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Effects of Heavy, Tracked-Vehicle Disturbance on Forest Soil Properties at Fort Benning, Georgia

May 2004

C.T. Garten, Jr., and T.L. Ashwood

Environmental Sciences Division

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EFFECTS OF HEAVY, TRACKED-VEHICLE DISTURBANCE ON FOREST SOIL PROPERTIES AT FORT BENNING, GEORGIA

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ABSTRACT

The purpose of this report is to describe the effects of heavy, tracked-vehicle disturbance on various measures of soil quality in training compartment K-11 at Fort Benning, Georgia. Pre-disturbance soil sampling in April and October of 2002 indicated statistically significant differences in soil properties between upland and riparian sites. Soil density was less at riparian sites, but riparian soils had significantly greater C and N concentrations and stocks than upland soils. Most of the C stock in riparian soils was associated with mineral-associated organic matter (i.e., the silt + clay fraction physically separated from whole mineral soil). Topographic differences in soil N availability were highly dependent on the time of sampling. Riparian soils had higher concentrations of extractable inorganic N than upland soils and also exhibited significantly greater soil N availability during the spring sampling.

The disturbance experiment was performed in May 2003 by driving a D7 bulldozer through the mixed pine/hardwood forest. Post-disturbance sampling was limited to upland sites because training with heavy, tracked vehicles at Fort Benning is generally confined to upland soils. Soil sampling approximately one month after the experiment indicated that effects of the bulldozer were limited primarily to the forest floor (O-horizon) and the surface (0-10 cm) mineral soil. O-horizon dry mass and C stocks were significantly reduced, relative to undisturbed sites, and there was an indication of reduced mineral soil C stocks in the disturbance zone. Differences in the surface (0-10 cm) mineral soil also indicated a significant increase in soil density as a result of disturbance by the bulldozer. Although there was some tendency for greater soil N availability in disturbed soils, the changes were not significantly different from undisturbed controls. It is expected that repeated soil disturbance over time, which will normally occur in a military training area, would simply intensify the changes in soil properties that were measured following a one-time soil disturbance at the K-11 training compartment.

The experiment was also useful for identifying soil measurements that are particularly sensitive to disturbance and therefore can be used successfully as indicators of a change in soil properties as a result of heavy, tracked-vehicle traffic at Fort Benning. Measurements related to total O-horizon mass and C concentrations or stocks exhibited changes that ranged from ≈25 to 75% following the one-time disturbance. Changes in surface (0-10 cm) mineral soil density or measures of surface soil C and N following the disturbance were less remarkable and ranged from ≈15 to 45% (relative to undisturbed controls). Soil N availability (measured as initial extractable soil N or N production in laboratory incubations) was the least sensitive and the least useful indicator for detecting a change in soil quality. Collectively, the results suggest that the best indicators of a change in soil quality will be found at the soil surface because there were no statistically significant effects of bulldozer disturbance at soil depths below 10 cm.

Key words: soil disturbance, tracked-vehicle training, soil C, soil N, particulate organic matter (POM), soil quality, ecological indicators, military land management

1. INTRODUCTION

Disturbance of soil physical properties and/or structure are commonly reported effects associated with the use of heavy, tracked vehicles in military training (Iverson et al., 1981; Prose, 1985; Braunack, 1986; Thurow et al., 1993; Ayers, 1994; Prosser et al., 2000; Belnap and Warren, 2002). In some environments, it has been shown that the effects of soil disturbance by tracked military vehicles can persist for decades (e.g., Iverson et al., 1981; Belnap and Warren, 2002). At Fort Benning, Georgia, field training with tracked vehicles has resulted in an overall loss of soil quality at some training sites where heavily disturbed, barren soils have negligible O-horizons, lower soil N availability, and lower soil C and N stocks than soils subject to minimal military use (Garten et al., 2003; Garten and Ashwood, 2004).

The purpose of this report is to describe the effects of heavy, tracked-vehicle disturbance on various measures of soil quality in training compartment K-11 at Fort Benning, Georgia. An experiment was performed by driving a D7 bulldozer through a mixed pine/hardwood forest. Pre-disturbance soil sampling was performed in both spring and autumn of the year preceding the disturbance to determine how site-specific topographic differences in soil quality would potentially affect post-disturbance sampling. The null hypothesis for the experiment was that disturbance caused by a heavy, tracked vehicle would not affect overall forest soil quality by changing soil C and N or by changing soil N availability. The bulldozer was considered here as a surrogate for a military, tracked vehicle of similar weight.

