Texture, climate and cultivation effects on soil organic matter content in U.S. Grassland Soils

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Texture, Climate, and Cultivation Effects on Soil Organic Matter Content in U.S. Grassland Soils

I. C. Burke,* C. M. Yonker, W. J. Parton, C. V. Cole, K. Flach, and D. S. Schimel

ABSTRACT

Soil organic C content, a major source of system stability in agroecosystems, is controlled by many factors that have complex interactions. The purpose of this study was to evaluate the major controls over soil organic carbon content, and to predict regional patterns of carbon in range and cultivated soils. We obtained pedon and climate data for 500 rangeland and 300 cultivated soils in the U.S. Central Plains Grasslands, and statistically analyzed relationships between C and soil texture and climate. Regression models of the regional soils database indicated that organic C increased with precipitation and clay content, and decreased with temperature. Analysis of cultivated and rangeland soils indicated that C losses due to cultivation increased with precipitation, and that relative organic C losses are lowest in clay soils. Application of the regression models to a regional climate database showed potential soil organic matter losses to be highest in the northeastern section of the Central Plains Grasslands, decreasing generally from east to west. These statistical data analyses can be combined with more mechanistic models to evaluate controls of soil organic matter formation and turnover, and the implications for regional management.

Soil organic matter is a major component of biogeochemical cycles of the major nutrient elements, and the quantity and quality of soil organic matter both reflect and control primary productivity. The amount of soil organic matter represents the balance of primary productivity and decomposition and as such is a sensitive and integrated measure of change in ecosystem function. Understanding the processes that control soil organic matter dynamics and their response to management is essential for informed use of agricultural land.

Jenny (1980) describes four sets of state factors responsible for the formation of soil organic matter, and illustrates the influence of parent material, time, climate, and biota as individual controls over soil properties. Controls over soil organic matter properties may have complex interactions; separate analysis of such controls may limit useful predictions. Parton et al. (1988) illustrate the use of a mechanistic model in evaluating simultaneously changing controls. Although such models can be highly successful, field data are necessary to validate predictions across complex gradients.

It is widely recognized that cultivation of grassland soils leads to depletion of soil organic matter (Alway, 1909; Russel, 1929; Hide and Metzger, 1939; Haas et al., 1957; and many others). Soil organic C losses of as much as 50% have been documented in the U.S. Central Plains Grasslands (Haas et al., 1957), with losses strongly dependent on management regime and regional location. The extent of soil organic matter depletion has been shown to depend upon the same variables as those controlling soil organic matter formation: climate (Haas et al., 1957; Honeycutt, 1986; Cole et al., 1989), soil texture (Tiessen et al., 1982; Schimel et al., 1985a), landscape position (Schimel et al., 1985a,b; Honeycutt, 1986; Yonker et al., 1988), and management regime (Janzen, 1987; Cole et al., 1988). An integrated assessment of soil organic matter losses across the U.S. Central Grasslands requires analysis of soils with varying temperature, precipitation, and soil physical properties.

The objectives of this paper were threefold: (i) to establish quantitative relationships between native soil organic matter levels in the Central Plains Grasslands and key driving variables: precipitation, temperature, and soil texture; (ii) to develop predictions of cultivation induced soil organic carbon loss as a function


of climate and soil texture; and (iii) to use these predictions to map potential soil organic C depletion.

METHODS
Description of the Database
Pedon data from the Central Plains Grasslands and adjacent areas were obtained from the National Soil Survey Lab. pedon database, USDA-SCS soil series investigations reports and our own field studies. In all, approximately 300 pedons representing cultivated soils and 500 pedons representing rangeland soils were analyzed. The pedon data were screened by taxonomic classification to exclude shallow soils, lithic subgroups, aquic suborders and aquic subgroups.

We calculated organic C and N concentration, sand, silt, clay and bulk density for the surface 20 cm from the raw pedon data. Bulk density was not provided for many pedons and was therefore estimated from particle size analysis and organic matter content (Rawls, 1983). Organic C and N mass were calculated by horizon and summed to a 20-cm depth.

Using U.S. Weather Bureau summaries (U.S. Dep. of Commerce, Weather Bureau, 1964), we calculated mean annual and growing season (April–September) precipitation and temperature for 600 sites throughout the Central Plains Grasslands. Climate data corresponding to each pedon location were associated with each pedon.

