Disturbance of Soil Organic Matter and Nitrogen Dynamics: Implications for Soil and Water Quality

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INTRODUCTION

Background

Military land managers are faced with the challenge of using a given amount of land for the purpose of training and troop readiness. This mission must be accomplished in an ecologically sound manner that meets military requirements and, at the same time, promotes the sustainability of ecosystems so that the military mission is not compromised by a degraded landscape. In some respects, military installations are representative of a larger set of issues faced by managers of many government lands. Areas set aside for the public's benefit, like national parks and recreational areas, can suffer a slow and almost undetectable degradation if the land is over-utilized by long-term human activities. Incipient degradation in a landscape is sometimes visible (for example, trampling of vegetation, vehicle tracks through otherwise undisturbed areas, and erosion created by the overuse of trails), but it can also be invisible to human observers.

We currently do not know where thresholds to sustainability exist for properties and processes in different ecosystems. However, thresholds may exist such that once a threshold is crossed the path to recovery of a degraded landscape may be qualitatively or quantitatively different than expected. Threshold values for key indicators of soil quality will likely vary depending on existing and historical land use, soil type, ecosystem type, and the specific soil function that is being assessed (Doran and Parkin, 1996). Therefore, one objective of this research is to examine land use/land cover differences in soil carbon and nitrogen as they represent a baseline for assessing changes in soil quality over time.

Vegetation dynamics and the sustainability of terrestrial ecosystems depends, in part, on soil quality which can be defined as "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). Soil organic matter (or soil carbon) and soil nitrogen are critical determinants of soil quality because of their relationship to soil structure and nutrient supply (Gregorich et al., 1994; Doran and

Parkin, 1996; Seybold et al., 1997). For this reason, the recovery of soil quality on degraded land is closely associated with the rate and capacity for soil organic matter accumulation.

We are conducting studies of soil organic matter (soil carbon) and soil nitrogen dynamics across a range of spatial scales at Fort Benning, Georgia. These studies are concentrated on the effects of anthropogenic and natural disturbances on key measures of soil quality and the potential recovery of soil quality following disturbance. We also plan to use GIS resources from Fort Benning for the purpose of scaling measurements at particular sampling locations to a site-wide spatial analysis of soil quality, soil nitrogen dynamics, and the potential for soil carbon sequestration. The research is being coordinated with other existing SERDP projects. Field data and models developed during the course of this project will be made available for incorporation into a data repository that is maintained by the US Army Engineer Research and Development Center on behalf of Fort Benning.

Objectives

The objectives of this study at Fort Benning can be summarized as follows:

1. characterize the effect of disturbances and land use on key measures of soil quality (i.e., describe how soil carbon and nitrogen dynamics are affected by current DoD land use activities and natural disturbance regimes),

2. determine whether there are thresholds associated with natural and/or anthropogenic disturbance that establish the potential recovery of soil quality on disturbed lands (i.e., describe how current DoD activities and/or land use activities affect the potential for short- to long-term recovery of soil quality in disturbed environments),

3. build dynamic models of soil organic matter for different land use categories to predict the recovery of soil quality and soil carbon sequestration on degraded soils,

4. plan long-term field experiments to test landscape based models used to predict the recovery of soil quality (including soil carbon sequestration) following disturbance caused by DoD activities, and

5. use existing GIS resources as a tool for analysis of spatial patterns of soil carbon and nitrogen and predict the effect of site disturbance and/or land use change on soil quality and nonpoint sources of nitrogen to surface water drainages.

Approach

Our approach involves measurements of soil bulk density, soil carbon, and soil nitrogen dynamics in ecosystems along gradients of disturbance and land use change (e.g., forests, old-fields, disturbed, and undisturbed lands) at Fort Benning, Georgia. A hierarchical classification of broad land use categories, disturbance regimes, soil types, and topography was developed on the basis of available GIS data layers. Soil samples (to a depth of 40 cm) are divided into surface litter and mineral soil. Both portions are analyzed for total carbon and nitrogen. Soil nitrogen availability is determined by measuring net soil nitrogen mineralization potential under laboratory conditions. Soil carbon inventories are further partitioned into labile, organomineral, and refractory pools using laboratory techniques. Measurements of soil properties have been made along both disturbance gradients, gradients of land use/land cover change, chronosequences, and sites set aside for future disturbance experiments. Information and data from the field studies are being incorporated into a mathematical model of soil carbon and nitrogen dynamics that allow prediction of the recovery of soil quality at Fort Benning. The model also allow us to explore disturbance thresholds that impact the potential for short- and long-term recovery of soil quality.

