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Estimating regional carbon stocks and spatially covarying edaphic factors using soil maps at three scales

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Abstract. Most estimates of regional and global soil carbon stocks are based on extrapolations of mean soil C contents for broad categories of soil or vegetation types. Uncertainties exist in both the estimates of mean soil C contents and the area over which each mean should be extrapolated. Geographic information systems now permit spatially referenced estimates of soil C at finer scales of resolution than were previously practical. We compared estimates of total soil C stocks of the state of Maine using three methods: (1) multiplying the area of the state by published means of soil C for temperate forests and for Spodosols; (2) calculating areas of inclusions of soil taxa in the 1:5,000,000 FAO/UNESCO Soils Map of the World and multiplying those areas by selected mean carbon contents; and (3) calculating soil C for each soil series and map unit in the 1:250,000 State Soil Geographic Data Base (STATSGO) and summing these estimates for the entire state. The STATSGO estimate of total soil C was between 23% and 49% higher than the common coarse scale extrapolations, primarily because STATSGO included data on Histosols, which cover less than 5% of the area of the state, but which constitute over one-third of the soil C. Spodosols cover about 65% of the state, but contribute less than 39% of the soil C. Estimates of total soil C in Maine based on the FAO map agreed within 8% of the STATSGO estimate for one possible matching of FAO soil taxa with data on soil C, but another plausible matching overestimated soil C stocks. We also compared estimates from the 1:250,000 STATSGO database and from the 1:20,000 Soil Survey Geographic Data Base (SSURGO) for a 7.5 minute quadrangle within the state. SSURGO indicated 13% less total soil C than did STATSGO, largely because the attribute data on depths of soil horizons in SSURGO are more specific for this locality. Despite localized differences, the STATSGO database offers promise of scaling up county soil survey data to regional scales because it includes attribute data and estimates of areal coverage of C-rich inclusions within map units. The spatially referenced data also permit examination of covariation of soil C stocks with soil properties thought to affect stabilization of soil C. Clay content was a poor predictor of soil C in Maine, but drainage class covaried significantly with soil C across the state.

Introduction

The soils of the world are thought to store two to three times as much carbon as the atmosphere (Eswaran et al. 1993; Kimble et al. 1991; Post et al. 1982; Schlesinger 1977). Increases in decomposition of soil organic matter resulting from global warming (Billings 1987) or from land use change (Houghton 1991) could significantly increase the atmospheric burden of CO_2, which would further enhance the greenhouse effect. Conversely, soils could also provide a reservoir for increased sequestration of atmospheric carbon under certain climatic and management regimes. Changes in soil carbon storage, either positive or negative, are unlikely to be uniform throughout the globe, because the distribution of soil carbon stocks, the factors that stabilize soil C, and the forces that contribute to change vary widely among regions. Of the many factors pertinent to potential changes of soil C storage, none is more fundamental than the question of how much carbon is currently present in soils. Knowledge is needed of the spatial distribution of present stocks of soil C across the globe. Moreover, better understanding of how soil C stocks vary spatially may help reveal the climatic and edaphic factors that contribute to stabilization of C in soil.

Until very recently, regional and global estimates of soil C stocks had to be made by extrapolating means of soil carbon content for broad categories of types of soils or vegetation across the areas occupied by those categories (Kimble et al. 1991; Post et al. 1982; Schlesinger 1977). Significant uncertainties exist for both the estimates of the mean C contents and the estimates of area covered for each category. The advent of geographical information systems (GIS) on soils may help constrain some of these uncertainties. Although specific map units must also be defined in a soils GIS, and an appropriate mean soil C content must also be determined for each class of map unit, GIS combines modern computational power with the use of spatially referenced data, and hence can provide finer scale resolution of estimates of soil properties than was previously practical. Provided that the data used are reliable, the probabilty of matching the correct mean estimate of soil carbon content with the correct area should increase as the scale of resolution becomes finer. It is theoretically possible that regional and global estimates of soil C stocks could be made from compiling data on thousands or even millions of soil map units using computerized GIS.

Unfortunately, data on many soil properties, such as carbon content, are not available on a fine scale for much of the world. For many regions, the best spatial data available on soils are found in the FAO/UNESCO

Soils Map of the World at a scale of 1:5,000,000 (FAO 1978–1981; Sombroek 1990). The FAO/UNESCO map has been digitized, but its use as a basis for estimating regional and global soil C stocks has not been examined.

The Soil Conservation Service (SCS) of the United States Department of Agriculture has accumulated a rich database on soils, both within the US and beyond. Soils maps of the United States at scales ranging from 1:12,000 to 1:5,000,000 are currently being digitized by SCS, using a GIS. Accompanying attribute data have been compiled and are frequently updated (SCS 1992). These data provide a new opportunity to examine spatial distributions of soil C stocks within the US and to compare estimates of soil C based on the relatively fine resolution SCS data with estimates based on the coarser scale FAO map. Specifically, the objectives of this study are to answer the following questions:

1. How do estimates of regional stocks of soil C based on the GIS of the SCS compare with previous estimates based on extrapolations of broad categories of soils and vegetation?
2. Can the STATSGO databases (1:250,000) for the USA be used to check or to calibrate regional estimates of soil C based on the FAO/UNESCO Soils Map of the World (1:5,000,000)?
3. Does the scale of digital soils maps affect estimates of soil C stocks?
4. Do soil properties that are thought to affect stabilization of soil C, such as drainage class and clay content, covary spatially with soil C stocks in a spatially referenced GIS database?

We chose the state of Maine for these studies because it was among the first states for which SCS digital databases were available. Maine also has soils with relatively high carbon content at 43 to 47 degrees latitude where C loss from soils could be important as the earth warms. We compared estimates of soil C stocks in Maine from three databases. First, we used the State Soil Geographic Data Base (STATSGO) provided by SCS for the state of Maine, which is at a scale of 1:250,000. Relations between spatial distribution of soil C stocks, clay content, and drainage class were also examined using STATSGO. Second, we used the SCS Soil Survey Geographic Data Base (SSURGO) for one 7.5 minute topographic quadrangle unit within the state of Maine, which was mapped at a scale of 1:20,000. The estimates from STATSGO and SSURGO are compared for this quadrangle. Finally, we extracted areas of soil taxa from map units and their inclusions in the 1:5,000,000 FAO/UNESCO Soils Map of the World and matched them with estimates of mean soil C contents to calculate total soil C stocks of the state. Published means of soil C stocks for temperate forests were also extrapolated across the entire state. These coarse scale estimates are compared with each other and with the estimate of total soil C stocks from STATSGO.

Methods

Definitions

We use the following definitions from the glossary of the Soil Science Society of America (1987):

map unit — 'a conceptual group of one to many delineations identified by the same name in a soil survey that represent similar landscape areas comprised of . . . the same kind of component soil, plus inclusions'

inclusion — 'a soil or miscellaneous land area within a delineation of a map unit that is not identified by the map unit name'

soil series — 'the lowest category of US system of soil taxonomy; a conceptualized class of soil bodies (polypedons) . . . commonly used to name dominant or codominant polypedons represented on detailed soil maps'

pedon — 'a three-dimensional body of soil with lateral dimensions large enough to permit the study of horizon shapes and relations, . . . [typically] from 1 to 10 square meters'

STATSGO

The STATSGO database includes a digitized map (1:250,000) of polygons classified as various map units (SCS 1992). For Maine, there are 1255 polygons and 70 different map unit classes (including one for water). We transferred these data into a PC ARC/INFO GIS format (Environmental Systems Research Institute 1989), which calculated the area of each polygon, and we then summed the areas of polygons of common map unit classes.