2. METHODS

2.1 STUDY SITE

The study site was located in the northeast corner of Fort Benning in a mature, second-growth, mixed evergreen-hardwood forest in training compartment K-11. The topography at the site included both poorly drained riparian zones adjacent to intermittent streams and well-drained upland forest stands. Forest management practices at the site have been implemented to promote growth and development of long-leaf pine (*Pinus palustris*).

The site's prior history included light military activity (i.e., infantry training) in addition to stand thinning and prescribed burning as part of the installation's timber management program. Prescribed burning to remove understory shrubs and hardwood saplings occurred in May 2002 and thinning occurred in late October 2002 (6 months prior to the experimental disturbance).

The disturbance was performed in May 2003 with several passes of a D7 bulldozer. The weight of the equipment was approximately 23,000 kg. The disturbance removed existing vegetation and forest floor organic matter from two rectangular areas (approximately 5 x 50 m in size). Most surface debris was piled at one end of the bulldozer cut, however a visual inspection of the site revealed that a minor part of the surface debris was buried by the disturbance.

2.2 SOIL SAMPLING

Pre-disturbance sampling was conducted in April and early October 2002 to characterize seasonal and topographic differences in soil C and N and soil N availability. In April, 16 sampling stations were established along transects that traversed both upland (n = 8) and riparian (n = 8) areas. The October sampling was performed at 17 stations (7 riparian and 10 upland). Post-disturbance sampling was conducted in June 2003 to characterize the effect of disturbance on soil quality. Results from the pre-disturbance sampling indicated topographic differences in soil properties (see results), therefore post-disturbance soil sampling was limited to upland locations. Seven sampling stations were randomly chosen along the disturbance zone created by the bulldozer. For each upland station in the disturbance zone, a control sampling station was selected in an undisturbed area ≈5 m from the disturbance.

In both pre- and post-disturbance soil sampling, replicate samples of the O-horizon (when present) were removed with a knife from a 214 cm^2 area above the mineral soil. Replicate mineral soil samples (0-30 cm) were then collected in butyrate plastic tubes using a soil probe (2.4 cm diameter) with hammer attachment (AMS, American Falls, ID). The distance between replicate samples was 1 to 2 m. A third sample (0-20 cm) was also collected at each sampling station by hammering a PVC pipe (5.1 cm diam x 25 cm long) into the mineral soil. The ends of the tubes and the pipes were capped to prevent soil loss during transport. Samples were transported to the laboratory and stored in a refrigerator (5 °C) prior to analysis.

2.3 SAMPLE ANALYSIS

2.3.1 Soil Carbon and Nitrogen

The dry mass of O-horizon material was determined after oven-drying at 75 °C. O-horizon samples were ground and homogenized in a sample mill and stored in airtight glass bottles prior to elemental analysis. Mineral soil samples collected in the butyrate tubes were cut into 10 cm increments and equivalent depth increments from the same sampling station were composited. Soil samples were dried to a constant weight at room temperature (21 °C) in a laboratory equipped with a dehumidifier. The air-dry soil samples were crushed with a rubber mallet and passed through a 2-mm sieve to remove gravel and coarse debris. A subsample of the soil (< 2 mm) was ground and homogenized in a ball mill and stored in an airtight container prior to elemental analysis.

2.3.2 Physical Fractionation of Soils

Part of each surface mineral soil sample (0-20 cm) collected in a PVC pipe was physically separated into particulate organic matter (POM) and mineral-associated organic matter (MOM) (Cambardella and Elliott, 1992). Twenty grams of air-dry soil were dispersed by shaking overnight in a 100 mL solution of sodium hexametaphosphate (5 g L^{-1}). The mixture was wet-sieved through a 0.053 mm sieve. POM was recovered by back washing the sieve, filtering (Whatman 541) the POM from the wash solution, and oven drying. The mixture that passed the 0.053 mm sieve was also oven dried to recover MOM (i.e., silt + clay). Both POM and MOM from each soil sample were weighed after oven drying (75 °C) and stored in airtight containers prior to elemental analysis.

