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Spatial covariation of soil organic carbon, clay content, and drainage class at a regional scale

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Abstract

Several factors affecting stocks of soil organic-C have been identified, including climate, soil texture, and drainage, but how these factors and their influence vary spatially is not well documented. The State Soil Geographic Data Base (STATSGO) was used to estimate soil organic-C stocks of Montana and Kansas and to map spatial variation of soil properties. Regressions across map units of area-weighted estimates of soil organic-C, clay content, and drainage class show that clay content is positively correlated with organic-C in Kansas, but that drainage class is a better indicator of soil with high and low organic-C stocks in Montana. About 85% of Kansas is covered by Mollisols. These grasslands of the North American Great Plains are where the paradigm relating clay content to stabilization of soil organic-C was developed. In contrast, clay content does not covary with soil organic-C across Montana. Only 30% of Montana is covered by Mollisols; the remainder includes rangeland, covered primarily by Aridisols and Entisols, and forests, covered by Inceptisols, Spodosols, and Histosols. Although other unidentified factors contribute to spatial variation in soil organic-C stocks in Montana, drainage class distinguishes the C-rich and the C-poor soils. When taken with similar results correlating soil C stocks with drainage class in a separate study of Maine, soil wetness emerges as an important controller of soil organic-C in northern states of the USA. Another objective was to compare STATSGO estimates (1:250,000 scale) of area covered by soil orders with estimates from the FAO/UNESCO Soils Map of the World (1:5,000,000). Agreement was excellent in Kansas and reasonably good in Montana. When used with regionally specific estimates for soil-C, the FAO map holds promise for regional and global extrapolation of soil C stocks.

1. Introduction

Gradients of temperature and precipitation have been related to spatial variation of stocks of soil organic matter (SOM) in the Great Plains of North America (Jenny 1941). Primary productivity and soil texture also vary along these climate gradients and are thought to be mechanistically related to production and stabilization of organic matter in soils (Burke *et al.* 1989; Parton *et al.* 1987). Association of organic matter with the mineral soil matrix, particularly with clay particles, results in physical and chemical protection of SOM from decomposition (Oades 1988). Rates of decomposition of SOM are limited by low temperatures in cold regions and by lack of oxygen in poorly drained soils (Billings 1987; Davidson and Lefebvre 1993).

While much is known about the factors that generally influence decomposition and stabilization of SOM, less is known about how these influences vary spatially and, hence, how stocks of soil C vary spatially. Regional and global estimates of distributions of soil C stocks are crude (Eswaran *et al.* 1993; Kern 1994; Kimble *et al.* 1991; Post *et al.* 1982; Schlesinger 1977; Sombroek *et al.* 1993) and are difficult to relate to spatial variation in the factors that determine soil C stocks. Expected warming of the earth resulting from accumulation of heat-trapping gases in the atmosphere will not be uniform throughout the globe, so knowledge of spatial distribution of soil C stocks and the factors that influence them will be crucial to understanding how non-uniform climate change will affect exchange of C between soils and the atmosphere.

Geographic information systems (GIS) of soils permit analysis of the spatial distribution of stocks of soil C and related edaphic parameters that are thought to affect soil C stocks. The first objective of this work is to use the State Soil Geographic Data Base (STATSGO) of the Soil Conservation Service (SCS) to relate spatial variation of soil C stocks to spatial variation of other soil parameters in two states of the Great Plains and Rocky Mountain regions. Kansas and Montana were chosen, as these were states where the digital SCS databases were available and in reasonably complete form. Prior work on soil C in these areas was based on regression analysis of individual pedon data on soil C concentrations and did not include a spatial analysis or an analysis of total C stocks. For example, Nichols (1984) found a strong positive correlation between clay content and soil C concentration among pedon description from the southern Great Plains. Sims and Nielsen (1986) found no significant correlation between clay content and SOM concentration in a pedon dataset for Montana. These analyses are instructive, but incomplete, because total soil C stocks are affected not only by SOM concentration, but also by bulk density and depth. Moreover, previous correlation analyses gave equal weight to each soil series within the dataset regardless of its relative importance spatially. Using a GIS database, mean total C stocks can now be calculated for each soil series and weighted according to estimated areal coverage of each soil series.

A second objective is to compare areal estimates of soil taxa using the STATSGO databases with areal estimates of related soil taxa in the FAO Soils Map of the World (1978–1981). The FAO map has been used as a basis for areal extrapolation of pedon data of soil C stocks (Eswaran *et al.* 1993; Sombroek *et al.* 1993), but the accuracy of the FAO map and potential errors associated with its use for extrapolation of soil C stocks have not been fully examined. A favorable comparison of the FAO map at 1:5,000,000 scale with the finer scale STATSGO database (1:250,000) in the United States would bolster confidence in extrapolations based on the FAO map.