The STATSGO databases are aggregated from county soil surveys and other data by SCS soil scientists in state offices who are familiar with the local soils. Hence, STATSGO is an expert-based aggregation of mostly the same county soil surveys upon which SSURGO map units are based. Each STATSGO map unit class is comprised of up to 21 soil series 'components.' In some cases, components were identified as associations of soil series, but in most cases, each component is identified with a single dominant soil series, and the remaining components are regarded as inclusions. For simplicity, we will hereafter use the terms 'soil series' and 'components' interchangeably with regard to STATSGO and SSURGO databases. However, the components also include designations of urban land, pits, rock outcrops, and water. Large bodies of water are given their own map unit.

Attribute data are provided for each map unit class in a 'components' table, which we imported into spreadsheet software. An estimate is provided of the fractional area of each map unit that is covered by each soil series. Each soil series is also classified, from soil order to family, and drainage class is also designated (very poorly, poorly, somewhat poorly, moderately well, well, somewhat excessively, and excessively). A total of 154 soil series are described in the Maine STATSGO database, and together they comprise the 69 map units.

We estimated the area of coverage for each soil series by the following equation:

$$A_{ss} = \sum_{mp} A_{mp} \times F_{ss,mp} \tag{1}$$

where A_{ss} is the total area of a soil series in the state (ss = 1 to 154), A_{mp} is the total area of a map unit class within the state (m) = 1 to 69), and $F_{ss,mp}$ is the fraction of that map unit covered by that soil series.

To calculate carbon content of each soil series, we imported into spreadsheet software the attribute data provided in the STATSGO 'layer' table. These attribute data include estimates of several properties of each layer (horizon) of each soil series, including percent clay content, depth, bulk density, organic matter concentration, and fractional rock content. Up to 6 layers are sometimes described, but most commonly, three layers that generally correspond to the A, B, and C horizons are indicated. Depth to the bottom of the lowest horizon varies, but the most common value for soils in the Maine STATSGO is 1.65 m. Data for O horizons are provided only for soils classified as Histosols or that have histic epipedons, so all soil C estimates in these analyses exclude forest floor material. High and low estimates are provided for bulk density, organic matter concentration, and fractional rock content. We used the midpoint between high and low estimates for all calculations. The C content of each soil series was then calculated:

$$C_{ss} = \sum_{h} D_h \times BD_h \times FE_h \times OM_h \times 0.58 \tag{2}$$

where C_{ss} is the carbon content per unit area (g C/cm^2) of the entire solum for the soil series, D_h is the depth (cm) of horizon h of that series,

BD_h is the bulk density (g dry soil/cm^3) of horizon h, FE_h is the dimensionless fraction of fine earth material <2 mm size class in horizon h (see next paragraph for elaboration), OM_h is the organic matter concentration (g OM/100 g dry soil) of horizon h, and 0.58 is the assumed fraction of C content of soil organic matter (Nelson & Sommers 1982).

Bulk density data used for the STATSGO database for the state of Maine were determined after equilibrating intact soil cores at 33 kPa in the laboratory and are expressed on a stone-free basis (Reinhart 1961; Rourke & Beek 1969). The presence of all rock fragments >2 mm must be accounted for in order to express these data on an areal basis. The STATSGO layer table provides estimates of the percentage of the mass of the bulk density soil sample that passes through a number 10 sieve (2 mm) as well as field estimates of the percentage of the mass of each horizon contributed by rocks between 7.5 and 25 cm and >25 cm. The estimate of the bulk density soil sample not passing through the sieve was added to the estimates of coarse rocks (>7.5 cm) to give total % rock mass. The fine earth fraction (FE_h by volume was calculated for each horizon assuming a particle density of 2.65 g/cm^3:

$$FE_h = \frac{\dfrac{100 - \%\mathrm{rockmass}_h}{BD_h}}{\dfrac{\%\mathrm{rockmass}_h}{2.65} + \dfrac{100 - \%\mathrm{rockmass}_h}{BD_h}}. \tag{3}$$

The area-weighted mean carbon content, C_{mp}, of each map unit was calculated:

$$C_{mp} = \sum_{ss} C_{ss} \times F_{ss,mp}. \tag{4}$$

The storage of carbon in soils of the entire state of Maine was calculated from estimates of areal coverage of each map unit and area-weighted carbon content of each map unit:

$$C_{state} = \sum_{mp} A_{mp} \times C_{mp}. \tag{5}$$

The total state-wide carbon storage for each soil series was calculated:

$$C_{ss,state} = \sum_{mp} A_{mp} \times F_{ss,mp} \times C_{ss}. \tag{6}$$

Total state-wide C storage was then summed for each soil taxon (orders, suborders, and great groups), and the area-weighted means were calculated:

$$C_{txn} = \frac{\sum_{ss} C_{ss,state}}{\sum_{ss} A_{ss}}. \tag{7}$$

For comparisons of spatial distribution of soil C with other soil parameters, the area-weighted mean clay content (%) of the surface and subsurface horizons was calculated for each map unit:

$$Clay_{mp,h} = \sum_{ss} Clay_{ss,h} \times F_{ss,mp}. \tag{8}$$

Drainage class designations for each soil series were converted to integer scores, ranging from 0 for very poorly drained soils to 7 for excessively drained soils. The area-weighted drainage class score for each map unit, DC_{mp}, was then calculated:

$$DC_{mp} = \sum_{ss} DC_{ss} \times F_{ss,mp} \tag{9}$$

The STATSGO databases are frequently updated, but when this study was conducted, estimates of OM concentration were missing for some soil series, particularly for subsurface horizons. Soil scientists from the SCS offices in Maine, New Hampshire, and New York provided estimates of these missing values. In some cases, their estimates were based on new data not present in our copy of the Maine STATSGO database, and in other cases they used data from similar soil series.

Estimates of percent OM usually occur in STATSGO as integers, although 0.5% is also included as the lowest possible nonzero estimate. When SCS laboratory analyses indicate that OM is $<0.5\%$, a value of zero is usually entered in the STATSGO database. Based on descriptions of numerous soil series in University of Maine technical bulletins that show OM concentration generally ranging from about 0.1% to 0.3% in C horizons (e.g. Rourke 1990; Rourke & Beek 1969; Rourke & Bull 1982), we substituted 0.2% OM for values of zero or for missing values in the lowest soil horizon.