SUMMARY OF RESEARCH ACTIVITIES AND RESULTS FOR FY01

Field Tasks

Data gathered during both the first (FY00) and the second (FY01) year of work made important contributions to our objective for the second year of the project (FY 01). Work in FY 01 was directed at objective 2 in the proposal: to determine whether there are thresholds associated with natural and/or anthropogenic disturbance that establish the potential recovery of soil quality on disturbed lands. In addition to the preparation of manuscripts and presentations at several meetings, ORNL Team 2 conducted spring soil sampling at Fort Benning with the following three objectives:

(1) soil sampling along existing disturbance gradients and at sites where NRCS restoration activities are planned or underway,

(2) soil sampling at sites harvested to control southern pine beetle damage, and

(3) preliminary soil sampling at K11 Experimental Disturbance Site.

Photographs and GPS coordinates were taken at 50 sampling locations.

ORNL Team 2 sampled soils along disturbance gradients in the vicinity of Underwood Road and Box Springs Road. Two control sites (i.e., forested areas), 2 medium-use sites, and 2 heavy-use site were identified for the purpose of verifying changes in soil quality with varying degrees of disturbance by heavy vehicle traffic. Additional soil sampling was conducted at 4 NRCS restoration sites. Two of the restoration sites had been planted in long-leaf pine and the remaining 2 were recently planted in grasses to minimize soil erosion on heavily disturbed soils. The purpose of sampling along the disturbance gradient and at the restoration sites was to verify changes in soil quality that were measured by ORNL Team 2 during the first year of work along disturbance gradients previously established by ORNL Team 1 (Dale et al.). In addition, beginning in late 2001, Fort Benning plans to restore disturbed land in the immediate vicinity of Underwood Road and Box Springs Road. Soil sampling by ORNL Team 2 will be used to define a baseline for soil quality in the disturbed areas prior to planned remediation. ORNL Team 2 intends to conduct follow-up sampling at various times following restoration along Underwood Road and Box Springs Road to determine the rate of recovery of soil quality following site restoration.

Soil and litter samples were also collected at 10 sites that had been harvested to control southern pine beetle outbreaks at Fort Benning. Three of the sites were 10 years old, 5 of the sites were 5 years old, and 2 of the sites were 1 year old. At each study site, control soil samples were collected from a near-by unharvested forest. The purpose of this soil sampling was to determine the immediate effects of forest harvesting on measures of soil quality and the historical changes in measures of soil quality following forest clearing. The data from this task should also be useful in our efforts to ascertain rates of recovery following soil disturbance.

ORNL Team 2 sampled soils at both the proposed low intensity and high intensity experimental disturbance areas in compartment K11. Soil sampling by ORNL Team 2 will complement pre-treatment vegetation sampling by ORNL Team 1 (Dale et al. -- Indicators of Ecological Change) at the experimental site. Two transects were placed perpendicular to the streams that bisect each experimental area. Soils were collected to a 40-cm depth at four near-stream and upslope locations on each transect. Organic horizons above the mineral soil were also sampled. The preliminary soil samples will be used to determine variability in measures of soil quality at the K11 Experimental Disturbance Site. Estimates of variability are needed to design more intensive pre-treatment soil sampling at the experimental site and to determine the number of pre-treatment samples required to detect changes in soil quality as a result of planned heavy vehicle traffic. Additional pre-treatment soil sampling by ORNL Team 2 (scheduled for October 2001) will be used to define the baseline for soil quality prior to experimental disturbance.

Laboratory Work

Laboratory work on FY01 soil samples from Fort Benning is continuing. Soil samples from 50 locations at Fort Benning have been analyzed. The dry mass and the carbon and nitrogen stocks in organic soil horizons was determined at each study site. Surface mineral soil samples (20 cm deep) from each site were treated to determine concentrations of extractable inorganic soil nitrogen. Laboratory incubations of surface mineral soil samples were completed but we are awaiting analysis of soil extractions to determine potential net soil nitrogen mineralization and nitrification (soil nitrogen availability) at each study site. Determinations of particulate organic matter (POM), organomineral soil carbon (MOM), and refractory soil carbon in surface mineral soil samples were completed and the data will be analyzed and interpreted in FY02. Mineral soil samples were cut into 10 cm increments to determine the vertical changes in soil carbon and nitrogen concentrations and stocks to a depth of 40 cm. Work during the first year by ORNL Team 2 indicated that these latter measurements are valuable indicators of changes in soil quality.