2. Methods

2.1. Calculation of soil parameters using STATSGO

A thorough description of how the STATSGO database is used to estimate soil C stocks is given by Davidson and Lefebvre (1993). Briefly, the STATSGO database includes a digitized map (1:250,000) of polygons classified as various map units (SCS 1992). STATSGO map units are aggregated from county soil surveys and other data by SCS soil scientists in state offices who are familiar with local soils. Estimates are given of the area within each map unit of up to 21 "components," which are inclusions of named soil series or urban, rock, or water designations. Drainage class and soil classification are also indicated, as are several other soil parameters which were not used in this analysis. Attribute data for each soil series include estimates of ranges of depth, bulk density, rock content, organic matter content, and clay content for each of several identified soil horizons, which usually include three horizons corresponding to the A, B, and C horizons. These attribute data provided in STATSGO were used to calculate soil organic carbon content for each horizon of each soil series using the midpoint of the range estimates for depth, bulk density, rock content, and organic matter content. It was assumed that soil organic matter is 58% C by weight (Nelson and Sommers 1982). Total organic-C content (kg C m^{-2}) was summed for all horizons

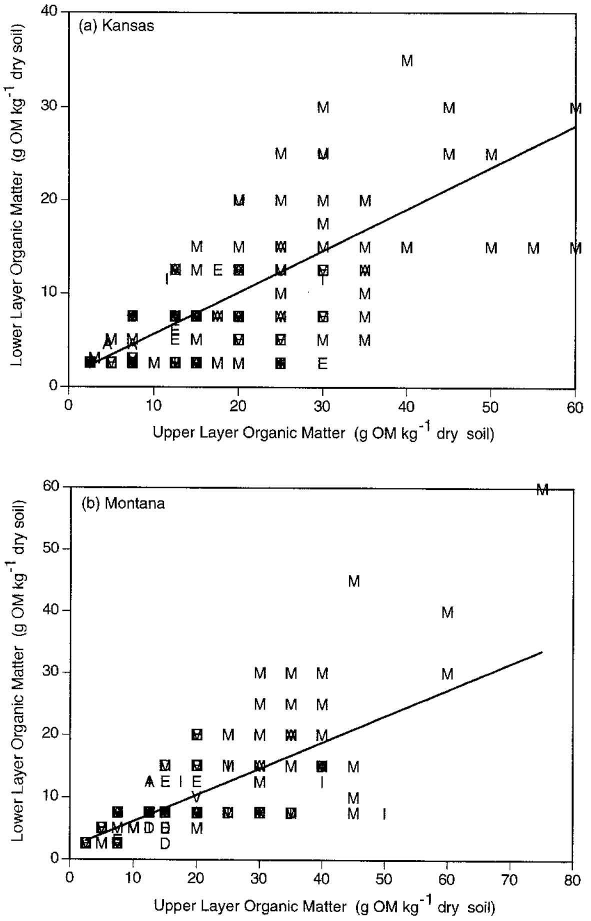

Fig. 1. Relation between organic matter contents of vertically adjacent horizons of soil profiles. For pairs of comparisons (*e.g.*, horizon 1 *vs.* horizon 2; horizon 2 *vs.* horizon 3) the OM value for the upper horizon is plotted on the X-axis and the OM value for the horizon below it is plotted on the Y-axis. For Kansas (a), $Y = 0.45X + 0.12$; $R^2 = 0.54$; and $n = 629$ pairwise horizon comparisons. For Montana (b), $Y = 0.42X + 0.20$; $R^2 = 0.51$; and $n = 286$ pairwise horizon comparisons. Both regressions are significant at $\alpha = 0.01$. The plotting symbols are: A = Alfisols; D = Aridisols; E = Entisols; I = Inceptisols; M = Mollisols; V = Vertisols.

of each soil series. Area-weighted estimates of organic-C content, clay content, and drainage class score were calculated for each map unit by multiplying the value for each soil series by the fraction of the map unit occupied by that soil series and summing the products for all soil series inclusions within the map unit. Similarly, the areal coverage for each soil series was calculated by summing estimates for all map units in the state. Total organic-C storage by each soil series was calculated by multiplying the estimate of total area of each soil series by the organic-C content of its profile. Area-weighted mean organic-C contents of soil orders and suborders were calculated by summing the total statewide organic-C storage of all soil series within a taxon and dividing that sum by the sum of the areas covered by the same group of soil series.

2.2. Missing data in STATSGO

Incomplete data are a common problem for many soils databases, including STATSGO, that are being used for global change research. Although unfortunate, the missing data do not preclude use of these databases. Learning to fill in missing values with reasonable estimates is a challenge that deserves attention and scrutiny.

Estimates of bulk density were missing for many of the soil series in the STATSGO dataset for Montana. An algorithm was provided by the SCS office in Montana for deriving estimates of bulk density using STATSGO data on soil textural class, rock fragment content, and organic matter content.

A few soil series for both states lacked estimates for organic matter (OM) for the surface horizon. Estimates were obtained from SCS scientists in Montana, Kansas, and other states responsible for the needed soil series descriptions.

Most of the soil series in both states were missing estimates of OM for subsurface horizons. An algorithm was generated for each state using the data from soil series that had complete profile data on organic matter (181 soil series in Montana and 326 soil series in Kansas). Figure 1 shows the regressions of OM concentration of an upper horizon *vs.* OM concentration of the horizon directly below it (*e.g.*, horizon 1 *vs.* horizon 2, horizon 2 *vs.* horizon 3, etc.). The regressions account for over 50% of the variation and are significant at $\alpha = 0.01$. The slope indicates that OM concentration decreases by a factor of about 0.45 from one horizon to the horizon below it. Although there were differences in OM concentration among soil series of different orders (Mollisols clearly have the highest OM concentration), there was no trend in the residuals of the