SSURGO

The largest contiguous section of Maine for which the digitized SSURGO data are currently available is the Old Orchard Beach quadrangle, which includes parts of York and Cumberland Counties along the southern coast of the state. The SSURGO data are provided in essentially the same format as the STATSGO data, and the spreadsheet analyses were also similar. The Old Orchard Beach quadrangle is mapped at 1:20,000. The SSURGO database for this quadrangle contains 1787 polygons that are identified as 100 different map unit classes. Each map unit is identified with a soil series name (or other designations such as urban land, water, and quarries). The fraction of each map unit covered by each named soil series is indicated in the attribute data. An 'inclusion' table provides estimates of the fractional coverage of up to six other soil series or other components within each SSURGO map unit. Areal coverage of each SSURGO soil series within the quadrangle was calculated using Eq. 1. The carbon content of each SSURGO soil series was calculated using Eqs. 2 and 3. Area-weighted estimates of carbon content of each SSURGO map unit were determined using Eq. 4. The storage of C in soils of the entire quadrangle was calculated from Eq. 5, substituting C_{quad} for C_{state} and using estimates of map unit areas and carbon contents of soil series from the SSURGO data.

The digital STATSGO map was reprojected to match the spatial resolution and geographic coordinate system of the SSURGO digital map of the Old Orchard Beach quadrangle. The boundaries of the 7.5 minute quadrangle were then used to extract an identical subset from this new STATSGO layer. The storage of C in soils of the quadrangle was again calculated using Eq. 5, but using the STATSGO estimates of area-weighted carbon content of the three STATSGO map units found within the quadrangle.

FAO/UNESCO Soils Map of the World

The state of Maine and nearly all of New England fall within two map units of the 1:5,000,000 scale FAO/UNESCO Soils Map of the World: Leptic Podzols and Orthic Podzols (thin and common Podzols, respectively). The digital version of the map indicates that Leptic Podzols and Orthic Podzols cover 20.0% and 80.0% of the area of the state, respectively. The paper version of the FAO map provides further division of each map unit into two or three subunit classes, and a table is also provided with the percentage of each subunit class that is covered by each of four soil taxa. The first and dominant taxon is always Leptic or Orthic

Podzol, and the other taxa (inclusions) for Maine are Dystric Gleysols, Lithosols, Gleyic Luvisols, and Dystric Histosols. We estimated the area of each subunit from the paper map, multiplied these areas by the fractional coverage of each taxon, and summed the areas for each taxon across map units (Eq. 1).

The FAO attribute data provide no information on soil C. To calculate total soil C content, we matched FAO soil taxa with appropriate STATSGO soil taxa and their mean carbon contents. Because the STATSGO taxa are based on the system of USDA Soil Taxonomy (Soil Survey Staff 1975), this matching is ambiguous and imperfect; we provide two scenarios. In the first, three of the taxa indicated in the FAO map were matched with three of the soil orders present in the Maine STATSGO (Podzols with Spodosols; Gleysols with Inceptisols; Histosols with Histosols). The fourth FAO taxon, Luvisols, is generally equated to Alfisols, but there are no Alfisols in the Maine STATSGO. As the fourth STATSGO soil order, Entisols, was not matched with any FAO taxon, we matched the Luvisols with the Entisols. In the second scenario, specific suborders or great groups (Haplorthods, Humaquepts, Fibrists) were matched with the FAO taxa as indicated by Van Baren (1987). Aquents were substituted for the missing Aqualfs as a match with Gleyic Luvisols. The area of each FAO taxon was then multiplied by the mean soil carbon content of the matched STATSGO taxon, and these products were summed for the state (Eq. 5).

Results and discussion

Soil carbon in Maine using STATSGO at a scale of 1:250,000

Using STATSGO, we calculate that the soils of Maine store 1.25×10^{15} g carbon (Table 1). Four soil orders, 11 suborders, and 17 great groups are represented in the STATSGO database for Maine. About 65% of the area is covered by Spodosols, but Spodosols comprise $<39\%$ of the carbon stored in the soils of the state (Table 1).

Two reasons are apparent for this difference in areal coverage of Spodosols and their contribution to total soil carbon of the state. First, the area-weighted average C content calculated from Eq. 7 for Spodosols (8.8 kg C/m^2) is lower than the arithmetic mean for all Spodosol soil series (10.4 kg C/m^2), which indicates that Spodosols with below average C content cover a large part of the area (Table 1). Many datasets on soils may be biased towards including descriptions of pedons with well developed profiles that typify classical traits of a pedogenic processes or that have unusual traits. Poorly developed soils with few interesting features

Table 1. Areal coverage and carbon stocks by soil taxa in STATSGO for the state of Maine.

Soil classification			No. of soil series	Area		Carbon content			Total carbon	
Order	Suborder	Great group				Arith-metic mean	Std. dev.	Area weighted mean		
				(km^2)	(%)	(kg/m^2)			(10^{12} g)	(%)
Entisols			11	1430	1.1	11.8	12.9	10.5	15	1.2
	Aquents	Fluvaquents	4	430	0.5	26.0	10.9	30.7	13	1.1
	Orthents	Udorthents	4	980	1.2	2.7	2.2	1.7	2	0.1
	Psamments	Udipsamments	3	20	0.0	4.9	1.1	5.0	0	0.0
Histosols			14	4050	4.8	88.7	51.3	104	422	33.8
	Fibrists		2	230	0.3	74.1	21.6	91.7	21	1.7
		Borofibrists	1	210	0.2	95.6		95.6	20	1.6
		Sphagnofibrists	1	30	0.0	52.5		52.5	1	0.1
	Folists	Borofolists	2	860	1.0	30.1	7.6	25.3	22	1.7
	Hemists		6	490	0.6	87.4	44.4	147	72	5.8
		Borohemists	5	440	0.5	88.8	54.3	156	69	5.5
		Sulfihemists	1	50	0.1	80.4		80.4	6	0.3
	Saprists	Borosaprists	4	2470	2.9	127	52.2	124	307	24.6

Inceptisols			46	20500	24.4	17.0	13.0	15.8	324	25.9
	Aquepts		27	18200	21.6	19.0	15.1	16.3	297	23.8
		Haplaquepts	19	14100	16.8	11.7	3.5	10.7	151	12.1
		Humaquepts	8	4100	4.9	36.1	19.7	35.6	146	11.7
	Ochrepts		19	2230	2.7	14.2	7.5	12.4	28	2.2
		Dystochrepts	13	290	0.3	15.8	8.8	21.7	6	0.5
		Eutrochrepts	6	1930	2.3	10.8	2.9	11.0	21	1.7
Spodosols			83	54600	64.9	10.4	4.1	8.8	481	38.5
	Aquods		5	680	0.8	15.0	6.0	20.4	14	1.1
		Fragiquods	1	90	0.1	12.6		12.6	1	0.1
		Haplaquods	4	590	0.7	15.6	7.0	21.7	13	1.0
	Orthods		78	53900	64.1	10.1	3.8	8.7	467	37.4
		Cryorthods	4	900	1.1	13.5	5.6	12.4	11	0.9
		Haplorthods	74	53000	63.0	9.9	3.7	8.6	456	36.5
All soils			154	80600	95.9	19.8	28.7	15.5	1250	100
Other				3480						
	Urban/rock			870						
	Water			2610						
Total area				84100	100					

and with low carbon content may not be studied as often, and hence, may not be as well represented numerically in many databases. Soils that are 'typical' examples of certain soil classifications may not be 'typical' or 'common' in the sense of covering large areas.

