SPATIAL PATTERNS IN CARBON STORAGE IN A LAKE STATES' LANDSCAPE

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Abstract: We estimated total organic carbon storage (C -- kg m^{-2}) in biomass, forest floor, and soil for a gently undulating glacial outwash landscape in east-central Minnesota (45° 25'N, 93° 10'W). Abandoned agricultural tracts are common, and nearly 40 percent of the area is wet mineral or organic soil. Quantitative models based on 745 point-observations were used to define empirical relationships between C storage and landscape variables describing forest cover type and terrain characteristics. Exponential regressions for individual cover types explained from 31 to 70 percent ($p<0.05$) of the variation in soil C and 39 percent ($p<0.05$) of the variation in peatland depth. Spatial patterns and quantities of C storage were estimated by applying these functions to a digital geographic database of cover type and terrain attributes. Landscape scale (~1:20,000) estimates of soil C followed a bimodal distribution with means at 4 kg m^{-2} (mineral soils) and 130 kg m^{-2} (peatlands). Biomass carbon for individual cover types ranged from 1 to 13 kg m^{-2}. Total C storage in all components, based on a 1m soil depth, was 32 kg m^{-2}, with over 90 percent stored in peatlands.

INTRODUCTION

Organic carbon (C) storage and its change are central issues in global change, but the magnitude of storage in forested systems is uncertain. Although the catena concept is firmly established in soil science, quantification of changes in soil C with landscape position is lacking. This is especially true in more recently glaciated regions such as the Lake States, where climate and a poorly-developed drainage network have led to abundant peatlands, occupying 10 to 30 percent of most basins. Modeled scenarios of global change suggest that both forest tree distribution and the balance between precipitation and evaporation may change, affecting C storage. Quantification of the C stored in these immature landscapes, the pools in which it is stored, and the relationship of that storage to landscape features will all aid in predicting the magnitude of C response to various scenarios of global change.

The overall objective of our research is to better understand the mechanisms responsible for C sequestration at landscape scales. Although not our ultimate goal, the predictive mapping of C storage is a necessary first step in this understanding. Our specific objective for this study was to quantify the magnitude and spatial patterns of organic C storage in a typical landscape in the Lake States.

METHODS

We sought to quantify spatial patterns of organic C storage (kg m^{-2}) in three pools on the landscape: 1) biomass, 2) forest floor, and 3) soil.

Site

We worked at the Cedar Creek Natural History Area (CCNHA), located 50 km north of Minneapolis-St. Paul, Minnesota, on the Anoka Sand Plain (45° 25'N, 93° 10'W). This National Science Foundation-Long Term Ecological Research (NSF-LTER) site is typical of sandy outwash areas of much of the Lake States. Natural vegetation includes prairie, oak savanna, closed forests, shrub carrs, marshes, lakes, and bogs (Pierce 1954). Many of the present ecosystems developed following agricultural abandonment. Soils are derived from deep (20 m), well-

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sorted glacial outwash of very uniform fine sand (> 90 percent sand). Slopes are gentle, usually less than 15 percent, and local relief ranges up to about 5 m. The regional climate is continental with a mean annual temperature of 6°C and annual precipitation of 660 mm (Grigal et al. 1974). The regional water table is at or near the soil surface in low-lying areas and only a few meters below the surface in the highest elevations. Nearly 40 percent of CCNHA is occupied by wet mineral or organic soils so that the 2200 ha site is an intricate upland-wetland mosaic. A few meters of horizontal distance often separate upland oak forests or old fields from adjacent wetlands.

Field Sampling

Samples and descriptions of soils, vegetative cover, and organic debris at the soil surface, referred to hereafter as forest floor, were collected along 19 transects crossing topographic changes of the major vegetation types. We sampled at two levels of intensity. Level #1 sites were at 25m increments along the transects (total = 745). We recorded landscape position and topography (slope gradient, curvature, and aspect); vegetation type; tree basal area, diameter, and condition; tall shrub cover and height; low shrub and forb cover; forest floor and A-horizon thickness; fiber type and depth of organic soil materials (if present); and location (based on global positioning system). Approximately one third of the level #1 sites were randomly selected for level #2 sampling (total = 250). Forest floor and soil samples were collected for laboratory determinations of organic C content. Mineral soils were sampled at 0-25 and 26-100 cm depths with a bucket auger, and organic soils were sampled in 50-cm increments until impenetrable with a McCauley peat auger. A 5 percent subset of soils was sampled for bulk density using the core method.