Modeling Tasks

ORNL Team 2 has begun to develop an approach to the determination of thresholds for soil quality based on simple mathematical models of soil carbon and nitrogen dynamics. The modeling incorporates the concept of desired future conditions based on targets for aboveground biomass and litterfall. Initial conditions are specified for different soil carbon pools as they indicate existing levels of soil quality. The model user specifies the rate of recovery and the extent of recovery to the desired future state. The model calculates belowground and aboveground biomass as well as the carbon inputs to soil. Soil carbon dynamics and stocks are calculated on the basis of carbon inputs and turnover times of various soil pools. Soil nitrogen stocks are calculated on the basis of soil carbon:nitrogen ratios. The model calculates potential excess nitrogen (i.e., available soil nitrogen) on the basis of predicted soil nitrogen stocks and measured potential net soil nitrogen mineralization rates.

Thresholds for soil quality are determined in this model on the basis of a comparison of system nitrogen requirements with potential excess nitrogen. If ecosystem nitrogen requirements exceed supplies, then the system is not sustainable. Simulations with the model indicate that there are various sets of conditions where soil carbon stocks become too low to achieve any recovery to a desired future state because:

(1) the inputs to soil carbon can not sustain soil organic matter and thus soil quality progressively deteriorates, or

(2) soil nitrogen availability falls below the nitrogen requirements of biomass and the desired future state can not be achieved.

The model is still under development as a result of research during FY01. Additional work with the model will incorporate data from prior soil sampling by ORNL Team 2 as well as data from the disturbance experiment planned by ORNL Team 1 (Dale et al. -- Indicators of Ecological Change) at training compartment K11. To the extent possible, ORNL Team 2 will collaborate with SREL (Collins et al. -- Thresholds of Disturbance: Land Management Effects on Vegetation and Nitrogen Dynamics) to develop a means for extrapolating laboratory measurements of net soil nitrogen mineralization potential to field estimates. The latter information would be particularly helpful in parameterizing and calibrating ORNL Team 2s model of soil carbon and nitrogen dynamics.

As part of preliminary model development and an analysis of refractory soil carbon, ORNL Team 2 undertook an analysis of fire history data in training compartments at Fort Benning. Some years (e.g., 1995-1996) are missing data on prescribed burns, but the median frequency of prescribed burns since ≈1984 is one fire every 3 years. However, there is considerable variation associated with this fire frequency and few if any areas are actually burned once every 3 years. Frequency of burning did not correlate with amounts of refractory soil carbon (charcoal) at specific locations on Fort Benning soils. The lack of correlation is probably explained by various other factors (like fire intensity and fuel load) that affect charcoal production, as well as by the missing data.

Products and Presentations

The preparation of presentations and manuscripts was a significant component of our research activity in FY01. On November 6th, 2000, Chuck Garten presented a paper at the ASA/CSSA/SSSA session on "Military Installation Land Use and Planning" entitled "Effect of Land Use on Soil Organic Carbon and Nitrogen Dynamics at Fort Benning, GA" in Minneapolis, MN. On November 14th, 2000, Chuck Garten presented a talk at the SEMP Research Coordination Meeting in Columbus, GA, entitled "Disturbance of Soil Organic Matter and Nitrogen Dynamics: Implications for Soil and Water Quality." On November 30th, 2000, Chuck Garten presented a one-hour progress report during a meeting of the SEMP Technical Advisory Committee at the Hyatt Regency Crystal City in Arlington, VA, on work accomplished by ORNL Team 2 during the first year of funding.