2.3.3 Soil Nitrogen Availability

Part of each surface mineral soil sample (0-20 cm) collected in a PVC pipe was used for the determination of potential net soil N mineralization and nitrification in 12-week aerobic laboratory incubations. The fresh soil was passed through a 6.3 mm sieve to remove coarse debris and rocks. A subsample of the sieved soil was air-dried to determine the dry mass-to-fresh mass conversion factor. A second subsample of sieved soil (≈ 12 g) was extracted by shaking for 2 hours in a 100 mL solution of 2 M KCl to determine initial extractable NH_4-N and NO_3-N. The remaining soil (< 6.3 mm) was placed in a plastic jar and incubated in the dark at room temperature (21 °C). Once a week, the lids were removed briefly from the jars to aerate the soil samples. Extractions of the incubating soils were repeated after 6 and 12 weeks to determine the production of NH_4-N and NO_3-N. Extractions were allowed to settle overnight in a refrigerator (5 °C). Potential net soil N mineralization was calculated as the difference between extractable inorganic N (NH_4-N + NO_3-N) at 6 or 12 weeks and the initial extractable inorganic N. Potential net soil nitrification was calculated in a similar manner from concentrations of extractable NO_3-N. In each case, the units were μg N g^{-1} air-dry soil, based the dry mass-to-fresh mass conversion factor from the initial soil sample.

2.3.4 Elemental Analysis

Samples were analyzed for total C and N using a LECO CN-2000 (LECO Corporation, St. Joseph, MI). The elemental analyzer was calibrated using LECO standards traceable to the National Institute of Standards and Technology (NIST), Gaithersburg, MD. Soil extracts were analyzed for NH_4-N and NO_3-N concentrations by digital colorimetry using a Bran+Luebbe AutoAnalyzer 3.

2.3.5 Calculations

Carbon and N stocks (g element m^{-2}) in the O-horizon were calculated as the product of concentration (g element g^{-1}) and dry mass per unit area (g m^{-2}). Carbon and N stocks in each increment of mineral soil were calculated as the product of concentration (g element g^{-1} soil), soil density (g m^{-3}), and increment length (m). Soil density was calculated on the basis of air-dry mass (< 2 mm) and the known volume of soil collected in the butyrate plastic tubes.

Soil C in POM (g POM-C g^{-1} soil) or MOM (g MOM-C g^{-1} soil) was calculated by multiplying the dry mass of the POM or MOM part (g part g^{-1} soil) by the respective C concentration (g C g^{-1} part). The fraction of soil C in POM (fPOM) was calculated based on the total C measured in the POM and MOM. The C stock in surface mineral soil that was associated with POM (POM-C) was calculated as the product of soil C stock (g C m^{-2}) and fPOM. The C stock in surface mineral soil that was associated with MOM (MOM-C) was calculated as the product of soil C stock (g C m^{-2}) and (1 - fPOM). Following appropriate substitutions in the equations, similar calculations were performed for soil N.

The annual potential rate of net soil N mineralization was calculated by extrapolating the net N mineralization in 12-week aerobic laboratory incubations to 52 weeks (g N produced g^{-1} soil) and dividing by the surface (0-20 cm) soil N concentration (g N g^{-1}). This calculation provides an estimate of the fraction of organic soil N that is potentially mineralized each year.

2.3.6 Statistical Analysis

Although pre- and post-disturbance soil sampling occurred in the same general area, the two data sets were not directly comparable because sampling was not undertaken at precisely the same locations. Measurements on pre-disturbance soil samples were analyzed for seasonal (April vs. October) and topographic (riparian vs. upland) differences using two-way ANOVA. If one of the main effects and the interaction were not statistically significant, the analysis was simplified to a one-way ANOVA in which the statistically significant main effect was retained. Post-hoc tests of differences between means were performed using Fisher's protected least significant difference (LSD). The results of pre-disturbance soil sampling was used for planning post-disturbance sampling. Post-disturbance soil samples were limited to upland sites and were analyzed for the effects of bulldozer disturbance using a paired t-test (each disturbance sampling station was paired with an undisturbed control station). Unless stated otherwise, statistical significance was indicated by $P \leq 0.05$.

3. RESULTS

3.1 PRE-DISTURBANCE SOIL SAMPLING

3.1.1 O-Horizon

There were no significant differences between sampling dates (April and October) for O-horizon measurements in training compartment K-11. Mean ±SE O-horizon dry mass in the pre-disturbance soil sampling was 1246 ±78 g m^{-2} (n = 33). The mean ±SE O-horizon C and N stocks were 490 ±35 (n = 33) and 9.1 ±0.8 (n = 33) g m^{-2}, respectively. There were no significant topographic differences in O-horizon C and N stocks despite a significant difference between riparian and upland sampling stations in O-horizon N concentrations and C:N ratios (Table 1). The O-horizon N concentration was significantly less and the C:N ratio was significantly greater at upland sampling stations.