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

Soil classification		No. of soil series	Area		Soil series organic-C content			Total organic carbon	
Order	Suborder				arith-metic mean	std. dev.	area weighted mean		
			(km^2)	(%)	– – – – – (kg m^{-2}) – – – – –			(10^{12}g)	(%)
Alfisols		51	9500	4.6	7.9	4.0	6.4	62	2.2
	Aqualfs	8	2000	1.0	8.8	2.7	7.5	17	0.6
	Udalfs	26	1100	0.5	8.8	4.4	8.5	10	0.3
	Ustalfs	17	6400	3.0	6.2	3.5	5.6	36	1.3
Aridisols		7	1300	0.6	5.6	2.0	6.8	9	0.3
	Argids	6	1300	0.6	6.0	1.8	6.9	9	0.3
	Orthids	1	<100	0.0	3.1	–	3.1	<1	0.0
Entisols		70	16800	7.9	7.1	3.7	7.3	124	4.3
	Aquents	9	500	0.3	10.8	3.8	10.2	6	0.2
	Arents	1	<100	0.0	6.1	–	6.1	<1	0.0
	Fluvents	29	3500	1.7	7.6	3.6	7.6	27	1.0
	Orthents	20	9100	4.3	5.2	2.7	7.6	69	2.4
	Psamments	11	3500	1.7	6.5	3.5	6.1	21	0.7
Inceptisols		18	3200	1.5	6.1	4.6	5.1	16	0.6
	Aquepts	1	<100	0.0	2.9	–	2.9	<1	0.0
	Ochrepts	17	3100	1.5	6.3	4.6	5.1	16	0.6
Mollisols		271	180000	84.7	14.6	7.3	14.6	2633	91.9
	Albolls	4	200	0.1	17.5	6.7	21.8	5	0.2
	Aquolls	31	6500	3.1	18.6	8.8	14.6	96	3.3
	Udolls	80	37600	17.7	15.0	8.9	17.9	676	23.6
	Ustolls	156	135500	63.8	13.6	5.7	13.7	1856	64.8
Ultisols	Udults	8	<100	0.0	6.5	4.2	4.7	<1	0.0
Vertisols	Usterts	4	1200	0.6	16.5	10.6	15.2	19	0.7
All soils		429	212400	–	12.0	7.3	13.5	2863	99.9
Urban and rock outcrops		–	200	0.1	–	–	–	–	0.1

regression that could be attributed to differences among soil orders. The regression equations shown in Fig. 1 were used to estimate OM concentrations in those horizons where data were missing.

2.3. Spatial variation of soil parameters

Once area-weighted estimates were calculated for each STATSGO map unit for soil organic-C stocks, clay content, and drainage class, correlations were computed across all map units. Statistical analyses of these spatial data are complicated by possible spatial autocorrelation, which violates the assumptions of parametric statistical tests. Inflation of correlation coefficients can also occur when spatial data are aggregated (Fotheringham and Wong 1991). Moreover, the large sample size (*i.e.*, large number of mapping units within each state) causes rejection of the null hypothesis at a 95% confidence

Table 2. Areal coverage and organic carbon stocks by soil taxa in STATSGO for the state of Montana.

Soil classification: Order	Soil classification: Suborder	No. of soil series	Area		Soil series organic-C content: arithmetic mean	Soil series organic-C content: std. dev.	Soil series organic-C content: area weighted mean	Total organic carbon	
			(km^2)	(%)	----- (kg m^{-2})	-----	-----	(10^{12}g)	(%)
Alfisols		71	22200	5.8	7.6	3.8	6.5	144	5.2
	Aqualfs	1	100	0.0	7.4	–	7.4	1	0.0
	Boralfs	60	21500	5.6	6.8	2.8	6.2	134	4.9
	Ustalfs	1	< 100	0.0	7.8	–	7.8	0	0.0
	Xeralfs	9	600	0.2	13.0	5.6	15.3	9	0.3
Aridisols		136	59400	15.6	7.0	2.3	7.9	467	17.0
	Argids	67	21800	5.7	6.9	2.2	8.9	195	7.1
	Orthids	69	37600	9.9	7.1	2.4	7.3	273	9.9
Entisols		205	89200	23.4	7.2	4.6	5.4	479	17.5
	Aquents	14	1200	0.3	15.5	6.6	19.6	23	0.8
	Fluvents	71	14000	3.7	9.2	3.2	8.9	126	4.6
	Orthents	107	72800	19.1	4.8	3.0	4.4	324	11.8
	Psamments	13	1100	0.3	7.7	4.7	4.7	5	0.2
Histosols	Fibrists	5	300	0.1	70.2	25.1	75.5	20	0.7
Inceptisols		111	53500	14.0	8.0	4.8	6.1	326	11.9
	Andepts	8	2500	0.7	7.8	4.0	3.6	9	0.3
	Aquepts	7	600	0.2	15.1	5.7	17.5	11	0.4
	Ochrepts	90	49100	12.9	7.3	4.1	6.0	296	10.8
	Umbrepts	5	600	0.2	10.5	8.7	8.0	5	0.2
Mollisols		476	114700	30.1	12.2	7.6	10.8	1233	44.9
	Albolls	1	< 100	0.0	16.4	–	16.4	1	0.0
	Aquolls	34	1400	0.4	25.0	15.6	21.0	30	1.1
	Borolls	400	110500	29.0	11.2	5.6	10.6	1175	42.8
	Rendolls	1	< 100	0.0	3.6	–	3.6	0	0.0
	Ustolls	14	300	0.1	11.7	5.6	12.6	4	0.1
	Xerolls	26	2300	0.6	10.9	3.4	9.8	23	0.8
Spodosols	Orthods	3	200	0.1	6.6	2.4	8.4	2	0.1
Vertisols		18	11400	3.0	8.2	3.8	6.4	73	2.7
	Torrerts	1	< 100	0.0	5.2	–	5.2	0	0.0
	Usterts	17	11400	3.0	8.4	3.8	6.3	72	2.6
All soils		1025	350800	92.2	9.9	7.8	7.8	2744	100.0
Urban, rock outcrops, and badlands			29700	7.8	–	–	–	–	–

level even when the R-squared value of least squares regression is as low as 0.11. Hence, interpretation of statistical significance of these regression analyses must be viewed cautiously. Regressions that are statistically significant may not be ecologically significant when only a very small fraction of the variance in carbon stocks can be explained by covariation in clay content and drainage class. On the other hand, when there is ecologically significant spatial covariance between soil C stocks and related soil parameters, as revealed by the R-square values, then the regressions provide a useful and revealing tool, despite the ambiguity of the tests of statistical significance.