Statistical Analysis
We used all possible subsets regression analysis (BMDP6V, BMDP Statistical Software Manual, 1985) in a full quadratic model to find the best predictive equation for soil organic C and N. Range and cultivated data sets were treated separately. Regressions were run to find the best predictors, each with average percent organic C as the dependent variable. Independent variables in the sets were: (i) a temperature variable, either mean annual temperature (MAT) or mean growing season temperature (GRT); (ii) a precipitation variable, either mean annual precipitation (APPT) or growing season precipitation (GRPT); and (iii) one or two texture variables, either silt + clay as one variable, or silt and clay as two separate variables. In each case, the best temperature predictor was MAT, the best precipitation variable APPT, and the best texture relationships were with silt and clay separately. Good relationships with percent organic C were produced, with maximum R^2's of 0.59 and 0.56 for range and cultivated soils, respectively. Because C mass is more generally useful than percent C, all further regressions were run with C mass to 20 cm as the independent variable.

The final analysis entered MAT, APPT, silt, and clay in a full quadratic model (all dual crossproducts and single squares) to predict 20 cm organic C mass, run for cultivated and rangeland soils separately. The best regression equation was chosen based on the adjusted R^2 and Cp statistics (Draper and Smith, 1966), and our evaluation of variables and controls over soil organic matter. For example, the regression including silt × MAT and clay × MAT as interaction terms was not selected as “best” since the two terms have countervailing effects. The same statistical analysis was run for 20 cm organic N mass, with C included as a predictor.

Regional Analysis
Best regressions from the statistical analysis described above were used to predict soil organic C levels across the Central Plains Grasslands for both cultivated and rangeland soils. We used an extensive U.S. Weather Bureau database to represent regional variation, and set soil texture as a constant (20% clay, 40% silt, 40% sand) for this analysis. Results therefore are potential levels if all grasslands soils were loam soils. The S program (Becker and Chambers, 1984) was then used to interpolate contours for mapping the predicted soil organic carbon across the Central Plains Grasslands.

RESULTS AND DISCUSSION
Regression Results
The best equation from the all possible subsets regressions showed soil organic carbon to be a function of MAT, MAT^2, APPT, APPT^2, APPT × silt, and APPT × clay (Table 1). The most significant variables for both range and cultivated soils were MAT and MAT^2, as shown by their standardized coefficients. Neither silt nor clay was entered by itself as a significant predictor. For range soils, 51% of the variance was explained by the regression, and for cultivated soils, 54%.

Soil organic carbon in both range and cultivated soils decreased with MAT to about 17 °C, and then leveled off (Fig. 1). Because the best equation includes a quadratic effect of MAT, the model describes an increase in soil organic C above 18 °C, slight within our range of MATs. We consider this increase to be an artifact of the quadratic model. The decrease of C with MAT is supported by other studies that show organic matter decreasing with increasing temperature as a result of increased decomposition rates (Jenny, 1930; McDaniel and Munn, 1985). There was no difference between the range and cultivated regressions with respect to MAT; coefficients of MAT and MAT^2 were nearly equal in the two regressions.

Both cultivated and rangeland regressions showed a strong response of soil organic C to annual precipitation (APPT), with organic C increasing to about 80 cm, then leveling off (Fig. 2). Again, there is a decrease in C above 100 cm precipitation that may be an artifact of the quadratic model. The increase in organic C with precipitation reflects increases in plant productivity, hence C inputs. This agrees with recent work by Sala et al. (1988), showing nearly linear increases in productivity with increased precipitation (30–120

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Table 1. Best regression of soil organic C (kg m^{-2} to 20 cm) vs. mean annual temperature MAT in °C, annual precipitation (APPT in cm), silt and clay (%).

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Range soils</th>
<th>Cultivated soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>Standardized coefficient</td>
</tr>
<tr>
<td>MAT</td>
<td>-8.27 × 10^{-1}</td>
<td>-1.64</td>
</tr>
<tr>
<td>MAT^2</td>
<td>2.24 × 10^{-2}</td>
<td>1.17</td>
</tr>
<tr>
<td>APPT</td>
<td>1.27 × 10^{-1}</td>
<td>1.08</td>
</tr>
<tr>
<td>APPT^2</td>
<td>-9.38 × 10^{-4}</td>
<td>-1.02</td>
</tr>
<tr>
<td>APPT × silt</td>
<td>8.99 × 10^{-4}</td>
<td>0.44</td>
</tr>
<tr>
<td>APPT × clay</td>
<td>6.00 × 10^{-4}</td>
<td>0.21</td>
</tr>
<tr>
<td>Constant</td>
<td>5.15</td>
<td>0.00001</td>
</tr>
<tr>
<td>R^2</td>
<td>0.51</td>
<td>P &lt; 0.0001</td>
</tr>
</tbody>
</table>
cm) across the Central Plains Grasslands. We interpret the leveling off of soil organic C above 80 cm annual precipitation as the net effect of decomposition rates increasing as rapidly as production above 80 cm annual precipitation. There were differences between the range and cultivated regressions with respect to the influence of precipitation on soil organic C, with higher standardized coefficients for APPT terms for range than cultivated soil regressions (Table 1). The difference in the effect of precipitation could be due to influences of tillage and residue management on soil moisture and fertility.