Table 1. Mean (±SE) pre-disturbance O-horizon N concentrations and C:N ratios at riparian and upland sampling stations in training compartment K-11.
The number of sampling stations is shown in parenthesis.

Variable	Sampling stations		F-value[a]
	Riparian (n = 15)	Upland (n = 18)	
N concentration (%)	0.814 ±0.044	0.656 ±0.051	5.2*
C:N ratio	49.4 ±1.8	70.1 ±8.0	5.4*

[a] Degrees of freedom = 1,31
$*P \leq 0.05$

3.1.2 Whole Mineral Soil

Sampling date had no significant effect on soil C or soil N concentrations in any of the mineral soil depth increments examined (0-10, 10-20, and 20-30 cm). However, there were significant differences in soil density, soil C and N concentrations, and soil C and N stocks between upland and riparian sites in training compartment K-11 (Table 2). Although riparian zones had significantly lower soil densities than upland areas, there was significantly more soil C and N in riparian zones because of large differences in soil C and N concentrations.

In general, soil C and N concentrations at riparian sampling stations were a factor of 2 or more greater than those at upland sampling stations. Mean ±SE C stocks over the top 30 cm of mineral soil were 5609 ±367 and 2748 ±131 g C m^{-2} in riparian and upland soils, respectively. Mean ±SE soil N stocks over the top 30 cm of mineral soil were 174 ±14 g N m^{-2} at the riparian stations and 85.4 ±7.2 g N m^{-2} at the upland stations. Topographic position had no significant effect on soil C:N ratios at any soil depth. The mean ±SE C:N ratios for the 0-10, 10-20, and 20-30 cm soil increments (n = 33 samples for each depth) were, respectively, 33.6 ±1.2, 37.4 ±2.3, and 38.7 ±5.0.

3.1.3 Physical Fractionation of Soils

None of the measurements associated with the physical separation of whole soil C or N between POM and MOM were significantly affected by sampling date. There were significant differences between riparian and upland sampling stations for measured amounts of POM and MOM, the fraction of soil C in POM (fPOM) and MOM (fMOM), and concentrations of C and N in MOM (Table 3). Soils from upland stations had greater amounts of POM and a greater fraction of soil C in POM. Riparian soils had greater C and N concentrations in MOM than soils from upland stations.

Soils from riparian sampling stations had significantly greater total soil C stocks and more C in POM and MOM than soils from upland sampling stations (Table 4). Carbon in the O-horizon and POM was summed to approximate labile soil C which was significantly greater in riparian soils than in upland soils (due to differences in amounts of POM-C). At riparian and upland sites, respectively, ≈62 and 49% of the total soil C was associated with MOM indicating greater relative amounts of stabilized soil C pool in areas adjacent to streams.

Table 2. Mean (±SE) pre-disturbance soil density, C and N concentrations, and C and N stocks at riparian and upland sites in training compartment K-11.
The number of sampling stations is shown in parenthesis.

Variable	Soil depth (cm)	Sampling stations		F-value[a]
		Riparian (n = 15)	Upland (n = 18)	
Soil density ($g\ cm^{-3}$)	0-10	0.972 ±0.025	1.143 ±0.034	15.6***
	10-20	1.245 ±0.028	1.382 ±0.020	16.8***
	20-30	1.367 ±0.035	1.441 ±0.022	NS
Soil C concentration (%)	0-10	2.97 ±0.25	1.45 ±0.09	37.1***
	10-20	1.32 ±0.12	0.50 ±0.03	49.9***
	20-30	0.89 ±0.12	0.29 ±0.02	28.5***
Soil C stock ($g\ C\ m^{-2}$)	0-10	2821 ±196	1638 ±96	32.5***
	10-20	1612 ±123	694 ±43	56.9***
	20-30	1176 ±129	415 ±31	39.1***
Soil N concentration (%)	0-10	0.092 ±0.008	0.044 ±0.015	32.2***
	10-20	0.039 ±0.004	0.015 ±0.001	34.2***
	20-30	0.030 ±0.006	0.009 ±0.001	13.9***
Soil N stock ($g\ N\ m^{-2}$)	0-10	88.4 ±6.9	50.7 ±4.2	23.3***
	10-20	47.1 ±4.1	21.0 ±2.1	34.8***
	20-30	38.9 ±6.3	13.7 ±1.7	17.3***

[a]Degrees of freedom = 1,31
***$P \leq 0.001$; NS = not significantly different

3.1.4 Soil Nitrogen Availability

There was no effect of sampling date on initial extractable NH_4-N, NO_3-N and inorganic N in pre-disturbance soil samples from training compartment K-11. For this reason, extraction data from April and October were combined prior to a comparison of riparian and upland soils. Extractable NH_4-N and inorganic-N were significantly greater in soils from riparian sampling stations (Table 5). At both riparian and upland sites, extractable NO_3-N was a small percentage (≤ 3%) of initial extractable inorganic soil N.

