LANDSCAPE ANALYSIS OF SOIL CARBON STORAGE ON THE OAK RIDGE RESERVATION

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INTRODUCTION

Land use/land cover (LULC) and land use change can be a significant determinants of C flux between terrestrial ecosystems and the atmosphere. It is estimated that approximately 90% of the forest carbon (C) storage in the Upper Piedmont, in Georgia, was lost from 1770 (presettlement) through 1870 by land use change to agriculture [1]. Recent analyses also indicate that land use change has been critical to the historical aboveground accumulation of C in U.S. forests [2]. Land use change can also produce significant changes in soil C stocks [3] and land use could influence potentials for soil C storage.

Prior studies indicate a large potential for landscape level variation in soil C and N stocks depending on differences in soil type, topography, past land use, current LULC, and climate [4,5]. For example, regional variation in soil N transformations is affected by the distribution of forest ecosystems, partly because differences in litter quality control soil N availability [6]. Soil N availability can vary significantly between different ecosystems and is correlated with annual biomass increment [7]. The widespread occurrence of N limitation on net primary production in terrestrial ecosystems [8] along with potential LULC differences in soil N availability [9], suggests that LULC might be used to predict patterns of soil C inputs and soil C storage at the landscape scale.

The U.S. State Department recently reaffirmed the potential role of forestry and agriculture as a means to mitigate climate change through C sequestration and announced that land use practices could be used to meet approximately half of the U.S. goal for carbon dioxide reductions under the Kyoto Protocol [10]. If we hypothesize that increased terrestrial C stocks can be obtained by the optimum use of landscapes for the purpose of C sequestration, then it is necessary to significantly improve our understanding of how LULC, soil N dynamics, topography, and other environmental factors affect soil C and N.

OBJECTIVE

The purpose of this study was to further our understanding of the role of LULC, soil N availability, and topography as determinants of soil C storage in a complex terrain. We examined the hypothesis that there are significant differences in soil C and N stocks and soil N dynamics between five LULC categories and four topographic positions (ridge, north-facing slope, south-facing slope, valley) on the U.S. Department of Energy's Oak Ridge Reservation (ORR), near Oak Ridge, Tennessee. In addition, the relative distribution of C between different soil pools (identified by simple physical methods of separation) was examined to determine if there are LULC differences in soil C turnover times.

APPROACH

The study was conducted on the ORR located in Anderson and Roane Counties, TN (35° 58' N latitude and 84° 17' W longitude). The 14,000 ha reservation was established in 1942 by the U.S. Government and there is limited public access to most of the land. LULC on the ORR in 1994 was 70% forest (31% deciduous forest, 31% mixed forest, and 8% evergreen forest), 14% urban, and 13% transitional land [11]. The climate in east Tennessee is classified as temperate and humid. The mean annual temperature is 14 °C and mean annual precipitation is 137 cm.

Seventy-three sampling sites were identified and a 5 (LULC) x 4 (topographic position) factorial design was utilized for soil sampling. The five LULC categories were: deciduous forest, mixed forest, evergreen forest/plantation, transitional land, and managed pastures. Transitional land included secondary successional sites that were primarily occupied by herbaceous annual and perennial vegetation. Pastures included managed hay fields. Forests varied in age, but all had closed canopies. Four topographic positions were sampled within each LULC category: ridge, north-facing slope, south-facing slope, and valley. Three to 4 sites were sampled within each combination of LULC and topography.

Differences among data grouped by LULC and topography were first tested using a two-way analysis of variance (ANOVA). If one of the main effects (LULC or topography) and the interaction (LULC x topography) were not statistically significant, the data were reanalyzed using a one-way ANOVA where the statistically significant main effect was retained. Unless stated otherwise, statistical significance was indicated by $P \leq 0.05$.

PROJECT DESCRIPTION

Soil sampling was performed in November and December, 1999, after autumn leaf-fall. Organic-horizons (Oi + Oe + Oa) were also sampled at each site. Soil samples were used for determination of potential net soil N mineralization and nitrification [12]. Potential net soil N mineralization was calculated as the difference between extractable inorganic-N at 7 or 13 weeks and the initial extractable inorganic-N from fresh soil samples. Net soil nitrification was calculated in a similar manner. Surface mineral soil samples were fractionated into particulate organic matter (POM) and mineral-associated organic matter (MOM) [13]. Dry litter fractions, whole soils, and soil fractions were analyzed for total C and N using a Perkin-Elmer 2400 CHNS Analyzer (Perkin-Elmer Analytical Instruments, Norwalk, CT) and a LECO CN-2000 (LECO Corporation, St. Joseph, MI). Both instruments were cross calibrated using internal standards with a known C and N concentration and a LECO soil standard (2.61 %C and 0.209 %N) traceable to the National Institute of Standards and Technology (NIST), Gaithersburg, MD.