The continuous predicted relationship among soil organic C, APPT, and MAT for a fixed texture is shown in Fig. 3a. This surface demonstrates that the APPT function was constant across all MAT values, and the MAT function was constant across all APPT's. Maximum predicted soil organic C was reached at APPT of about 80 cm, regardless of MAT, and similarly, minimum predicted organic C is reached at MAT of 18°C, for any APPT.

Silt and clay terms were included in the all possible subsets regressions as interaction terms with precipitation (APPT × silt and APPT × clay) (Table 1). Many investigators have documented the effect of texture on soil organic matter turnover processes. Clay has been shown to participate in the protection of soil organic matter from decomposition by adsorption and aggregation, slowing turnover and effectively increasing soil organic matter (Jenkinson, 1977; Sorenson, 1981; Paul, 1984; Schimel et al., 1985, 1986; O'Halloran et al., 1985). Increasing silt content also increases water holding capacity, so that soil texture interacts with climate in controlling ecosystem processes (Van Veen et al., 1983; Schimel and Parton, 1986). Texture effects via water availability may be important by influencing plant productivity, hence inputs to soil organic carbon. In our rangeland models, the APPT × silt term contributed more to the regression than the APPT × clay term, suggesting stronger regional correlation of soil organic C with silt than with clay. Predicted patterns of soil organic C across textures (Fig. 2) depend on the combination of silt and clay, so that clay and loam soils are similar, but sandy soils are predicted to have considerably lower organic C than the fine or medium textured soils. These results correspond to those predicted by Parton et al. (1987) using the CENTURY soil organic matter model.

![Fig. 1. Predicted relationship between mean annual temperature and soil organic C at set precipitation and texture in range and cultivated soils.](image1)

![Fig. 2. Predicted relationship between soil organic carbon and annual precipitation at a set temperature in clay (50% clay, 20% silt), loam (20% clay, 40% silt), and sandy loam (10% clay, 30% silt) soils. The difference between the range and cultivated organic C represents the predicted absolute soil organic C loss due to cultivation.](image2)

![Fig. 3. Predicted response surface of soil organic C to continuous, simultaneous variation in mean annual temperature and annual precipitation in range and cultivated soils for a set loam texture (20% clay, 40% silt).](image3)
Table 2. Best regression of soil N (kg m⁻², to 20 cm) vs. soil C (kg m⁻², to 20 cm), mean annual temperature, annual precipitation (APPT), silt and clay (%).

<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Range soils</th>
<th>Cultivated soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
<td>Standardized coefficient</td>
</tr>
<tr>
<td>Carbon</td>
<td>8.11 × 10⁻⁴</td>
<td>0.95</td>
</tr>
<tr>
<td>Clay</td>
<td>8.61 × 10⁻⁴</td>
<td>0.06</td>
</tr>
<tr>
<td>Constant</td>
<td>1.51 × 10⁻²</td>
<td></td>
</tr>
</tbody>
</table>

Because soil organic N was closely related to soil organic C in both data sets, C can be used to predict soil organic N. Clay was the only variable needed in addition to organic C to describe organic N to 20 cm (Table 2). The regression equations show a slight narrowing of C/N ratios from 10 in rangeland soils to 9 in cultivated soils. These results correspond with earlier work showing greater relative losses of C than N, and a gradual narrowing of C/N ratio with cultivation (Haas, et al., 1957; Honeycutt, 1986).

Cultivation Effects

Organic C loss due to cultivation can be calculated by subtracting the cultivated from the rangeland regression equations (Table 3). Since the data sets do not represent paired range and cultivated sites, we have no estimates of organic C loss per site, and no simple computation of error can be made, although the distribution of samples was similar. The regression equation indicated that absolute organic C loss increased with precipitation (net effect of APPT and APPT²) and silt content (APPT × silt), and decreased with temperature (net effect of MAT and MAT²), and clay content (APPT × clay). In general, predicted absolute organic C loss increases with total organic C content (Fig. 3b).

