase 2 soil characterization study. Data points represent mean values for each level of site impact (L = low, M = moderate, S = severe) for bottomland (hatched bars) and upland (solid bars) sites. Bars labeled with the same letter are not significantly different (P<=0.05); separate means comparisons were performed for bottomland and upland sites.



adjacent upland areas, rather than on-site activities. Although evidence of direct physical impact (soil or vegetation disturbance) was found in a few bottomland sites within the Fort Benning study area, none occurred within the set of Phase 1 sampling sites. The primary consequence of upland disturbance (both military and non-military) in adjacent bottomland areas was an accelerated rate of sedimentation. In most cases, this was manifest as deposition of fine particulates (most likely silt and clay fractions), but in bottomlands located downslope from severely-impacted uplands significant deposits of coarse particulates (primarily sand) were observed.

The response of soil total C and related parameters to site impact level was similar for both Phase 1 and Phase 2 of the study. Phase 2 sites were selected with the intent of minimizing variability resulting from differences in soil type and vegetation associations, thus clarifying the relationships between site impact and response variables. Although Phase 2 results provided little additional information on the relationship between site impact and total C, total N, dissolved organic C or microbial biomass C, the response of the derived variables microbial biomass C:total C and dissolved organic C:total C to site impact was more clearly illustrated by Phase 2 results. Similarly, a well-defined response was observed for metabolic quotient, qCO_2, particularly for upland sites.

For both upland and bottomland sites, the observed decrease in soil total C and total N with increasing level of impact was indicative of the reduction in soil organic matter content of surface horizons. The positive relationship shown for microbial biomass C:total C and dissolved organic C:total C vs. site impact may be related to a disproportionate loss of stable soil organic matter (i.e., humus) in the O and A horizons due to physical soil disturbance. In addition to wholesale loss of soil organic matter in surface soils (decreasing total C and total N concentration) via erosion or mixing of soil horizons, it is likely that chronic physical disturbance of topsoil may stimulate decomposition of the more recalcitrant soil organic matter fractions. For example, tillage of agricultural soils favors breakdown of soil organic matter through increased aeration and breakup of soil aggregates with exposure of previously inaccessible organic matter to microbial attack (Haynes, 1999). Similarly, Neff and Asner (2001) suggested that disruption of soil aggregates through physical disturbance can indirectly increase dissolved organic C release by increasing the surface area of the aggregates. Burford and Bremner (1975) found a high correlation between dissolved organic C and mineralizable C among soils with widely varying pH, texture and organic matter content.

The response of qCO_2 to soil disturbance was consistent with the responses of dissolved organic C:total C and microbial biomass C:total C, all of which suggest that resource (organic C) quality *increased* with soil disturbance, i.e. there was a lower proportion of recalcitrant soil organic matter, even as total soil C storage *decreased* with increasing disturbance. This relates to the earlier observation that chronic soil disturbance may have created a more favorable environment, e.g., increased soil oxygenation, for decomposition of the more stable organic matter fractions, and therefore served to reduce, rather than increase, environmental stress for soil micoorganisms.

Based on combined results of Phases 1 and 2 of this study, both dissolved organic C:total C and microbial biomass C:total C demonstrated their potential as indicators of site condition in upland soils. The potential value of the dissolved organic C:total C parameter as a robust ecological indicator beyond the boundaries of this study, cannot be determined solely from these results. The microbial biomass C:total C parameter, on the other hand, has been widely used as an indicator of bioavailability of soil organic C (Anderson and Domsch, 1989; Sparling, 1992). Although the biochemical processes governing the relationship between qCO_2 and soil impact or condition are not known with any certainty, our study results suggest that this parameter also may be a useful indicator of ecological condition or change, primarily for upland areas. Based on prior research, the utility of the metabolic quotient as an ecological indicator may be relatively region- or site-specific, and/or limited by the ability to identify appropriate assumptions and criteria for reliable use of this parameter (Wardle and Ghani, 1995).

Summary and Conclusion

Impacts to upland soils and ground cover due to military and related anthropogenic activities at the Fort Benning study site included (1) disturbance or loss of vegetation and increased area of bare ground, (2) disruption of the soil A horizon and effective burial or dilution of biologically-active topsoil with organic-poor lower horizons, (3) increased erosion in uplands and deposition of sediment in bottomland areas, and (4) loss of soil A horizon in severely-impacted upland areas. Impacts to bottomland soils were primarily associated with soil disturbance in adjacent upland areas, and typically involved accelerated deposition of clay and silt (moderately-impacted areas) or sand (severely-impacted areas). The primary impact of increased sedimentation, with regard to soil C and N dynamics, was dilution and/or burial of organic matter contained in the native wetland soils.

Decreasing soil total C and total N was closely associated with increasing level of site impact, reflecting the loss of organic matter in the soil A horizon. While dissolved organic C responded inconsistently to site impact, microbial biomass C and soil respiration showed a significant decrease with increasing site impact, consistent with the trend observed for total C. However, changes in microbial biomass C with impact level were not directly proportional to changes in total C, as demonstrated by the significant increase in microbial biomass C:total C with site impact. The response of microbial biomass C:total C to site impact, and concomitant increase in dissolved organic C:total C, suggested an increase in the proportion of bioavailable C in the soil organic matter pool. This may have occurred via a simultaneous increase in decomposition of resistant soil organic matter fractions due to physical soil disturbance and increased fragmentation of newly-deposited plant litter. The decrease in qCO_2 with increasing disturbance is consistent with this scenario, where microbial efficiency of C assimilation increases as the proportion of recalcitrant soil organic matter fractions decreases (increased site impact).

The variability of soil organic matter-related parameters among sites of low to moderate disturbance was of particular interest in this study. Soil properties displaying a high degree of correlation to known site condition (as determined from visual assessment) are potential candidates for use as ecological indicators in areas where site disturbance history is not known, or present site condition is not easily determined by visual assessment. Such indicator parameters may be particularly useful for monitoring trends in ecological condition, i.e., the progression of ecosystem degradation or recovery associated with disturbance or restoration activities. Thus, while our findings for sites with extremely high or low disturbance are not particularly revealing, the response of soil parameters to a wide range of site disturbance level provides information of relevance to the development and refinement of ecological indicators.

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