The second reason that Spodosols are less important with respect to carbon than their areal coverage might suggest is that Histosols cover $<5\%$ of the area of the state, but they contribute $>33\%$ of the soil carbon storage of the entire state (Table 1). The scale (1:250,000) and structure of the STATSGO database, which provides spatial estimates of inclusions within map units, allow recognition of Histosols and calculation of their contribution to soil C stocks of the state of Maine.

As with nearly all types of spatial extrapolation (Eswaran et al. 1993; Kimble et al. 1991; Post et al. 1982; Schlesinger 1977), estimates of error terms for the calculations from STATSGO data are very difficult to obtain. High and low estimates are provided in STATSGO for organic matter (OM) concentration, bulk density (BD), and percentage rock mass, but equally important sources of error are depth increments of soil layers and areal coverage of soil series within map units, for which no range of values is provided in STATSGO.

Although we lack a specific error term that would conveniently express our confidence that the actual soil carbon storage of the state falls within a certain range, we can argue on *a priori* grounds that the STATSGO estimate is likely to be more accurate than other coarser scale extrapolations. STATSGO provides detailed information on presence of inclusions such as Histosols, which clearly comprise a significant part of the soil C storage of the state (Table 1). A GIS approach permits calculation of the contribution of each described soil series according to both its areal coverage and its C content.

Comparing STATSGO with SSURGO (1:20,000) for one quadrangle

Comparison of estimates from STATSGO with data of finer scale resolution provides some indication of accuracy of STATSGO at a selected locality. The total soil C content of the Old Orchard Beach quadrangle estimated from the SSURGO data is 2.5×10^{12} g, which is about 13% lower than the estimate for the same area from the coarser scale STATSGO data (Table 2). Of the three STATSGO map units that occur within the quadrangle, one estimate is 5% lower than the corresponding SSURGO estimate, and the other two are 29% and 23% higher (Table 2). The Naumburg series (Aeric Haplaquods) covers between 12% and 13% of the quadrangle (about 19 km^2) according to both SSURGO and STATSGO databases (and covers only 0.48% of the state according to STATSGO).

Table 2. Comparison of SSURGO and STATSGO estimates of soil carbon for each of the STATSGO map units (MP) that occur within the Old Orchard Beach Quadrangle in York and Cumberland Counties, Maine.

Soil taxa	Area (hectares)		Soil C (10^{12} g)	
	SSURGO 1:20,000	STATSGO 1:250,000	SSURGO 1:20,000	STATSGO 1:250,000
STATSGO MP # 47				
Entisols	113	0	0.029	0.000
Histosols	411	592	0.351	0.518
Inceptisols	1536	518	0.329	0.163
Spodosols	5244	6291	0.676	1.110
Other	97	0	0.002	0.000
TOTAL	7401	7401	1.387	1.791
STATSGO MP # 53				
Entisols	95	126	0.020	0.044
Histosols	195	126	0.164	0.100
Inceptisols	2960	5400	0.504	0.761
Spodosols	2848	628	0.325	0.069
Other	181	0	0.007	0.000
TOTAL	6279	6279	1.020	0.974
STATSGO MP # 61				
Entisols	0	0	0.000	0.000
Histosols	59	88	0.054	0.078
Inceptisols	12	0	0.002	0.000
Spodosols	94	65	0.012	0.009
Other	95	107	0.003	0.000
TOTAL	260	260	0.071	0.087
Entire quadrangle				
Entisols	208	126	0.049	0.044
Histosols	665	806	0.569	0.696
Inceptisols	4508	5918	0.835	0.924
Spodosols	8186	6984	1.113	1.188
Other	373	107	0.012	0.000
TOTAL	13940	13940	2.478	2.852

The STATSGO attribute data for this common soil series indicate that the surface horizon is 48 cm deep, but the SSURGO contribute data for York County indicate that it is only 13 cm deep. In four profile descriptions of untilled pedons of the Naumburg series in Maine, the depth of the surface horizon ranges from 13 to 25 cm (Rourke & Bull 1982). The higher estimate of 48 cm in STATSGO occurs because the attribute data are from the generalized Soil Interpretation Record (SOI-5) of the SCS, which, for the Naumburg series, covers a broad region that includes New York state where this series apparently has a much deeper surface horizon than in Maine. This difference in depth of one horizon in one soil series results in a difference of 0.20×10^{12} g C in the Old Orchard Beach Quadrangle, which is nearly half of the difference in the calculation of total soil carbon storage in that quadrangle using the STATSGO and SSURGO datasets (Table 2).

In a similar comparison of soil C stocks estimated from STATSGO and from county soil survey data in Pottawattamie County, Iowa, Grossman et al. (1992) calculated 7% less carbon using the STATSGO database. The fact that their STATSGO estimate is lower than their estimate based on county soil survey data and our STATSGO estimate is higher than our SSURGO estimate suggests that a consistent bias caused by scale may not exist, but similar comparisons are needed for other parts of the state and region, as digitized versions of SSURGO become available. Some localized deviation from median conditions is expected, so it is not surprising that the STATSGO and SSURGO databases do not agree perfectly when compared in a small area such as the Old Orchard Beach quadrangle (Table 2). Local errors in STATSGO estimates, such as those we calculated for this quadrangle, probably cancel in a state-wide analysis. For purposes of assessing the amount of soil C that will be exposed to varying degrees of climate change, we suspect that these local differences are insignificant.

The FAO/UNESCO Soils Map of the World (1:5,000,000)

Very few, if any, soils maps were designed to attempt to describe variation in soil C. Indeed, the soils classification systems used today, including the USDA Taxonomy and the FAO map legend, are not well structured to characterize differences in soil C content among classes. Moreover, soil mappers draw boundaries according to numerous criteria that depend on the purpose and the scale of the map. Map units are not homogeneous in soil maps at any scale, and the amount of information about presence of inclusions varies among maps. Given these limitations, assumptions must be made in order to use soil maps to estimate soil C storage.

When soil orders were used to match STATSGO taxa with FAO taxa in scenario 1, the estimates of areal extent of these groups agreed remarkably well (Table 3). Both datasets show that Histosols cover about 5% or 6% of the area of the state. Use of soil suborders and great groups in scenario 2 resulted in poorer areal matches with the FAO taxa, because these more specific STATSGO taxa cover smaller portions of the state. The estimates of soil C stocks for the entire state are 1.34 and 1.67×10^{15} g C for scenarios 1 and 2, respectively (Table 3). Use of aquic suborders in scenario 2 resulted in higher estimates of soil C. Despite the problem of

Table 3. Calculation of soil carbon stocks of Maine using FAO map units and STATSGO attribute data. Two scenarios are provided using different matches between FAO and STATSGO soil taxa.