2.4. *FAO/UNESCO Soils Map of the World*

The FAO/UNESCO Soils Map of the World (FAO 1978–1981; Sombroek *et al.* 1993) is mapped at a scale of 1:5,000,000. A digital version is available, but it shows only the major taxonomic classes. The paper version at the same scale includes subclasses, and these were digitized by Woods Hole Research Center staff for Montana and Kansas. The area of each digitized polygon within these two states was calculated using GIS software. The FAO database also includes estimates of the area occupied by "inclusions" (FAO soil classes other than those for which the map unit is named) within each map unit class. The total area of each taxonomic FAO soil class was calculated by multiplying the area of each polygon by the fractions occupied by the dominant soil class and by the inclusions and summing these products for each soil class. Totals for each state were calculated by summing estimates for all polygons.

3. Results and discussion

3.1. *Tabular summary of soil organic-C stocks*

Mollisols cover about 30% of Montana and about 85% of Kansas (Tables 1 and 2). Mollisols constitute about 45% and 92% of the soil organic-C in Montana and Kansas, respectively. In Kansas, only Vertisols have organic-C contents as high as Mollisols, but the Vertisols cover less than 1% of the area. In Montana, Histosols, Aquents, and Aquepts also have high organic-C contents, and they also cover less than 1% of the area. Hence, none of the C-rich soils other than Mollisols cover a large enough area to significantly influence total organic-C storage in the soils of these two states. This result differs from a similar analysis of the STATSGO database of Maine (Davidson and Lefebvre 1993), where 5% areal coverage by Histosols was sufficient to account for about 1/3 of the total soil C storage of the state, whereas the more common Spodosols (65% of area of Maine) contributed only 39% of the soil C. The Maine data indicate that a relatively minor area (5%) of C-rich Histosols significantly affects calculations of soil C stocks, but the Kansas and Montana data indicate that these contributions are trivial below 1% areal coverage.

Presence of soils containing below average organic-C content is important in Montana, as it is in Maine (Davidson and Lefebvre 1993). The area-weighted mean organic-C content is only 7.2 kg C m^{-2} for Montana soils, whereas the arithmetic mean for all Montana soil series is 9.9 kg C m^{-2} (Table 2). The soils of Montana are diverse, with Aridisols, Entisols, and Inceptisols each covering over 10% of the area (Table 2). Quantitative estimates of the relative areal contributions of soils with below average C content are necessary for making reasonably accurate estimates of regional soil C stocks.

3.2. *Maps of organic-C, clay content, and drainage class scores*

The map of soil organic-C stocks of Kansas shows a trend of increasing soil organic-C from west to east (Fig. 2a), which generally corresponds to west-to-east gradients of increasing clay content (Fig. 2b) and decreasing drainage class score (Fig. 2c; a score of 1 is very poorly drained, while 7 is exsessively drained). These gradients also covary with a general west-to-east gradient of increasing precipitation (Burke *et al.* 1989; Jenny 1941). The outlines of some of the river drainage patterns can also be seen in both the carbon and drainage class maps of Kansas. Carbon-rich Haplustolls and Hapludults of aquic, cumulic, and fluvic subgroups occupy the river bank areas and are surrounded largely by entic, pachic, and typic subgroups of Mollisols with lower organic-C stocks.