Laboratory Methods

Loss-on-ignition (LOI) was determined for all forest floor and soil samples by ashing overnight at 450°C. Approximately 30 percent of the samples were used to develop relationships between LOI, total organic C on a gravimetric basis (g kg^{-1}) (David 1988), and soil bulk density (kg m^{-3}) (Grigal et al. 1989). The relationships were used to calculate C and bulk density for the remaining samples. Organic C on a volumetric basis was calculated to 1 m for mineral soils and to the depth of sampling for organic soils.

Forest floor C concentrations were converted to mass per unit area based on the quantitative field sampling. Biomass of trees was based on published allometric relationships (Alemdag 1983, 1984). We developed our own biomass relationships for shrubs and forbs based on either cover and height (shrubs) or cover (forbs). These latter data had been previously collected at CCNHA (Suhartoyo 1991). All biomass data included estimates of root mass. Biomass was expressed as mass per unit area, and its C content was considered to be 47.5 percent (Raich et al. 1991).

Spatial Data

We developed a digital geographic database that included vegetation cover type, peatland locations from an order II soil survey, and a digital terrain model. The information was stored in a raster format using 10-meter grid cells. Scales for input data ranged from 1:15,000 to 1:20,000. Digital maps of slope gradient, slope curvature, aspect direction, plan and profile slope curvature, and both horizontal and vertical proximity to local topographic highs and lows (peatlands) were calculated for each grid cell in the geographic database using methods described by Moore et al. (1993) and Bell et al. (1992). The transect sampling locations and the digital geographic database were registered to standard geographic coordinates to facilitate spatial comparisons.

Spatial Modeling

Estimates of total organic C were partitioned by vegetation type. Eight types (pine, oak, upland mixed hardwoods, savanna, old field, lowland conifers, lowland hardwoods, and lowland non forested) were recognized in both the geographic data base and at transect locations. The latter three types were primarily located in peatlands.

Using digital overlay techniques, each transect location was defined by combinations of landscape features (slope, vegetation type, etc.) as defined in the geographic database. Simple means were used to describe forest floor and biomass C by vegetation type. Linear and exponential statistical models were developed for soil C. Peatland depths cannot be ascertained from simple surface data (Swanson and Grigal 1989), and were estimated by functions related to distance to mineral soil and elevation. A 75 percent random subset of transect observations was used to calibrate statistical relationships between landscape attributes and soil organic C concentrations. The remaining observations were used to obtain an unbiased estimate of model performance (model validation).

After the quantitative relationships were calibrated and validated, digital overlay techniques were used to define the landscape attributes for each grid cell in the geographic database, and the statistical models were applied to these attributes on a cell-by-cell basis to predict and map organic C storage for each pool (biomass, forest floor, soil).

RESULTS AND DISCUSSION

Organic C and LOI were closely related, with $r^2= 0.97$ for mineral soils with LOI < 14 percent dry weight, $r^2= 0.83$ for mineral soils with LOI >= 14 percent, and $r^2= 0.88$ for organic soil materials.

Biomass and forest floor C varied among vegetation types (Fig. 1). For upland sites, soil organic C concentration varied significantly with terrain attributes including slope gradient and horizontal distance and elevation above peatland. Correlations with the data used to calibrate the relationships (r_c^2) ranged from 0.93 to 0.95, and correlations with the validation data (r_v^2) ranged from 0.31 to 0.70 among vegetation types. Peatland depth was best estimated by distance to nearest mineral soil and elevation, with $r_c^2 = 0.29$ and $r_v^2 = 0.39$. Carbon density varied significantly with depth in peatlands because of differences in both C concentration and bulk density. It ranged from 0.52 kg m^{-2} cm^{-1} for the 0 to 50 cm depth, 0.76 kg m^{-2} cm^{-1} for the 50 to 100 cm depth, and 0.49 kg m^{-2} cm^{-1} for depths below 100 cm ($p < 0.001$). For all of the predictive relationships, the mean $r_c^2 = 0.83$ and the mean $r_v^2 = 0.50$.