FAO map		Matching STATSGO data: Scenario 1				Matching STATSGO data: Scenario 2			
Taxon	Area (%)	Taxon	Area[1] (%)	Mean C content[1] ($kg\ m^{-2}$)	Total C content[2] (10^{12} g)	Taxon	Area[1] (%)	Mean C content[1] ($kg\ m^{-2}$)	Total C content[2] (10^{12} g)
Lithic & Orthic Podzols	58.5	Spodosols	64.9	10.4	512	Haplorthods	63.0	9.9	487
Dystric Gleysols	25.4	Inceptisols	24.4	17.0	364	Humaquepts	4.9	36.1	772
Dystric Histosols	6.0	Histosols	4.8	88.7	448	Fibrists	1.0	74.1	376
Gleyic Luvisols	1.5	Entisols[3]	1.7	11.8	14	Aquents[3]	0.5	26.0	32
Lithosols	8.4	Urban, rock outcrops, water	4.1	0.0	0	Urban, rock outcrops, water	4.1	0.0	0
ALL	100		100	16.6[4]	1338		73.5	20.7[4]	1667

[1] From Table 1.
[2] Total carbon content is calculated by multiplying the area of the state, the fraction covered by the FAO map class (second column of this table), and the mean carbon content ($kg\ m^{-2}$) of the matching STATSGO taxon.
[3] Luvisols are usually equated with Alfisols, but Alfisols are not present in the STATSGO database, whereas Entisols that are present in STATSGO appear to have no other match with the FAO map.
[4] Area-weighted estimates of mean soil carbon content are calculated for all soils by dividing the sum of the estimated carbon contents by the total area covered by soils (excluding urban, rock, and water).

matching soil taxa, this exercise shows that data on inclusions within map units of the 1:5,000,000 FAO map can be used to recognize the presence of soils that are spatially relatively unimportant but that contribute significantly to soil C stocks.

This analysis indicates that the 1:5,000,000 FAO map has potential for providing a reliable basis to estimate soil C storage, but that matching FAO soil taxa with appropriate means of soil C content is problematic. Because the FAO map is very coarse in scale, pairing of FAO taxa with USDA Taxonomy soil orders may be appropriate for estimating soil C stocks, as demonstrated by scenario 1 (Tables 3 and 4). If we had not had STATSGO, however, it would have been difficult to determine which scenario shown in Table 3 provides the most appropriate matching of taxa. Similar comparisons are needed in other regions and across other soil taxa to gain more confidence in appropriate matching of mean soil C estimates with FAO soil taxa.

Other coarse scale extrapolations

Another, simpler approach to coarse scale extrapolation that might be used with the FAO map is to ignore inclusions and to extrapolate based on the names of map units. As all of Maine is mapped as Podzols in the 1:5,000,000 FAO map, the area of the state would be multiplied by an appropriate mean carbon content for Podzols or Spodosols. Using the published mean of 16.3 kg C/m^2 for all temperate Spodosols (33 pedons) to 50 cm depth in the SCS international database (Kimble et al. 1991), the extrapolated estimate for the entire state is 1.31×10^{15} g C (Table 4). Using the arithmetic mean of the carbon content of all Spodosols within the STATSGO database for Maine (10.4 kg C/m^2; 83 soil series; Table 1), the extrapolated estimate for the entire state is 0.84×10^{15} g C (Table 4). The STATSGO arithmetic mean for C content of Maine Spodosols results in the lowest estimate of total C (49% lower than the estimate using the entire STATSGO database; Table 4), because using the mean of Spodosols ignores the carbon rich Histosols. When the international database of Kimble et al. (1991) is used for Spodosols, the estimated total carbon for the state is high, presumably because the SCS international database includes several Spodosol pedons from other temperate regions that contain more carbon than the Maine soils, such as the Aquods of Florida (Stone et al. 1993). In this case, ignoring the presence of Histosols in Maine is more than compensated for by using an unrealistically high mean carbon content for the Spodosols of Maine.

Another approach to coarse scale estimation of soil C is to use classifications of vegetation rather than soil map units. Published estimates

Table 4. Estimates of total soil carbon stocks in the state of Maine.

Method	Mean soil carbon content (kg/m^2)	Total soil carbon stock (10^{15} g)
Extrapolations assuming the state is homogeneous:		
Cool temperate forest	12.7[1]	1.02
Temperate forest	11.8[2]	0.95
Temperate Spodosols	16.3[3]	1.31
Maine Spodosols	10.4[4]	0.84
Estimates using data on inclusions within map units:		
FAO/UNESCO Soil Map of the World		
Scenario 1	16.6[5]	1.34[6]
Scenario 2	20.7[5]	1.67[6]
Maine STATSGO	15.5[5]	1.25[4]

[1] Post et al. 1982.
[2] Schlesinger 1977.
[3] Kimble et al. 1991.
[4] This study; Table 1.
[5] Area-weighted mean: total soil C stocks divided by area of soil in the state.
[6] This study; Table 3.

of mean mineral soil carbon content of 'cool temperate forests' (Post et al. 1982) and 'temperate forests' (Schlesinger 1977) are 12.7 and 11.8 kg C/m^2, respectively. The Schlesinger (1977) estimate includes carbon in the litter layer, whereas the data available to Post et al. (1982), to Kimble et al. (1991), and in this analysis of STATSGO include only C in the mineral soil horizons of most forest soils (although data on organic horizons of Histosols and histic epipedons of other soils are included). Assuming that the entire state of Maine can be characterized as temperate forest, as would be done in a global map of vegetation types, extrapolations of the means published by Post et al. (1982) and Schlesinger (1977) are 1.02 and 0.95 $\times$ 10^{15} g C, respectively, for the soils of Maine (Table 4).

Using means for temperate forests caused low estimates (18% to 34% lower than STATSGO) because these means ignore the presence of wetlands and other poorly drained soils that occupy little area but are rich in soil C. Assuming that Maine is covered entirely by forest may not seem like too large of an error, as forests were estimated to cover 89% of the area of the state in 1982 (Powell & Dickson 1984). Wetlands and other poorly drained soils were estimated to cover less than 8% of the area, but this small fraction of area contributes a large fraction of total soil C stocks, as is evidenced by the large contribution of total C by Histosols and Aquepts (Table 1).

If this analysis is characteristic of regions where Spodosols and Histosols are common, which includes much of Canada, northeastern USA, Scandinavia, and Siberia, total soil C stocks of these regions may have been underestimated by previous approaches based on vegetation types by as much as one-third. By providing data on spatially referenced estimates of inclusions within map units, the STATSGO GIS approach shows that an area dominated by temperate forests and mapped as Podzols contains significant amounts of C in poorly drained Histosols. Conversely, areas mapped as Histosols in soils maps and as wetlands in vegetation maps may have significant inclusions of Podzols and forests, so these sources of error could cancel in a global analysis. However, until similar studies can be completed in other regions, these regional and global estimates of soil C stocks remain uncertain. Two other studies also indicate that C storage in Spodosols (Stone et al. 1993) and Histosols (Eswaran et al. 1993) may be underestimated because of insufficient sampling of soils at depth.

Spatial variation of other soil properties

All of the soil series with more than 40 kg C/m^2 were very poorly drained (score of zero, Fig. 1a). Most of these soils series are classified as Histosols. Area-weighted mean soil carbon contents were negatively correlated with area-weighted mean drainage class scores across map units (Fig. 1b). In other words, when soils with low drainage class scores covered large fractions of map units, those map units generally had high carbon contents.