There were complex interactions between time of sampling and sampling location for measurements of both potential net soil N mineralization and nitrification (Table 5). In April, riparian soils exhibited more potential net soil N mineralization than upland soils, but there was no significant difference in October soil samples. Potential net nitrification was significantly greater in riparian soils than upland soils in both April and October (although there was a 10% probability that the difference in April samples was due to chance alone). When data from the April sampling period were used, calculated potential rates of net N mineralization in riparian soils were significantly greater than those in upland soils. However, when data from the October sampling period were used, there was no statistically significant difference between riparian and upland sites.

Table 3. Mean (±SE) pre-disturbance particulate organic matter (POM), fraction of soil C in POM and mineral-associated organic matter (MOM), and C and N concentrations in MOM at riparian and upland sites in K-11.
The number of sampling stations is shown in parenthesis.

Variable	Sampling stations		F-value[a]
	Riparian (n = 15)	Upland (n = 18)	
POM (g POM g^{-1} soil)	0.772 ±0.024	0.841 ±0.008	8.3**
Fraction of soil C in POM	0.317 ±0.018	0.406 ±0.014	15.2**
Fraction of soil C in MOM	0.683 ±0.018	0.594 ±0.014	15.2**
C concentration in MOM (%)	6.44 ±0.51	4.08 ±0.28	17.9***
N concentration in MOM (%)	0.268 ±0.020	0.174 ±0.013	16.4***

[a] Degrees of freedom = 1,31
**$P \leq 0.01$; ***$P \leq 0.001$

Table 4. Mean (±SE) pre-disturbance C stocks (g C m^{-2}) in different soil pools at riparian and upland sites in training compartment K-11.
The number of sampling stations is shown in parenthesis.

Soil C pool	Sampling stations		F-value[a]
	Riparian (n = 15)	Upland (n = 18)	
O-horizon	455 ±56	519 ±46	NS
Particulate organic matter (POM)	1404 ±117	950 ±62	12.9**
Labile organic matter	1859 ±146	1469 ±93	5.4*
Mineral-associated organic matter	3028 ±215	1382 ±76	59.9***
Total[b]	4888 ±311	2851 ±132	40.9***

[a] Degress of freedom = 1,31
[b] 20 cm soil depth
*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$; NS = not significantly different

Table 5. Mean (±SE) pre-disturbance concentrations of extractable NH_4-N, NO_3-N and inorganic N, potential net N mineralization and nitrification during a 12-week aerobic laboratory incubations, and the calculated annual rate of potential net N mineralization in surface (0-20 cm) mineral soils from riparian and upland sites at training compartment K-11.

The number of sampling stations is shown in parenthesis.

Variable	Sampling Date	Sampling stations		F-value
		Riparian	Upland	
Extractable NH_4-N ($\mu g\ g^{-1}$)	--	3.8 ±0.5 (15)	1.7 ±0.3 (18)	14.3***
Extractable NO_3-N ($\mu g\ g^{-1}$)	--	0.09 ±0.030 (15)	0.05 ±0.02 (18)	NS
Extractable inorganic N ($\mu g\ g^{-1}$)	--	3.9 ±0.5 (15)	1.8 ±0.3 (18)	14.9***
Net soil N mineralization ($\mu g\ N\ g^{-1}$)	April	13.3 ±3.9 (8)	0.8 ±0.5 (8)	10.0**
	October	1.3 ±1.3 (7)	1.8 ±0.5 (10)	NS
Net nitrification ($\mu g\ N\ g^{-1}$)	April	9.1 ±4.0 (8)	1.3 ±0.6 (8)	$3.7^{\dagger}$
	October	2.1 ±0.9 (7)	0.3 ±0.2 (10)	5.0*
Net N mineralization rate (yr^{-1})	April	0.080 ±0.015 (8)	0.014 ±0.008 (8)	14.9**
	October	0.008 ±0.008 (7)	0.027 ±0.009 (10)	NS

$^{\dagger}P \leq 0.10$; $*P \leq 0.05$; $**P \leq 0.01$; $***P \leq 0.001$; NS = not significantly different

3.2. POST-DISTURBANCE SOIL SAMPLING

3.2.1 O-Horizon

Multiple properties of the forest floor were affected by the experimental disturbance (Table 6). Measurements of O-horizon dry mass, C concentrations and stocks, N stocks, and C:N ratios were significantly reduced at sampling points in the disturbance zone relative to paired controls. The disturbance reduced O-horizon dry mass by ≈60% and C stocks by ≈71%. O-horizon N concentration was the only forest floor measurement not significantly affected by the experimental disturbance.