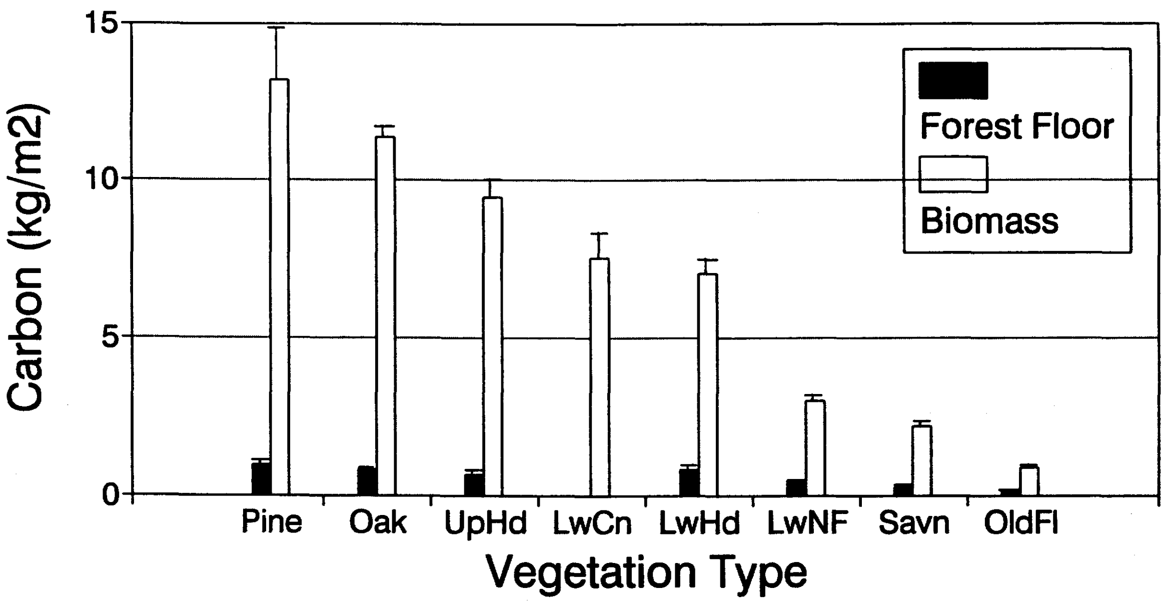

Figure 1. Carbon storage in biomass and forest floor in eight vegetation types of the Cedar Creek Natural History Area. Mean and standard error indicated. Pine = pine, Oak = oak, UpHd = upland mixed hardwoods, LwCn = lowland conifers, LwHd = lowland hardwoods, LwNF = lowland non forested, Savn = savanna, and OldFl = old field.

When applied to all of CCNHA, organic C storage is heavily weighted to the peatlands (Table 1). Reports of C storage in peatlands are rare. Gorham (1991) estimated global carbon storage in peatland soils, and his estimate (133 kg m^{-2}) is nearly equal to our estimate for peatland soils at CCNHA (131 kg m^{-2} -- Table 1).

In terms of C storage in uplands, Grigal and Ohmann (1992) reported mean C storage of five upland forest cover types in five geographic zones in a gradient across the Lake States. The C data for upland sites at CCNHA are at the low end of their range for forest floor (0.5 - 3.0 kg m^{-2}) and biomass (7.0 - 10.0 kg m^{-2}), and are much lower than their range for soil C (7.0 - 15.0 kg m^{-2}) (Table 1). As a result, total system C at CCNHA is much lower that reported by Grigal and Ohmann (1992) for upland forests (12.0 - 24.0 kg m^{-2}); total C storage in uplands of CCNHA is only 9 kg m^{-2}. The lower estimates for CCNHA reflect the influence of the coarse texture of the mineral soil. Although the pine types in the gradient study were also coarse textured, their surfaces were somewhat finer-textured. In addition, CCNHA has experienced more agricultural disturbance than have the sites from the gradient study. Finally, because CCNHA is at the southwest extreme of Lake States forests, precipitation is lower and temperatures are higher than for most of those forests, further reducing C storage.