Several authors have documented the effects of precipitation and texture on organic matter losses due to cultivation. Honeycutt (1986) demonstrated significant increases in soil organic matter losses with increased precipitation, suggesting higher decomposition and erosion rates with higher precipitation. Tiessen et al. (1982) and Schimel et al. (1985a) have shown organic matter losses to be highest in medium textured soils.

Table 3. Regression equations predicting soil C and N losses (kg m⁻², to 20 cm) due to cultivation. Coefficients were determined by subtracting regressions for cultivated soils from regressions for rangeland soils.

<table>
<thead>
<tr>
<th>Soil organic C losses</th>
<th>Soil N losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent variable</td>
<td>Coefficient</td>
</tr>
<tr>
<td>MAT</td>
<td>-7.70 × 10⁻²</td>
</tr>
<tr>
<td>MAT²</td>
<td>1.40 × 10⁻³</td>
</tr>
<tr>
<td>APPT</td>
<td>6.89 × 10⁻²</td>
</tr>
<tr>
<td>APPT × silt</td>
<td>-4.8 × 10⁻⁴</td>
</tr>
<tr>
<td>Constant</td>
<td>-1.06</td>
</tr>
</tbody>
</table>

Predicted relative organic C loss expressed as percent of total soil organic C was calculated for soils of sandy loam, loam, and clay textures (Fig. 4). Clay soils, with the highest predicted soil organic C pools, have low predicted relative C losses (Table 3). Loams have higher predicted relative organic C losses, because the higher silt content increases losses, even though predicted total organic C is nearly the same as clay soils (Fig. 2). Sandy loam soils have the highest relative organic C loss, primarily because more of the organic matter is available to decomposers.

Regional Analysis

Figure 5a illustrates predicted levels of soil organic C across the Central Plains Grasslands for loamy soils. The results showed soil organic C increasing in the eastward direction, concomitant with increasing precipitation. Organic C was highest in the northeastern Central Plains Grasslands and lowest in the southwest, following increasing temperatures southward and decreasing precipitation westward.

Predicted trends in soil organic C depletion (Fig. 5c) suggest that there is no change in C loss with latitude, apparently because mean annual temperature affects soil organic matter similarly in cultivated and rangeland soils. There were, however, large changes in C loss with longitude, with greatest depletions predicted in the northeastern section of the Central Plains Grasslands. These results correspond with the findings of Haas et al. (1957), who showed lower absolute losses of soil organic C and N in Montana and Wyoming than in Kansas and Oklahoma.

Regional soil organic matter data bases are useful for validating regional ecosystem models. The soil C regression equation developed in this paper has been compared with the independently developed Century soil organic matter model (Parton et al., 1987) by simulating regional patterns of soil C for the soils with different textures in the Central Grasslands Region. Figure 6 shows a comparison of regression estimated soil C levels with simulated soil C levels for 56 sites.
Fig. 5. Regional patterns in soil organic carbon in range (a), and cultivated (b) loam soils (20% clay, 40% silt) as predicted from regression equations, using a regional climate database. Potential soil organic carbon depletion from cultivation of these loam soils is shown in (c).

(APPT ranging from 30–120 cm and MAT from 4 to 23 °C) in the Central Grassland with three different textures (sandy, loam, clay). In general, the simulation model and the statistical model output closely compared for C levels for rangeland soils in this region (C regression = -0714 + (1.18 × C simulated, $R^2 = 0.76$).

Recent work has indicated that management practices that decrease tillage and residue incorporation can reduce soil organic matter losses, and even increase soil organic C to a limited extent (Cole et al, 1988; Janzen, 1987; Holland and Coleman, 1987; Doran, 1980a,b). Our predictions do not account for new management practices that incorporate improved crop varieties, relatively new fertilizer technology, or various cropping, tillage, and rotation strategies. We anticipate that more detailed and mechanistic predictions for soil organic matter status in the Central Plains Grasslands must include specific information on the spatial patterns of management history and status. Predictions of future soil organic matter properties will most appropriately be integrated through a combination of mechanistic modeling and geographic information systems.

Extrapolation of the regression equations outside of the Central Plains Grasslands region is probably limited to the range of the independent variables used in our statistical model. In addition, statistical relationships are likely to be different in regions that are less generally N limited than is true for the Central Plains Grasslands. Mechanistic models, integrating more variables, are more likely to be applicable to distant regions, since the assumption that processes are the same across systems is better than that statistical relationships are the same across systems. Application of both statistical and mechanistic models to other regions is especially useful in extending and modifying our understanding of general controls over ecosystem processes.

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REFERENCES

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