Elevational differences of only a few meters often separate excessively drained eskers from very poorly drained bogs in Maine. Organic C often accumulates in very poorly drained soils, probably because of lack of adequate diffusion of oxygen into the soil to promote decomposition. In this region, spatial distribution of drainage patterns influences accumulation of soil C. Although not identical, several areas of agreement can be seen between the maps of drainage class scores and soil carbon stocks from the STATSGO database for Maine (Fig. 2). This relation is also apparent in the curvilinear regression, in which 54% of the variation in area-weighted means of carbon contents of map units was accounted for by area-weighted drainage class scores (Fig. 1b). This regression analysis must be interpreted with caution, however, because of possible spatial autocorrelation and because of possible inflation of correlation coefficients when aggregated data are used (known as the ‘modifiable areal unit

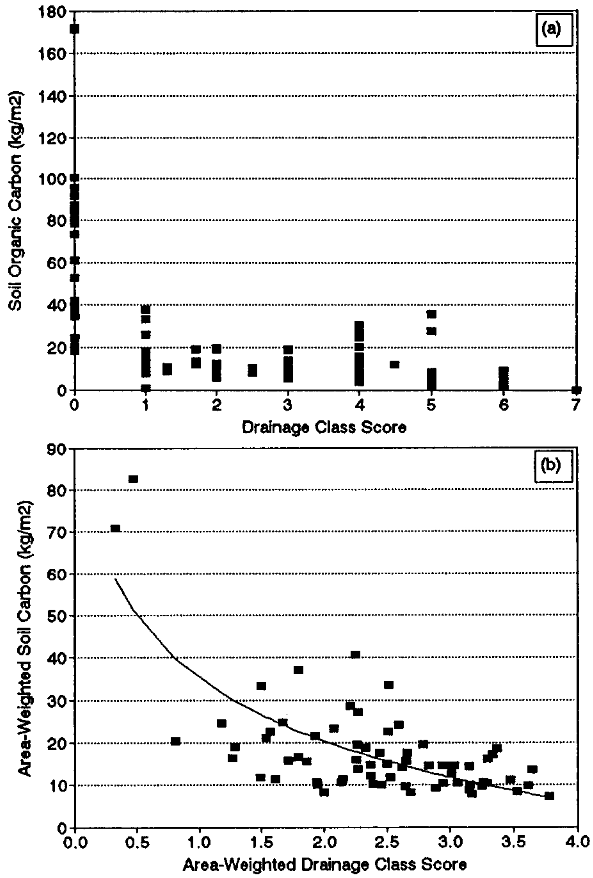


Fig. 1. In the upper panel (a), soil carbon contents of the 154 soil series of the Maine STATSGO are shown according to groupings of their respective drainage class scores, which range from zero for very poorly drained soils to 7 for excessively drained soils. In the lower panel (b), area-weighted soil carbon contents of the 69 STATSGO map units for Maine are shown as a function of the area-weighted drainage class scores of map units. The equation for the regression line is $Y = (-48.84 \times \log X) + 35.2$; the $R^2 = 0.54$; and the regression is significant at $\alpha = 0.01$.

problem' for which no solution has been agreed upon by statisticians, see Fotheringham & Wong 1991). Despite the difficulty of applying appropriate statistical tests, it is clear that only those soils designated as very poorly drained have accumulated substantially more carbon than soils of other drainage class designations (Fig. 1a). If climate change and/or human land uses alter drainage of these lands, then soil C storage could decline.

Clay content was a poorer predictor of soil C than was drainage class

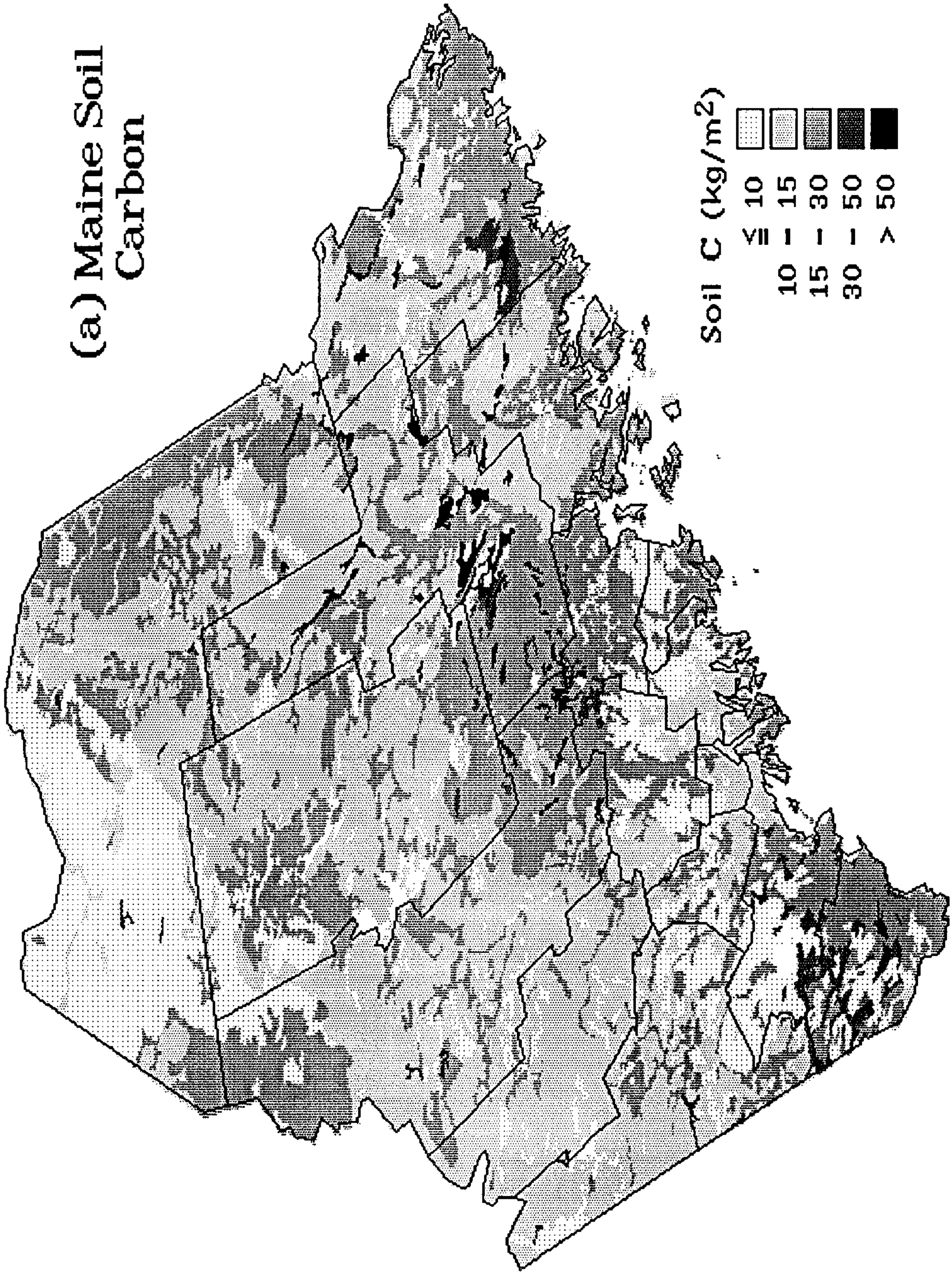
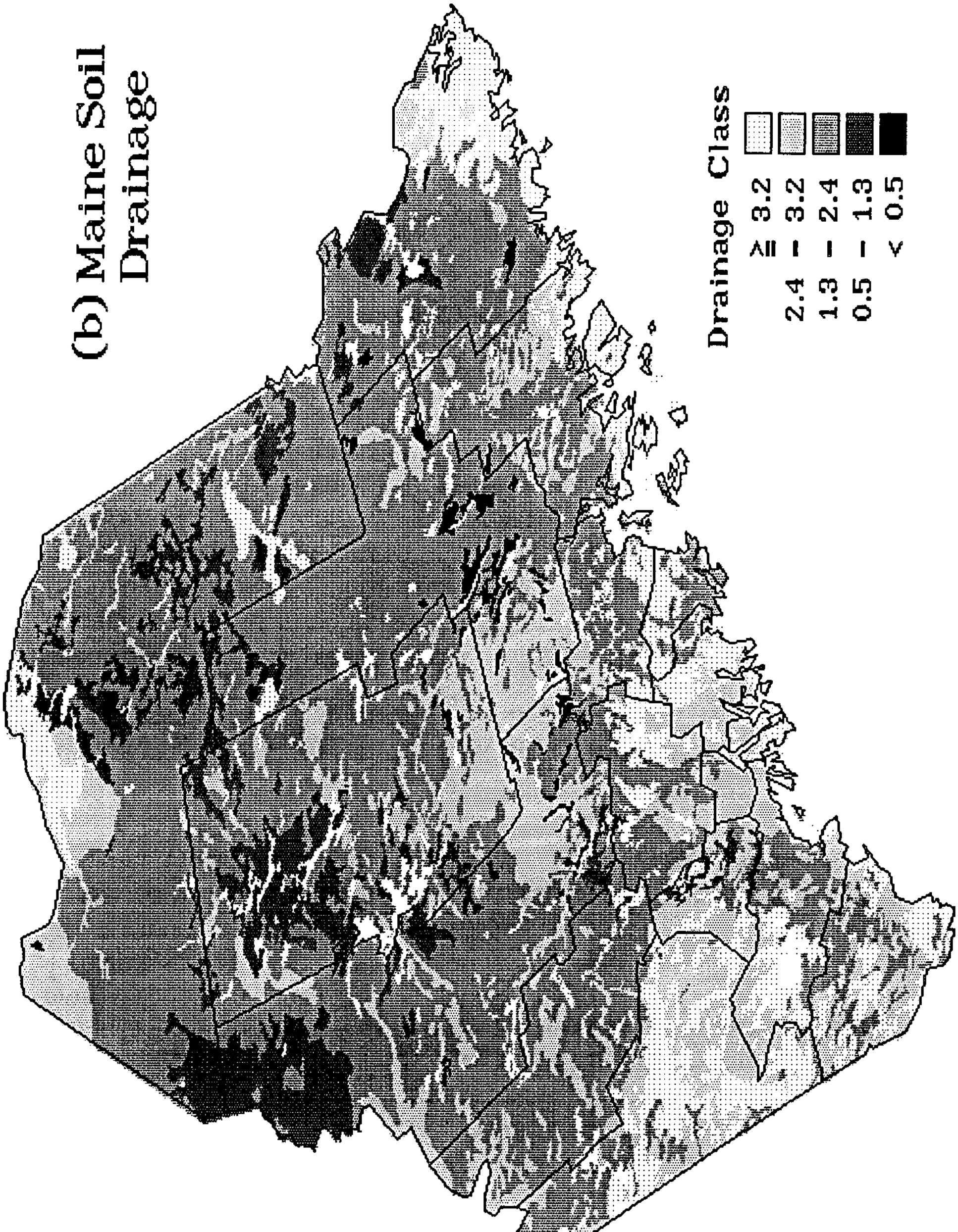