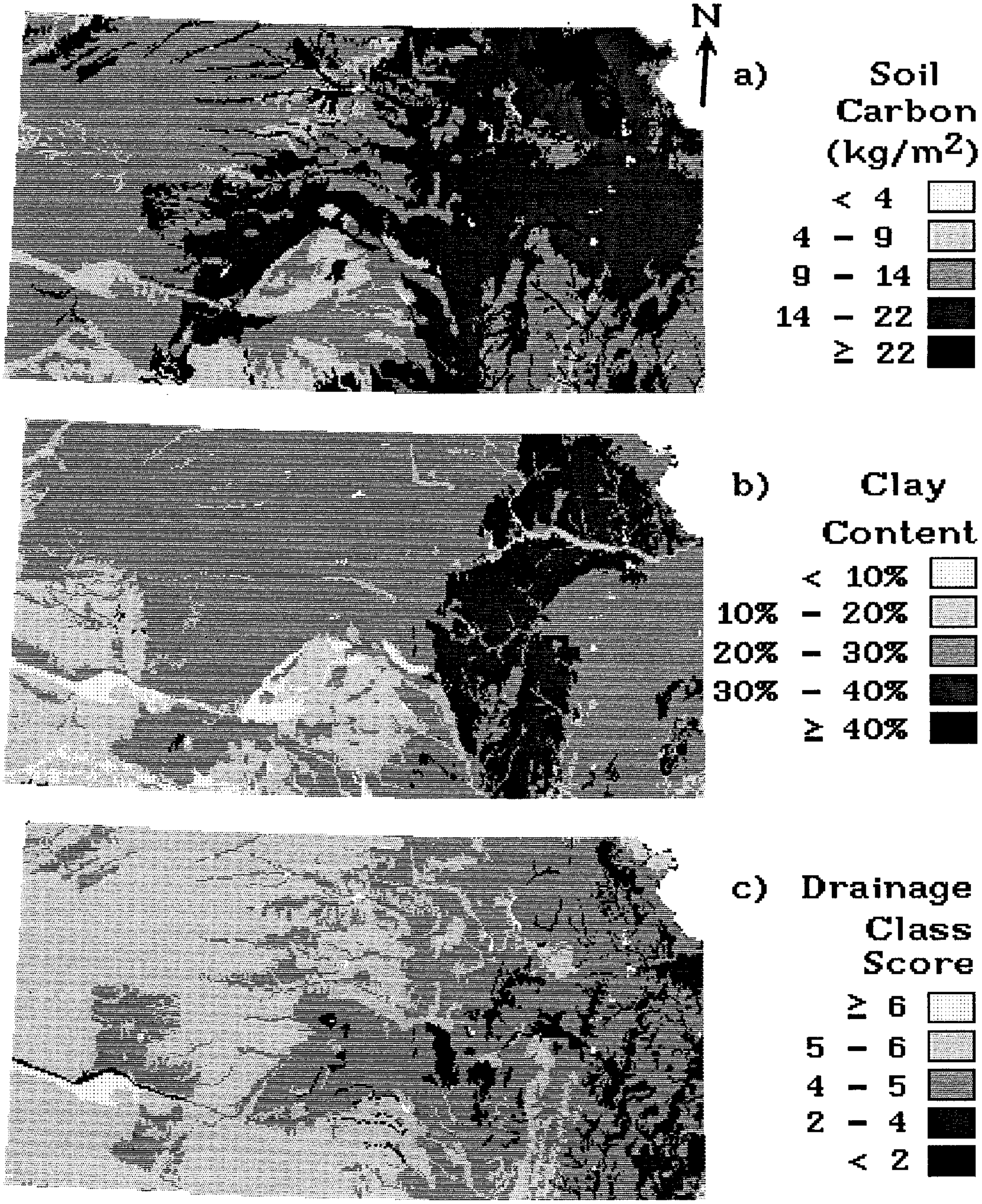

Fig. 2. Maps of Kansas generated from STATSGO: (a) soil organic-C stocks; (b) clay content of the surface horizon; and (c) drainage class score. Values of these parameters for each map unit are means of soil series weighted by their respective areal coverage within the map unit. Drainage scores range from 1 for very poorly drained soils to 7 for excessively drained soils.

The carbon map of Montana shows many small map units of high organic-C content scattered throughout the mountainous western region (Fig. 3a), and these C-rich map units in western Montana are dominated by Fluvaquents and Histosols that have low drainage class scores (Fig. 3c). In the eastern part of the state, the drainage class map reveals a few of the river drainage patterns, but many parts of the Missouri River and most of the Yellowstone River are not readily apparent in any of the