Mean O-horizon dry mass measured at upland control points during post-disturbance sampling (640 g m^{-2}) was approximately half that measured in pre-disturbance sampling (1246 g m^{-2}). Similarly, mean post-disturbance stocks of C (310 g C m^{-2}) and N (3.19 g N m^{-2}) in the O-horizon at control sampling points were ≈37 and 65% less, respectively, than those measured during pre-disturbance soil sampling. The pre- and post-disturbance differences were not unexpected because a prescribed fire removed understory vegetation and O-horizons from the K-11 training compartment prior to the experimental disturbance. Lower O-horizon N concentrations (0.51 ±0.03%) in post-disturbance samples indicated that N losses from fire partly contributed to an observed post-disturbance increase in O-horizon C:N ratios.

Table 6. Mean (±SE) O-horizon properties at upland sites disturbed by a bulldozer and at paired, undisturbed (control) sites in K-11.
The number of sampling stations is shown in parenthesis.

Measurement	Treatment		Mean difference	Paired t-value
	Control (n = 14)	Disturbed (n = 14)		
Dry mass (g cm^{-2})	640 ±57	257 ±112	-384	3.26**
C concentration (%)	47.8 ±0.9	36.7 ±1.5	-12.9	9.19***
C:N ratio	100.5 ±7.5	73.5 ±8.7	-36.2	4.5**
C stock (g C m^{-2})	310 ±30	91 ±38	-219	4.9***
N stock (g N m^{-2})	3.19 ±0.34	1.39 ±0.60	-1.81	2.9*

$^*P \leq 0.05$; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$

3.2.2 Whole Mineral Soil

The effects of bulldozer disturbance on mineral soil properties are presented in Table 7. Disturbance significantly increased soil density in the 0-10 cm depth increment, but differences between control and disturbed sites were not statistically significant for the 10-20 and 20-30 cm soil increments. Throughout the soil profile, there was a decrease in soil C concentrations in the disturbance zone, and for each depth increment there was a 10% probability that the differences occurred by chance alone. Surface (0-10 cm) soil C stocks and N concentrations in the disturbance zone were also reduced by ≈37 and 40%, respectively, relative to control sampling points. Although there was a tendency for lower soil N stocks at disturbed sites relative to control sites, the differences were not statistically significant.

Post-disturbance soil density at control sites (1.13 g cm^{-3}) was similar pre-disturbance soil density at upland sites (1.14 g cm^{-3}) in the K-11 training compartment. Although not directly comparable, pre-disturbance soil C concentrations (1.45%) and stocks (1638 g C m^{-2}) were more similar to soil C concentrations (1.50%) and stocks (1931 g C m^{-2}) in the disturbance zone and less than soil C concentrations (2.71%) and stocks (3041 g C m^{-2}) measured at control sites during post-disturbance soil sampling (Table 7).

3.2.3 Physical Fractionation of Soil

Post-disturbance sampling indicated no differences between control and bulldozer disturbed sites in the amount of POM in surface mineral soils (Table 8). The amount of POM present was similar to that measured in pre-disturbance surface mineral soil samples from upland sampling sites (i.e., 0.841 g POM g^{-1} soil). Although concentrations of C and N in both POM and MOM tended to be less in soils from the area disturbed by the bulldozer, the differences were not significantly different. However, the fraction of soil C and N in POM (i.e., POM C and N expressed relative to total soil C and N) was significantly reduced in surface mineral soils under the disturbance (Table 8). Compared to controls, the fraction of soil C and N in the POM part was reduced by ≈20% and ≈32%, respectively, in soils from the disturbance zone.

Table 7. Mean (±SE) soil density, C and N concentrations, and C and N stocks at upland sites disturbed by a bulldozer and at paired, undisturbed (control) sites in training compartment K-11.

The number of sampling stations is shown in parenthesis.