Carbon stocks (g C/m^2) were calculated for the O-horizon as the product of concentration (g C/g) and dry mass per unit area (g/m^2). Carbon stocks (g C/m^2) in each mineral soil increment were calculated as the product of concentration (g C/g soil), bulk density (g soil/m^3), and increment length (m). Cumulative C stocks in the mineral soil were calculated by summing surface (0-20 cm) and subsurface (20-40 cm) mineral soil stocks. Relative amounts of POM and MOM were expressed as dry grams per gram total soil. Soil C in the POM or MOM part was calculated by multiplying the dry mass of each part (g part/g soil) by the respective C concentration (g C/g part). The fraction of soil C in the POM part (Fp) was calculated as: (g POM-C/g soil) ÷ (g POM-C/g soil + g MOM-C/g soil). Carbon stocks in the surface mineral soil that were associated with POM (POM-C) were calculated as the product of Fp and soil C stocks (g/ m^2). MOM-C stocks were calculated in a similar manner.

RESULTS AND DISCUSSION

LULC Differences in Soil Nitrogen Availability

The effect of LULC (but not topography) on potential net soil N mineralization and net nitrification was statistically significant during both the first 6 weeks and the last 7 weeks of the aerobic laboratory incubations. We believe soil N transformation rates during the first 6-weeks of the laboratory incubations were a result of soil disturbance (sieving). Measured rates during the last 7-weeks were probably more representative of potential rates under different LULC categories. The results indicated significantly higher rates of net soil N transformations and higher soil N availability under pastures compared to other LULC categories. This finding was consistent with lower soil C/N ratios, that would favor net soil N mineralization, and significantly higher initial extractable soil nitrate under pastures.

O-Horizon Carbon and Nitrogen Stocks

The effect of LULC on O-horizon C concentrations, stocks, and C/N ratios was statistically significant reflecting differences related to the quantity and quality of aboveground litter inputs. O-horizon C concentrations and stocks under transitional land and pastures were significantly less than those under forests. The highest O-horizon C/N ratios were found under evergreen forests and the lowest O-horizon C/N ratios were found under pastures. Mineral soil C/N ratios generally decline when forests are replaced by pastures and transitional lands because forest litter, which has a high C/N ratio, is replaced by herbaceous vegetation, which has a lower C/N ratio [14].

The effect of LULC on litter quality translated to forest floor humus layers. Mean humus C/N ratios were significantly greater in evergreen forests than in mixed and deciduous forests. Although topography had no significant effect on C stocks in the entire O-horizon, topography had a significant effect on C stocks in the forest floor humus layer. Forest humus C stocks in valleys were significantly less than those on ridges and slopes.

Mineral Soil Carbon Stocks

Surface mineral soil (0-20 cm) C stocks were 3 to 4 times greater than those in the subsurface soil (20-40). The effects of LULC and topography on surface mineral soil C stocks were not statistically significant, however, the effect of topography on subsurface soil C stocks was statistically significant. Subsurface soil C stocks in valleys were higher than those at other topographic positions.

The effect of LULC on surface mineral soil C/N ratios was statistically significant, but the effects of LULC and topography on subsurface soil C/N ratios were not significant. Soils in valleys are generally wetter and 1 to 2 °C cooler than those on ridges and slopes [15]. On a seasonal basis, humus layers and subsurface soils in valleys could be sufficiently cooler (and subsurface soils could be sufficiently wetter) to inhibit decomposition losses leading to significantly higher C and N stocks than at other topographic positions on the ORR.

Partitioning of Soil Carbon

Overall, the effects of LULC and topography on surface soil C stocks on the ORR were not statistically significant, but there were LULC differences in the distribution of soil C between various soil pools. The effect of LULC on labile soil C stocks (which included C stocks in O-horizons plus POM-C in the mineral soil) and MOM-C stocks was statistically significant. The effect of topography on the fraction of surface mineral soil C in the POM part was also statistically significant. Forest stands had significantly greater labile soil C stocks than pastures due to their more extensively developed O-horizons. Pastures had significantly higher stocks of MOM-C than forests.

APPLICATION

One of the primary objectives of this research was to identify factors affecting landscape level differences in soil C storage over a complex terrain. At the outset we recognized that there are two potential advantages to the use of LULC for regional assessments of soil C storage and N dynamics. First, LULC is easily classified on the basis of remote sensing [16]. Second, unlike most soil properties, LULC is amenable to future management for enhancing soil C storage at the scale of regional landscapes.