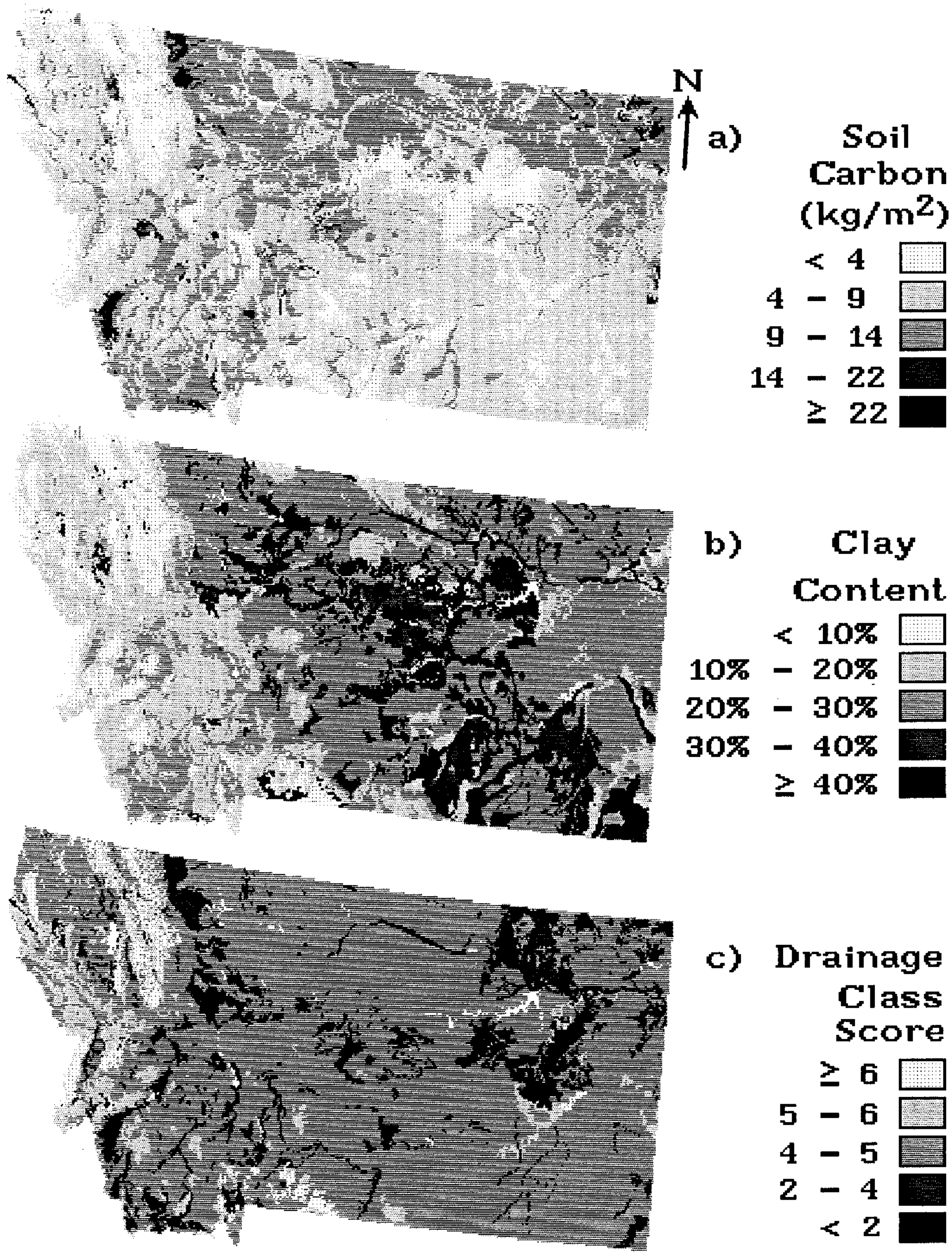

Fig. 3. Maps of Montana generated from STATSGO: (a) soil organic-C stocks; (b) clay content of the surface horizon; and (c) drainage class score. Values of these parameters for each map unit are means of soil series weighted by their respective areal coverage within the map unit. Drainage scores range from 1 for very poorly drained soils to 7 for excessively drained soils.

three Montana maps (Fig. 3a-c). These rivers are bordered primarily by Torrifluvents that generally are not significantly different from the soils that surround them with respect to organic-C stocks, clay content, and drainage class. The Borolls that dominate the northern wheat growing area have

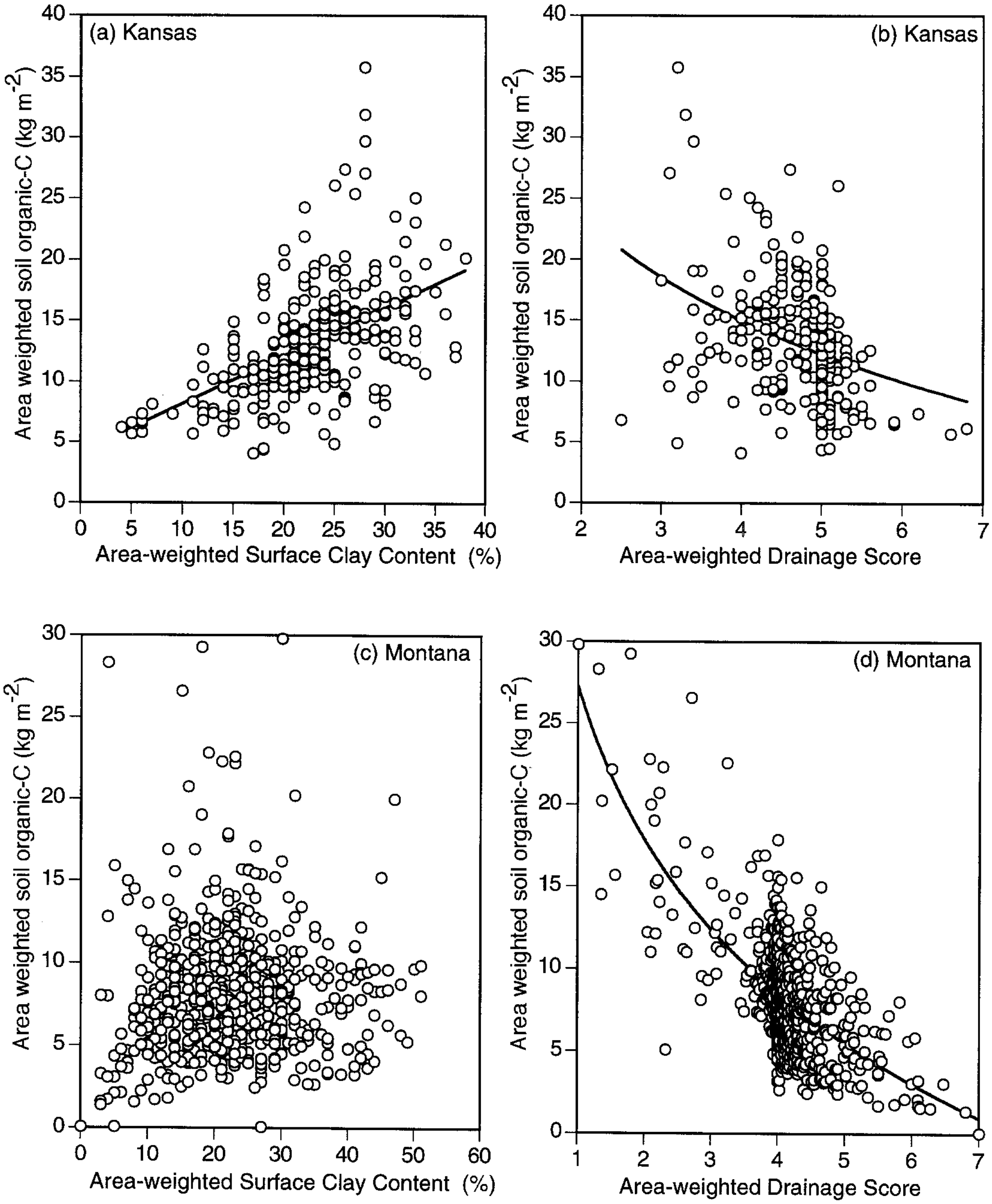

Fig. 4. The relation between clay content and organic-C and between drainage class and organic-C. For Kansas, organic-C = (0.40 × clay) + 4.1; $R^2 = 0.28$; $n = 274$ map units (a). Also for Kansas, organic-C = $(-28.6 \times \log \text{drainage}) + 32.2$; $R^2 = 0.13$; $n = 274$ map units (b). For Montana, organic-C is not correlated with clay content (c). Also for Montana, organic-C = $(-31.1 \times \log \text{drainage}) + 27.2$; $R^2 = 0.48$; $n = 692$ map units (d). Drainage scores range from 1 for very poorly drained soils to 7 for excessively drained soils.

more organic-C than do the Orthents that dominate the southeastern rangelands of Montana, but these two areas are not distinguished by differences in clay content or drainage class.