Measurement	Soil depth (cm)	Treatment		Mean difference	Paired t-value
		Control (n = 7)	Disturbed (n = 7)		
Soil density (g cm^{-3})	0-10	1.13 ±0.03	1.32 ±0.05	0.18	2.74*
	10-20	1.41 ±0.06	1.48 ±0.05	0.08	NS
	20-30	1.54 ±0.05	1.57 ±0.02	0.03	NS
C concentration (%)	0-10	2.71 ±0.41	1.50 ±0.31	-1.20	2.35†
	10-20	0.66 ±0.11	0.45 ±0.37	-0.21	2.37†
	20-30	0.43 ±0.09	0.23 ±0.03	-0.20	2.10†
N concentration (%)	0-10	0.055 ±0.008	0.033 ±0.007	-0.022	1.99†
	10-20	0.010 ±0.003	0.006 ±0.003	-0.004	NS
	20-30	0.004 ±0.001	0.003 ±0.001	-0.001	NS
C stock (g C m^{-2})	0-10	3041 ±450	1931 ±356	-1110	2.05†
	10-20	909 ±114	654 ±184	-255	NS
	20-30	658 ±140	366 ±53	-292	1.98†
N stock (g N m^{-2})	0-10	62.0 ±9.4	41.5 ±7.9	-20.5	NS
	10-20	13.4 ±3.8	8.5 ±4.2	-4.9	NS
	20-30	5.2 ±2.1	4.1 ±1.5	-1.1	NS

$^{\dagger}P \leq 0.10$; $^{*}P \leq 0.05$; NS = not significantly different

3.2.4 Soil Nitrogen Availability

The effects of bulldozer disturbance on measures of soil N availability are presented in Table 9. Although there was a tendency for greater amounts of extractable soil N and greater amounts of net soil N mineralization and nitrification in samples from the disturbance zone, the differences were not significantly different from undisturbed (control) samples. There was a high degree of variability that overshadowed differences in post-disturbance measures of surface (0-20

Table 8. Mean (±SE) amounts of particulate organic matter (POM), concentrations of C and N in POM and mineral-associated organic matter (MOM), and the fraction of soil C or N in POM at upland sites disturbed by a bulldozer and at paired, undisturbed (control) sites in K-11.

The number of sampling stations is shown in parenthesis.

Measurement	Treatment		Mean difference	Paired t-value
	Control (n = 7)	Disturbed (n = 7)		
Particulate organic matter (g POM g^{-1} soil)	0.847 ±0.005	0.831 ±0.016	-0.016	NS
POM C concentration (%)	0.79 ±0.05	0.61 ±0.16	-0.18	NS
MOM C concentration (%)	5.19 ±0.30	4.91 ±1.01	-0.28	NS
Fraction soil C in POM	0.457 ±0.016	0.368 ±0.032	-0.090	4.3**
POM N concentration (%)	0.014 ±0.002	0.009 ±0.003	-0.004	NS
MOM N concentration (%)	0.220 ±0.019	0.200 ±0.041	-0.020	NS
Fraction soil N in POM	0.248 ±0.027	0.168 ±0.033	-0.080	2.8*

*$P \leq 0.05$; **$P \leq 0.01$; NS = not significantly different

Table 9. Mean (±SE) post-disturbance concentrations of extractable NH_4-N, NO_3-N, and inorganic N, potential net N mineralization and nitrification during a 12-week aerobic laboratory incubations, and the calculated annual rate of potential net N mineralization in surface (0-20 cm) mineral soils from control and disturbed sites in training compartment K-11.

The number of sampling stations is shown in parenthesis.

Measurement	Treatment		Mean difference	Paired t-value
	Control (n = 7)	Disturbed (n = 7)		
Extractable NH_4-N (μg g^{-1})	2.9 ± 0.9	3.0 ±1.3	0.1	NS
Extractable NO_3-N (μg g^{-1})	0.0 ±0.0	0.6 ±0.5	0.6	NS
Extractable inorganic N (μg g^{-1})	2.9 ±0.9	3.6 ±1.6	0.7	NS
Net soil N mineralization (μg N g^{-1})	6.0 ±2.4	9.6 ±5.8	3.6	NS
Net nitrification (μg N g^{-1})	8.1 ±3.3	12.1 ±7.0	4.0	NS
Net N mineralization rate (yr^{-1})	0.058 ±0.022	0.067 ±0.036	0.013	NS

NS = not significantly different

cm) soil N availability. The calculated annual rates of net soil N mineralization, which were normalized for the amount of soil N present in each sample, were intermediate between rates measured for riparian (0.08 yr^{-1}) and upland (0.014 yr^{-1}) soils during pre-disturbance soil sampling in April 2002.