Growing forests are a practical, productive, and low-cost approach to C sequestration on lands with otherwise low productivity and little standing biomass [17]. However, this is not an optimal approach to C sequestration on lands like the ORR where the landscape is about 70% forest cover with existing large aboveground C stocks. Recent estimates place only 37% of the total C storage in forest ecosystems on the ORR in forest soils (58300 kg C/ha) and the remaining 63% (99388 kg C/ha) is contained in aboveground biomass [18]. Although C storage in forest biomass far exceeds that in soils, aboveground C stocks are subject to sudden and dramatic changes through ecosystem disturbance. Soil C is more protected and some components of soil C appear to have a much longer turnover time than C stored in aboveground biomass [19].

Effects of geology, soil type, and past land use were confounded with both current LULC and topography in the present study. Despite the relegation of many potential sources of variation to the error term in each ANOVA, the main effect of LULC was still significant for many variables related to soil C storage and soil N dynamics. Geology, soil type, and past land use are all potentially important determinants of soil C and N dynamics across regional landscapes. However, topography, geology, and soil type are not amenable to change in ways that would significantly alter soil C and N storage in a timely manner (i.e., over several decades).

Although there was no significant effect of LULC on total surface soil C stocks, the partitioning of C among various soil pools has important implications for the stability C storage under different LULC categories. Studies, in east Tennessee, of soil C dynamics under perennial herbaceous vegetation [20] and forests [21] indicate the turnover time of labile soil C is approximately 3 to 4 years while that of MOM-C is at least an order of magnitude greater. The ratio of stocks of MOM-C to labile C in each LULC category indicated greater stability of surface soil C (i.e., longer turnover times) under transitional lands and pastures than under forests.

Spatial variation in soil C and N dynamics on the ORR is complex and only partially explained by LULC, topography, and other sources of variation. Although there were interactions between LULC and topography for some soil properties, each interaction tended to be one of magnitude rather than direction. Despite some complexities, we conclude that, in the absence of large differences in elevation that can create climate gradients, variation in soil C storage and soil N dynamics at scales comparable to the ORR (approximately 14,000 ha) can be interpreted, at a minimum, on the basis of LULC categories and differences in topography. Our findings tend to support a prior published conclusion that differences in moisture (as influenced by topography) are a potentially important source of variation in soil C and N storage at the local scale, while LULC is relatively more important for variation at larger scales [5].

FUTURE ACTIVITIES

Fire, disease, and human development can quickly and dramatically reduce aboveground C stocks, but long-term studies suggest that, in the absence of disturbance, soil C stocks are relatively constant. A recent analysis indicates that forest soil C concentrations at Walker Branch Watershed on the ORR were spatially variable but temporally unchanging from 1972 to 1993 [18]. This suggests that soil C stocks are near steady state. Although soil C storage on the ORR is only about 40% of the total C sequestration potential under forest vegetation, it appears to be a relatively invariant reservoir even with the prospect of significant changes in LULC.

Recently, the southern pine beetle has reached epidemic proportions in eastern Tennessee. The most effective method of control is tree removal which, at most, could affect about 8% of the ORR. Such changes in land use could result in an estimated maximum loss of approximately 100 Gg in aboveground C (1000 ha of forested land). The conversion of forests to transitional land could also result in a substantial short-term loss of labile soil C as well as a temporary increase in soil N availability.

The absence of significant LULC differences in soil C storage suggests that, over the long-term, total soil C stocks will remain unchanged as a result of forest clearing and the overall turnover time of soil C could even increase if the land use change is to managed pastures. Multiple studies, in addition to the current research, indicate that soil C storage under long-term pastures is similar to that under mature forests [22,23,24]. If cleared forest soils are disturbed through plowing, there could be significant losses of soil C [25]. Such losses might be avoided if forest recovery occurs through natural succession from transitional land to deciduous forests. Our future opportunity is to monitor changes in soil C as a function of LULC change.

SUMMARY

Soils were sampled at different topographic positions under different LULC categories on the Oak Ridge Reservation near Oak Ridge, Tennessee. Differences in LULC influenced soil C/N ratios, the distribution of soil C between labile and mineral-associated organic matter, and measures of soil N availability, but not total soil C stocks. Soils under transitional areas and managed pastures contained more MOM-C which has a slower turnover time than labile soil C. Because of higher soil C stocks and greater proportions of MOM-C, we conclude that the LULC categories most favorable to soil C sequestration on the ORR, but not necessarily total ecosystem C storage, are transitional lands and managed pastures.

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