Fig. 2. Map of soil area-weighted carbon contents (a) and area-weighted drainage classes (b) delineated by STATSGO map units for Maine. County boundaries are superimposed for reference. Soil carbon contents were grouped arbitrarily to create five classes of shading.



The ranges of drainage class scores for each class of shading were chosen so that each shading class would include the same number of map unit classes as its respective shading class in the soil carbon map.

score. Histosols with high carbon content generally have low clay contents in both surface and subsurface horizons (Figs. 3a, b), which causes a weak negative relation between area-weighted values of carbon content and clay content across map units (Figs. 3c, d). In the southern Great Plains states of the USA, where Mollisols are common, soil C storage has been shown to be positively correlated with clay content (Burke et al. 1989, 1990; Nichols 1984). Clay may help to stabilize soil C through physical and chemical protection from decomposition in these prairie soils. In Maine, which is dominated by Spodosols and Histosols, the relation between clay and soil carbon storage does not hold. Clay was a poor predictor of soil C across soil series and across map units (Fig. 3). This result is not surprising in view of the processes of genesis of Histosols and Spodosols in which clay has little influence. The result is significant, however, because it illustrates the danger of extrapolating understanding of processes from one region, such as the southern Great Plains of the USA, to another region, such as New England. Clay content was also a poor predictor of soil C concentration in soils of Montana, which include many Mollisols, but with frigid or cryic temperature regimes (Sims & Nielson 1986). Clay content may not be as useful as drainage class in predicting distribution of soil C throughout cool regions of northern grassland, temperate forest and boreal forest biomes.

Conclusions

I. Analysis of the State Soil Geographic Data Base (STATSGO) indicates that the soils of Maine store more C than would be calculated by several common approaches to regional and global extrapolations. Assuming that all of Maine is covered by Spodosols or by temperate forests, as would be the case in most coarse scale regional extrapolations, the calculated carbon storage in soils is between 23% and 49% lower than the estimate from this study using STATSGO.

II. The FAO/UNESCO Soils Map of the World has potential for use in regional and global extrapolations of soil C contents when data on inclusions are used, but matching FAO soil taxa with appropriate mean soil C contents is problematic. The STATSGO soil orders matched well with the FAO taxa, but more comparisons are needed to gain confidence in appropriate matching across a broader range of soil types. Using this comparative approach, the rich SCS databases for the USA might be used to assign carbon values to FAO map units for global extrapolation.