4. DISCUSSION

Pre-disturbance sampling revealed that site-specific, topographic differences in soil properties could potentially influence the interpretation of data from the disturbance experiment. In particular, there were major differences between riparian and upland sites that existed prior to the experimental disturbance. Soils from riparian areas in compartment K-11 had greater total C stocks and greater amounts of C in different soil parts (e.g., POM and MOM). In addition, a larger amount of C was associated with MOM in riparian soils than in upland soils. Topographic differences in N availability were also indicated by the incubation of pre-disturbance samples with a tendency toward higher N availability in riparian soils. The latter difference was, however, highly dependent on the time of soil sampling. Other than the effect on soil N availability, time of sampling made no difference to the interpretation of data from pre-disturbance soil samples. Greater amounts of C and N in riparian soils may be caused by depositional processes that move organic matter and nutrients from upland areas to riparian zones as well as higher levels of soil moisture in riparian zones that can inhibit decomposition of soil organic matter. Greater soil N availability in riparian zones at training compartment K-11 is consistent with results from other research that has examined topographic variation in forest soil N dynamics (Garten et al., 1994).

The forest at the experimental site was both thinned of trees and subjected to a prescribed burn prior to disturbance by the D7 bulldozer. In general, forest harvesting and prescribed fires have little or no effect on forest mineral soil C and N (Johnson and Curtis, 2001; Wan et al. 2001). Thinning and burning complicated planned pre- and post-disturbance comparisons of the bulldozer's effect on measures of soil quality, however their occurrence probably had no effect on paired comparisons between undisturbed and disturbed soils at upland sampling sites where soils were subjected to the same pre-disturbance forest management practices. Post-disturbance sampling was limited to upland sites in the K-11 training compartment because training with heavy, tracked vehicles at Fort Benning is generally confined to upland soils.

Soil sampling approximately one month after the experimental disturbance indicated that effects of the bulldozer were limited primarily to the forest floor (O-horizon) and the surface (0-10 cm) mineral soil. O-horizon dry mass and C stocks were significantly reduced, relative to undisturbed sites, and there was an indication of reduced mineral soil C stocks in the disturbance zone. Differences in the surface (0-10 cm) mineral soil also indicated a significant increase in soil compaction (i.e., soil density) as a result of disturbance with the bulldozer. However, the effects of soil compaction were not observed below the 0-10 cm depth increment. There was also a reduction in POM-C and N in the disturbance zone but no measurable effect on N availability due to a high degree of variation in measurements associated with the soil incubations for determination of potential net soil N mineralization.

Overall, effects of the bulldozer on measures of soil quality were consistent with reported differences among sites subject to minimal, light, moderate, and heavy training regimes at Fort Benning, Georgia. Greater soil density, less soil C, and less C and N in surface POM has been reported at sites where soils have been repeatedly impacted by tracked-vehicle training (Garten et al., 2003). In the present study, differences between undisturbed and disturbed forest soils were detectable at one month after only a few passes with the D7 bulldozer. The null hypothesis for the experiment was, therefore, partially rejected because there were declines ($P \leq 0.10$) in surface soil C and N as a consequence of heavy vehicle traffic. The removal of surface mineral soil by the bulldozer caused lower surface soil C and N concentrations in the disturbance zone. Although there was some tendency for greater soil N availability in disturbed soils, the changes were not significantly different from undisturbed controls. Thus, the null hypothesis with respect to soil N availability was not rejected. It is expected that repeated soil disturbance over time, which normally occurs in a military training area, would simply intensify the changes in soil properties that were measured following a one-time soil disturbance at the K-11 training compartment.

Finally, the experiment was also useful for identifying soil measurements that are particularly sensitive to disturbance and therefore can be used successfully as indicators of a change in soil properties as a result of heavy, tracked-vehicle traffic at Fort Benning. Measurements related to total O-horizon mass and C concentrations or stocks exhibited changes that ranged from ≈25 to 75% following the one-time disturbance. Changes in surface (0-10 cm) mineral soil density or measures of surface soil C and N following the disturbance were less remarkable and ranged from ≈15 to 45% (relative to undisturbed controls). Soil N availability (measured as initial extractable soil N or N production in laboratory incubations) was the least sensitive and the least useful indicator for detecting a change in soil quality as a result of heavy, tracked-vehicle disturbance. Collectively, the results suggest that the best indicators of a change in soil quality will be found at the soil surface because there were no statistically significant effects of bulldozer disturbance at soil depths below 10 cm.

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