3.3. Spatial trends of soil parameters

The area-weighted organic-C content of each map unit was compared to the respective area-weighted clay contents and area-weighted drainage class scores. In Kansas, organic-C is positively correlated with clay content ($R^2 = 0.28$; Fig. 4a) and is negatively correlated with drainage class score ($R^2 = 0.13$; Fig. 4b). In contrast, organic-C content was not correlated with clay content in Montana (Fig. 4c), but was negatively correlated with drainage class ($R^2 = 0.48$; Fig. 4d). Multiple linear regression using both clay content and drainage class did not significantly improve the reduction in sums of squares over the best single parameter model in either state. Clay content of the surface horizon was used in the regressions shown, but similar results were obtained when clay content of the subsurface (usually B) horizon was used.

Other factors must also contribute to spatial variation in soil organic-C content, as the R^2 values for these regressions are all below 0.5. On the other hand, the regressions reveal that clay content is a stronger covariant with C stocks in Kansas than in Montana, and drainage class is a better covariant in Montana than in Kansas.

Nearly half of the variation in soil C stocks among map units of Montana can be attributed to drainage class, but the C-rich map units of Montana that contribute to a large reduction in sums of squares in regression analyses occupy only a small fraction of the area of the state. Little correspondence is evident between drainage class and organic-C stocks for large areas of eastern Montana (Fig. 3a,c). Drainage class is useful for distinguishing many of the excessively well drained Montana soils with organic-C stocks <4 kg C m^{-2} from poorly drained soils that have >14 kg C m^{-2}, but the map units dominated by moderately well and well drained soils (drainage scores 4 and 5) have a wide range of intermediate organic-C contents (Fig. 4d). On the other hand, clay content is not correlated with organic-C in Montana, and so drainage class remains the best state-wide indicator of organic-C for Montana.

The contrasting results for Kansas and Montana probably reflect the relative importance of Mollisols in the two states. Where Mollisols dominate, as in Kansas, organic-C stocks and clay content are correlated. Where other soils are common, such as Montana and Maine (Davidson and Lefebvre 1993), spatial variation in soil C stocks is not correlated with spatial variation in clay content. Instead, drainage class is the best indicator of the soil organic-C content in Montana and Maine, where poorly drained soils contain the highest carbon stores. Somewhat poorly drained soils also are indicative of soil C accumulation near river channels in Kansas.

The paradigm relating soil C with clay was developed in the American Great Plains where Mollisols are common (Jenny 1941; Parton *et al.* 1987; Burke *et al.* 1989). Soil models based largely on the clay-carbon relationship are being applied to regional and global extrapolations and to climate change scenarios (Parton *et al.* 1993; Potter *et al.* 1993; Schimel *et al.* 1994). The results of this and previous analysis of spatially explicit STATSGO data support the paradigm within the geographical region and biome where it originated (grassland soils of Kansas), but do not support it outside the region (forest soils of Maine and Montana). Clay has little role in soil formation, and hence accumulation of soil C stocks, in the largely forested Spodosols and Histosols of Maine. Montana includes both grasslands and forested mountain regions, and, overall, clay is not a good indicator of soil-C stocks of Montana. In these northern regions of the USA, it appears that soil wetness, as indicated here by drainage class, is the best index that distinguishes among soils with very high and very low organic-C content, presumably because of O_2 limitation of decomposition in wet soils. Protection from decomposition in clay microaggregates may be a general phenomenon affecting stabilization of SOM in most soils, but other factors, such as temperature, soil wetness, and aeration may exert stronger influences than clay content in many soils. This finding may have important implications if climate change affects precipitation, evapotranspiration, drainage patterns, and soil wetness. If mid-continental regions become warmer and drier, storage of C in soils may decline (Billings 1987).

3.4. Comparison of STATSGO and FAO databases

Equating soil taxa from the FAO map unit legend to USDA Soil Taxonomy (Soil Survey Staff 1975)

Table 3. Comparison of areas occupied by soil taxa calculated from STATSGO and the FAO/UNESCO Soil Map of the World for the state of Kansas.

Soil order (USDA soil taxonomy)	STATSGO area (%)	FAO soil taxa (FAO map legend)	FAO area (%)
Alfisols		Eutric Planosols	2.1
		Orthic Luvisols	0.1
		Chromic Luvisols	0.4
		Calcic Luvisols	1.3
	4.6	TOTAL	3.9
Aridisols	0.6		0.0
Entisols		Eutric Fluvisols	0.1
		Eutric Regosols	12.5
		Calcaric Regosols	0.5
	7.9	TOTAL	13.1
Inceptisols		Gleysols	<0.1
		Eutric Cambisols	0.8
	1.5	TOTAL	0.8
Mollisols		Mollic Planosols	0.1
		Gleyic Phaeozems	4.0
		Luvic Phaeozems	17.3
		Luvic Kastanozems	48.0
		Haplic Phaeozems	10.1
		Haplic Kastanozems	0.7
		Calcic Kastanozems	1.8
	84.7	TOTAL	82.0
Ultisols	<0.1		0.0
Vertisols	0.6		0.0
Urban and rock outcrops	0.1	Lithosols	0.2

taxa is imperfect and ambiguous. The system of Van Baren (1987) was used to match FAO taxa with appropriate USDA soil orders (Tables 3 and 4). Although matching with suborder and great group is possible, the matches become more circumspect as the specificity increases.