Two reports were submitted during FY01 to the SEMP project leader and Fort Benning personnel for their review. The first manuscript was entitled Effect of Military Training on Indicators of Soil Quality at Fort Benning, Georgia. The purpose of this research was to investigate the effects of soil disturbance on several key indicators of soil quality at Fort Benning, Georgia. Once the reviews are completed, the manuscript will be sent to the journal Ecological Indicators. The second manuscript was entitled Land Use/Land Cover Differences in Soil Carbon and Nitrogen Dynamics at Fort Benning, Georgia: Implications for Thresholds of Soil Quality. The report summarized data from field studies in FY00. The goal of this research was to investigate the effects of soil disturbance and land use/land cover on various indicators of soil quality at Fort Benning, Georgia. Once the reviews are completed, the manuscript will be published and distributed as an ORNL technical manuscript.

IMPORTANT FINDINGS AND CONCLUSIONS FOR FY01

Samples from FY01 field work are still undergoing some laboratory analyses for measures of soil nitrogen dynamics (i.e., laboratory measurements of net soil nitrogen mineralization and nitrification). Consequently, the interpretation of these data will not be completed until sometime in FY02. Preliminary soil sampling at the K11 Experimental Disturbance Area indicates that there are upslope and near-stream differences in soil carbon and nitrogen stocks that will have to be accommodated in the experimental design to determine the effects of heavy vehicle traffic on soil quality. Preliminary results from sampling along disturbance gradients in FY01 tends to verify the differences in soil quality that were observed along disturbance gradients in FY00.

Other principal conclusions from ORNL Team 2 research, which relate primarily to land use, from studies along a gradient of military disturbance at Fort Benning can be summarized as follows:

(1) reference and light military use sites were similar with respect to all measured soil properties (including soil carbon and nitrogen concentrations), except soil bulk density,

(2) surface soil bulk density (i.e., soil compaction) was significantly greater at heavy military use, moderate use, and remediated sites,

(3) soil carbon concentrations and stocks increased in the following order -- heavy use < moderate use = remediated < light use = reference sites,

(4) amounts of carbon and nitrogen associated with particulate organic matter were similar at reference and light use sites but significantly lower at heavy use, moderate use, and remediated sites,

(5) along a pine forest chronosequence, the fraction of whole soil carbon in the particulate organic matter pool and POM-C stocks gradually increased with stand age,

(6) soil carbon concentrations and stocks, indicated that soil quality at moderate military use sites was intermediate between that at reference and heavy military use sites,

(7) soil carbon:nitrogen ratios at reference, light use, and remediated sites were significantly greater than those at heavy use and moderate use sites.

The principal conclusions and findings, which relate primarily to land cover, from studies under different land use/land cover categories at Fort Benning can be summarized as follows:

(1) there were significant land use/land cover differences in surface soil bulk density -- surface soil compaction increased in the following order: deciduous and mixed forests < evergreen forests and transitional land < barren land,

(2) soil bulk density under forest stands was significantly less than that under barren land for all depth increments examined, except 30-40 cm,

(3) land use/land cover differences in soil physical properties were minor: most of the soils examined had a high sand content, particularly those from barren sites,

(4) extractable soil ammonium was significantly greater under deciduous and mixed forest stands than under barren land while extractable soil nitrate was significantly greater under barren land than under forests,

(5) net nitrogen mineralization in soils from deciduous forests, mixed forests, and transitional lands was generally greater than that in soils from evergreen forests and barren land,

(6) stocks of labile soil carbon (i.e., carbon in O-horizons plus particulate organic matter corrected for refractory soil carbon) increased in the following order: barren < transitional land < forests,

(7) a small and highly variable portion of soil carbon in particulate organic matter was comprised of refractory soil carbon which had chemical properties similar to charcoal,

(8) stocks of organomineral soil carbon and total soil carbon were similar under forest and transitional land cover and were greater than those under barren land,

(9) the partitioning of carbon among various soil pools has important implications for the stability and dynamics of soil carbon storage (and soil quality) under different land use/land cover categories,

(10) using a simple dynamic model to predict the recovery of soil carbon on barren land through revegetation, predicted stocks of labile soil carbon recovered faster than stocks of organomineral soil carbon, and the predicted recovery of soil carbon stocks was directly proportional to the rate of carbon inputs to the labile soil carbon pool,

(11) model simulations under "no burning" conditions indicated that soil carbon stocks under barren land could recover to levels currently measured in forest soils at Fort Benning in ≈100 years (if there are no limiting nutrients),

(12) model simulations indicated that controlled burning causes labile soil carbon stocks to fluctuate, a reduction in organomineral soil carbon, and a steady accumulation in refractory soil carbon (all relative to that predicted under the "no burning" conditions).

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