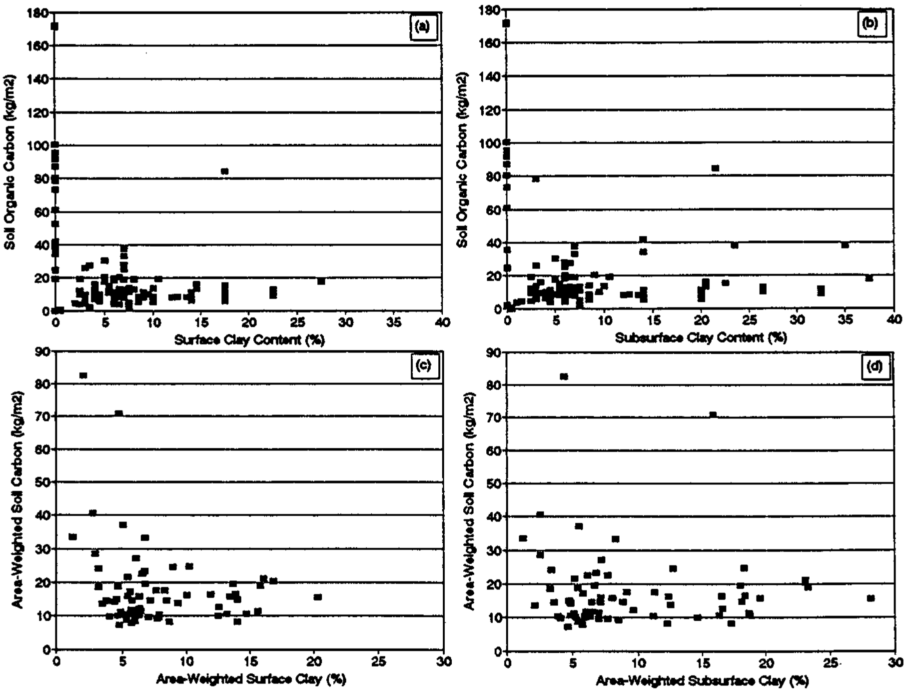


Fig. 3. Soil carbon contents of the 154 soil series of the Maine STATSGO as a function of clay content of the surface horizon (a) and clay content of the subsurface horizon (b). Area-weighted soil carbon contents of the 69 Maine STATSGO map units as a function of area-weighted clay content of the surface horizon (c) and area-weighted clay content of the subsurface horizon (d). Weak negative correlations exist, with the R^2 of least squares linear regression being 0.09, 0.03, 0.06, and 0.00 for data in panels a, b, c, and d, respectively.

III. The scale (1:250,000) and structure of the STATSGO database, which provides spatial estimates of inclusions within map units, allow recognition of Histosols and calculation of their contribution to soil C stocks of the state of Maine. Histosols cover less than 5% of the area of the state, but contain over one-third of the soil C storage. This approach provides a promising basis for scaling up county soil survey data to make regional estimates of soil C stocks.

IV. Spatial variation in soil C contents and other soil properties can be compared when GIS databases are used. In contrast to the correlation between clay content and soil C content observed in areas dominated by Mollisols in the southern Great Plain states, the Maine STATSGO data show that clay content is a poor predictor of soil C, but that drainage class covaried significantly with soil C. Because drainage is a key factor for accumulation of soil C in this region, changes in climate or in land use which affect drainage patterns could also affect storage of C in soils of northeastern North America and other regions where Spodosols and Histosols are common.

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References

Billings WD (1987) Carbon balance of Alaskan tundra and taiga ecosystems: past, present and future. Quaternary Science Reviews 6: 165—177

Burke IC, Schimel DS, Yonker CM, Parton WJ, Joyce LA & Lauenroth WK (1990) Regional modeling of grassland bigeochemistry using GIS. Landscape Ecology 4: 45—54

Burke IC, Yonker CM, Parton WJ, Cole CV, Flach K & Schimel DS (1989) Texture, climate, and cultivation effects on soil organic matter content in US grassland soils. Soil Sci. Soc. Am. J. 53: 800—805

Environmental Systems Research Institute (1989) PC ARC/INFO. Redlands, California USA

Eswaran H, Van Den Berg E & Reich P (1993) Organic carbon in soils of the world. Soil Sci. Soc. Am. J. 57: 192—194

FAO (1978—1981) FAO/UNESCO Soil Map of the World 1:5,000,000 Volumes II—X. Maps per (Sub)continent and Explanatory Texts. UNESCO, Paris

Fotheringham AS & Wong DWS (1991) The modifiable areal unit problem in multivariate statistical analysis. Environment and Planning A23: 1025—1044

Grossman RB, Benham EC, Fortner JR, Waltman SW, Kimble JM & Branham CE (1992) A demonstration of the use of scil survey information to obtain areal estimates of organic carbon. In: Technical papers, Remote Sensing and Data Acquisition (Volume 4: 457—465). American Society of Photogrammetry and Remote Sensing and American Congress of Surveying and Mapping, Bethesda, Maryland, USA

Houghton RA (1991) Tropical deforestation and atmospheric carbon dioxide. Climatic Change 19: 99—118

Kimble JM, Eswaran H & Cook T (1991) Organic carbon on a volume basis in tropical and temperate soils. In: Transactions of the 14th International Congress of Soil Science (Volume V: 248—253). Commission V. International Society of Soil Science, Kyoto, Japan

Nelson DW & Sommers LE (1982) Total carbon, organic carbon and organic matter. In: Page AL, Miller RH & Keeney DR (Eds) Methods of Soil Analysis (pp 539—579). American Soc. of Agronomy, Wisconsin, USA

Nichols JD (1984) Relation of organic carbon to soil properties and climate in the southern great plains. Soil Sci. Soc. Am. J. 48: 1382—1384

Post WM, Emanuel WR, Zinke PJ & Stangenberger AG (1982) Soil carbon pools and world life zones. Nature 298: 156—159

Powell DS & Dickson DR (1984) Forest Statistics for Maine 1971 and 1982. USDA Forest Service Northeastern Station Resource Bulletin NE-81

Reinhart KG (1961) The problem of stones in soil-moisture measurement. Soil Sci. Soc. Am. Proc. 25: 268—270

Rourke RV & Beek C (1969) Chemical and Physical Properties of the Charlton, Sutton, Paxton and Woodbridge Soil Series. Technical Bulletin 34, Maine Agricultural Experiment Station, University of Maine, Orono, Maine, USA

Rourke RV & Bull DC (1982) Chemical and Physical Properties of the Becket, Colton, Finch, Lyman, Masardis, Maumburg, and Skerry Soil Mapping Units. Technical Bulletion 108, Maine Agricultural Experiment Station, University of Maine, Orono, Maine, USA

Rourke RV (1990) Chemical and Physical Properties of the Aurelie, Burnham, Easton, Lille, Linneus, Monadnock, Nicholville, and Tunbridge Soil Map Units. Technical Bulletin 137, Maine Agricultural Experimental Station, University of Maine, Orono, Maine, USA

SCS (1992) State Soil Geographic Data Base (STATSGO) Data User Guide. United States Department of Agriculture Soil Conservation Service, National Soil Survey Center, Lincoln, Nebraska, USA

Sims ZR & Nielsen GA (1986) Organic carbon in Montana soils as related to clay content and climate. Soil Sci. Soc. Am. J. 50: 1269—1271

Soil Science Society of America (1987) Glossary of Soil Science Terms. Soil Science Society of America, Wisconsin, USA

Soil Survey Staff (1975) Soil Taxonomy. Agricultural Handbook No. 436 US Government Printing Office, Washington DC, USA

Sombroek WG (1990) Geographic quantification of soils and changes in their properties. In: Bouwman AF (Ed) Soils and the Greenhouse Effect (pp 225—244). John Wiley and Sons, New York

Schlesinger WH (1977) Carbon balance in terrestrial detritus. Annual Review of Ecology and Systematics 8: 51—81

Stone EL, Harris WG, Brown RB & Kuehl RJ (1993) Carbon storage in Florida Spodosols. Soil. Sci. Soc. Am. J. 57: 179—182

Van Baren J (1987) Soils of the World. Elsevier Science Publishing Company, Inc., New York, USA