The matching shown for Kansas is remarkably good (Table 3). Both STATSGO and FAO databases show Mollisols occupying slightly over 80% of the area. The matching is less good for the more diverse soils of Montana, where the FAO map overestimates the areas covered by Mollisols, Alfisols, and Spodosols and underestimates the areas of Aridisols, Entisols, Inceptisols, Vertisols, and Lithosols (Table 4). Because Mollisols and Spodosols contain soil organic-C stocks that are above average for Montana (Table 2), using the areas from the FAO map to extrapolate state pedon data would cause an overestimation of statewide soil organic-C stocks by about 15%.

Although imperfect, this degree of disagreement for Montana is probably well within the range of other sources of uncertainty in global scale extrapolations of soils data (Eswaran *et al.* 1993). When taken with similarly good agreement for Maine (Davidson and Lefebvre 1993), the contiguous USA (Kern 1994), and Kansas (this study), these results should be interpreted as fairly encouraging. Rea-

Table 4. Comparison of areas occupied by soil taxa calculated from STATSGO and the FAO/UNESCO Soil Map of the World for the state of Montana.

Soil order (USDA soil taxonomy)	STATSGO area (%)	FAO soil taxa (FAO map legend)	FAO area (%)
Alfisols		Albic Luvisols	11.1
		Orthic Luvisols	0.0
		Orthic Solonetz	3.1
	5.8	TOTAL	14.2
Aridisols		Calcic Yermosols	0.1
		Haplic Yermosols	0.3
		Haplic Xerosols	0.8
		Luvic Yermosols	0.1
		Luvic Xerosols	3.1
		Solonchaks	0.1
	15.6	TOTAL	4.5
Entisols		Eutric Fluvisols	0.2
		Eutric Regosols	2.5
		Calcaric Regosols	16.4
		Dystric Regosols	0.1
	23.4	TOTAL	19.2
Histosols	0.1		0.0
Inceptisols		Eutric Cambisols	1.0
		Dystric Cambisols	2.4
		Mollic Gleysols	0.0
		Humic Cambisols	0.2
		Calcaric Gleysols	0.1
		Vitric Andosols	6.8
	14.0	TOTAL	10.5
Mollisols		Orthic Greyzems	0.3
		Luvic Chernozems	0.8
		Luvic Phaeozems	0.1
		Luvic Kastanozems	23.2
		Haplic Kastanozems	10.5
		Mollic Solonetz	1.3
		Calcic Kastanozems	0.0
		Haplic Chernozems	8.0
	30.1	TOTAL	44.2
Spodosols	0.1	Orthic Podzols	6.6
Vertisols	3.0		0.0
Urban, rock outcrops, badlands	7.8	Lithosols	0.9

sonable results can be obtained using a soils map at this coarse scale. If the 1:5,000,000 FAO map were greatly in error for the United States, then its use elsewhere would be extremely dubious. The degree of reliability of the FAO map unit designations is currently much lower for Africa, South America, and Asia (Richter and Babbar 1991). Efforts currently underway to improve the quality of the FAO

Table 5. Comparison of estimates of soil organic carbon stocks for Mollisols and grassland ecosystems.

Study	Soil/ecosystem type	Mean organic Carbon
		kg C m^{-2}
Eswaran *et al.* (1993)	Mollisols	13.1[a,b]
Kern (1994)	Mollisols of contiguous USA	12.1[b]
Kimble *et al.* (1991)	temperate Mollisols	9.1[c]
Post *et al.* (1982)	cool temperate steppe	13.3[b]
Schlesinger (1977)	temperate grassland	19.2[d]
This study	Montana Mollisols	10.8[a,d]
This study	Kansas Mollisols	14.6[a,d]

[a] area-weighted mean calculated from total C stocks divided by total area.
[b] to 100 cm depth.
[c] to 50 cm depth.
[d] variable depth as reported in profile descriptions of the database; usually includes C horizon.

map in these regions of the world (Sombroek *et al.* 1993) should also yield more reliable estimates of spatial distribution of soil C stocks.

These results also show, however, that the attribute data applied to various map units must be chosen with care. The area-weighted mean organic-C content of Mollisols is 14.6 and 10.8 kg C m^{-2} in Kansas and Montana, respectively (Tables 1 and 2). Using a single average for all Mollisols in the FAO map of North America, for example, would result in significant errors at the scale of individual states. Although regional errors might cancel in a global analysis, regional variation of soil C stocks and the factors that influence soil C would be obscured. Distinguishing at least among sub-orders improves regional estimates of regional variation in organic-C stocks.

Other published means for Mollisols or for temperate grassland soils that have been applied to regional and global extrapolations range from 9 to 19 kg C m^{-2} (Table 5). The low estimate results from including only the top 50 cm of soil (Kimble *et al.* 1991), and the high estimate results from a relatively small dataset strongly influenced by C-rich chernozems of the former Soviet Union (Schlesinger 1977). The intermediate estimates of Eswaran *et al.* (1993), Kern (1994), and Post *et al.* (1982) are means from large pedon databases that may be appropriate for global scale extrapolation, but more specific data are needed for regional extrapolations.

These results show that soil maps can be used effectively as a tool to calculate regional stocks of soil C and to study the spatial distribution of soil C stocks and related edaphic parameters. As layers in a GIS database, maps of soil C should also provide a useful basis for modeling the effects of changes in land use and climate on storage of C in terrestrial ecosystems.

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