Table 1. Carbon storage in the landscape of Cedar Creek Natural History Area. All data in kg m^{-2}. Sums are based on either the full depth (Total System) or 1 m of organic soil in peatlands. Standard errors, based on cell-to-cell variation in estimates, were less than 1% of the mean in all cases.

	Uplands	Peatlands	Landscape
Biomass	6.0	6.0	6.0
Forest Floor	0.5	0.5	0.5
Soil	4.0	131	52
Total System	9.0	138	59
Total (1 m soil)	9.0	69	32

Total organic C storage over all 2070 ha of CCNHA (excluding lakes) is 1.22 x 10^{12} g, of which the soil contributes nearly 90 percent, 1.08 x 10^{12} g. If C storage in peatlands is only considered to 1 m, as is mineral soil, C storage in soil is 0.55 x 10^{12} g. Our approach to estimating organic C storage in soil, which explained roughly half the spatial variation at CCNHA, treats the landscape as a continuum rather than as a set of discrete map units. The soil organic C storage was based on terrain attributes derived from a continuous representation of the topographic surface. In contrast, a discrete approach can also be used to estimate soil C, based on the area and the estimated C density of each soil map unit. Using that approach, estimated soil C storage to 1 m at CCNHA is 0.50 x 10^{12} g. The continuous approach is much more amenable to modeling changes in C storage with changes in climate on these landscapes.

CONCLUSIONS

Peatlands store over 90 percent of the organic C in the landscape at CCNHA, and are important when considering the C storage of forested systems in the Lake States. More work is needed to reduce the uncertainty currently associated with estimates of C pools in northern forests. The techniques that we used are applicable to broader areas, and could rapidly move our understanding of C storage forward.

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LITERATURE CITED

Alemdag, I.S. 1983. Mass equations and merchantability factors for Ontario softwoods. Canadian Forestry Service, Petawawa National Forestry Institute. Information Report PI-X-23.

Alemdag, I.S. 1984. Total tree and merchantable stem biomass equations for Ontario hardwoods. Canadian Forestry Service, Petawawa National Forestry Institute. Information Report PI-X-46.

Bell, J. C., R.L. Cunningham, and M.W. Havens. 1992. Calibration and validation of a soil-landscape model for predicting soil drainage class. Soil Science Society of America Journal 56:1860-1866.

David, M.B. 1988. Use of loss-on-ignition to assess soil organic carbon in forest soils. Commun. Soil Sci. Plant Anal. 19:1593-1599.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to global warming. Ecological Applications 1:182-195.

Grigal, D.F., L.M. Chamberlain, H.R. Finney, D.V. Wroblewski and E.R. Gross. 1974. Soils of the Cedar Creek Natural History Area. Minn. Agr. exp. Sta. Miscell. Rep. 123. 47 p.

Grigal, D. F., S. L. Brovold, W. S. Nord, and L. F. Ohmann. 1989. Bulk density of surface soils and peat in the North Central United States. Canadian Journal Soil Science 69:895-900.

Grigal, D. F. and L. F. Ohmann. 1992. Carbon storage in upland forests of the Lake States. Soil Science Society America Journal 56:935-943.

Moore, I. D., P.E. Gessler, G.A. Nielsen, and G.A. Peterson. 1993. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal 57:443-452.

Pierce, R.L. 1954. Vegetation cover types and land use history of the Cedar Creek Natural History Reservation, Anoka and Isanti Counties, Minnesota. M.S. thesis, University of Minnesota, Minneapolis. 137 p.

Raich, J.W., E.B. Rastetter, J.M. Melillo, D.W. Kicklighter, P.A. Steudler, B.J. Peterson, A.L. Grace, and C.J. Vorosmarty. 1991. Potential net primary productivity in South America: application of a global model. Ecological Applications 1:399-429.

Suhartoyo, H. 1991. Analysis of vegetation of the Cedar Creek Natural History Area using methods of classification and ordination. M.S. thesis, University of Minnesota. St. Paul, MN. 125 p.

Swanson, D.K. and D.F. Grigal. 1989. Vegetation indicators of organic soil properties in Minnesota. Soil Science Society of America Journal 53:491-495.