SOIL STRUCTURE CHARACTERIZED USING COMPUTED TOMOGRAPHIC IMAGES

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ABSTRACT.—Fractal analysis of soil structure is a relatively new method for quantifying the effects of management systems on soil properties and quality. The objective of this work was to explore several methods of studying images to describe and quantify structure of soils under forest management. This research uses computed tomography and a topological method called Multiple Resolution Blankets (MRB) to quantify soil structure. Differences among the signatures of macro-pore scale soil density were explored in intact cores removed under forest canopies. The MRB topological signatures are better able to separate treatment differences than the box-counting method that has been used in the past. The use of these techniques to quantify the effects of forest management systems on soil structure is encouraged.

Recently fractals have been used to examine heterogeneity of several natural structures, such as sandstone and fracture surfaces. Fractal analysis is a technique to evaluate whether materials with irregular surfaces are self-similar for multiple scales. Non-fractal objects are not self-similar. Soil structure is composed of an irregular fabric. Packed soils are homogeneous and therefore might be non-fractal. Intact soils have heterogeneous surfaces and have the potential to be fractal. Management of soils may affect whether or not soil structure is fractal. Soil quality in terms of soil structure may be quantified by evaluating whether or not a soil is fractal.

There are different methods for measuring the fractal dimension *D*. Not all fractal methods explain soil structure equally well because of the limitations in image resolution, size, and the limitations of the specific fractal method. Gimènez (1995) and Ogawa (1998) used a box-counting method to analyze soil images. Both found that the fractal dimension *D* is highly dependent on the threshold value chosen when converting a gray scale image into a binary image. Ogawa (1998) suggested that the assumptions required for mathematical fractal objects were never perfectly met.

Obtaining a succinct representation of a natural heterogeneous object is challenging. A 3-D probability box-counting fractal analysis method has been used to study soil structure obtained from computed tomography (CT) images of soil density. This method avoids problems caused by conversion of gray scale images into binary images; however, the method is not sufficiently sensitive to separate different soil structures without errors (Zeng and others 1996).

Albregtsen and others (1992) compared three methods of 3-D fractal analysis to distinguish between normal and malignant cell structure. They found that the Multiple Resolution Blankets gave the best discrimination between the two classes of cells (Peleg and others 1984). Talibuddin and others (1994) also concluded that the performance of the MRB method was the most reliable and efficient method for fractal parameter estimation on small datasets. The MRB signature shows promise for distinguishing soil structure and has the potential for developing better parameters to distinguish and describe soil structure. Unlike other fractal methods, the MRB signatures can also provide additional information on soil pore and solid arrangements for soil structures that other fractal methods cannot. The structural information

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can be used to quantify both fractal and non-fractal objects. Therefore, the objective of this research was to explore several methods of studying images to describe and quantify soil structure.

MATERIALS AND METHODS

Soil cores were taken from the A horizon of a Menfro silt loam soil (fine-silty, mixed, mesic Typic Hapludalf). Four 76 mm long by 76 mm diameter intact soil cores were taken within selected 1 m^2 sites in both a forest and grass field. Four soil cores were uniformly packed with air-dried soil collected from a cultivated field passed through a 2-mm sieve but retained on a 1-mm sieve. Another four soil cores were uniformly packed with soil that passed a 1-mm sieve. The average bulk density of cores was 1.10 ± 0.07 Mg m^{-3} for forest soil, and 1.51 ± 0.03 Mg m^{-3} for grass soil and 1.40 ± 0.01 Mg m^{-3} for packed soil. Air-dried soil cores were CT scanned and then oven-dried to constant weight to allow determination of the bulk density.

Computed Tomography (CT)

The resolution of the CT scanner was 0.1- by 0.1- by 2 mm thick (voxel size- the three dimensional equivalent of a two dimensional pixel). The scanner units are in Hounsfield units. The numerical value in the Hounsfield unit depends on the attenuation coefficient of the material relative to the attenuation of water. Output of the Hounsfield unit can be converted to gray scale values to display as images.

Soil MRB Signatures

The MRB method is designed to allow the calculation of the gray-scale surface area (*A*) that is produced using a wide range of blanket sizes (*k*). The area of the pixel value surface measured at different blanket thickness ($k*\varepsilon$, where ε is a constant, and *k* is the blanket integer variable from 1 to an upper limit) will decrease at larger blanket thickness values. The gray-scale surface area is measured by calculating the volume between upper and lower blankets divided by 2ε. The SIG_C was calculated by finding the slope of the best fit straight line through the three points: *{[log(k -1), log (A(k -1))], [log(k), log (A(k)), [log(k +1), log (A(k +1))]}*.

The upper signature identified as SIG_U is derived from the higher gray scale values using the maximum operator to detect the surface characteristic of the higher value pixels. Lower fractal signature identified as SIG_L, is derived from the lower values and uses the minimum operator to measure the lower value pixels (Peleg and others 1984). These signatures ranged from 2.00 to 3.00. They were evaluated to measure the differences in the structural arrangements of soil cores. SIG_C was used to detect the heterogeneity and hierarchical nature of soil structure. SIG_U reflects the shape and size of pores, and SIG_L reflects the aggregates shape and size. Following the guidelines suggested by Talibuddin and others (1994), we set the lower limit of *k* as 10 and the upper limit of *k* as 40.

The difference between the MRB signatures from soil CT images were calculated using the following equation:

$$Dist(i, j) = \sum_{k=1}^{n} (SIG_{C_i}(k) - SIG_{C_j}(k))^2 \log\left(\frac{k + \frac{1}{2}}{k - \frac{1}{2}}\right)$$

For blanket integers of *k* = 10, 11, ...40, the smaller the difference between two soil cores based on their MRB signatures, the more similar the structures are and the more likely they can be grouped together (Cheng 2001).

RESULTS AND DISCUSSIONS

MRB Signature (SIG_C)

Figure 1 plots the average SIG_C vs. the blanket integer *k*. The shape of the SIG_C vs. *k* function for the packed cores had more strongly sloping curves with slopes of -0.0170 and –0.0120 compared to intact soil cores in the blanket integer of range from *k* = 10 to 40.

The average SIG_C slope of packed soil cores is about four times that of the intact soil cores (table 1). The intact soil cores had less sloping curves with slopes of -0.0043 and –0.0027. Images that have a constant SIG_C over the range of blanket integers are fractal. The signatures of all four soils were not flat lines.

For values of *k* ranging from 10 to 40, the SIG_C vs. *k* for the intact forest and grass soil cores was nearly flat indicating their density surface appears to be fractal within the range of *k* = 10 to 40 (fig. 1). For non-fractal objects, the SIG_C vs. *k* is characterized by variable SIG_C values and is represented by a sloping curve or line. The SIG_C of the density surface for packed soil cores indicated sloping curves; this indicated they were not fractal.

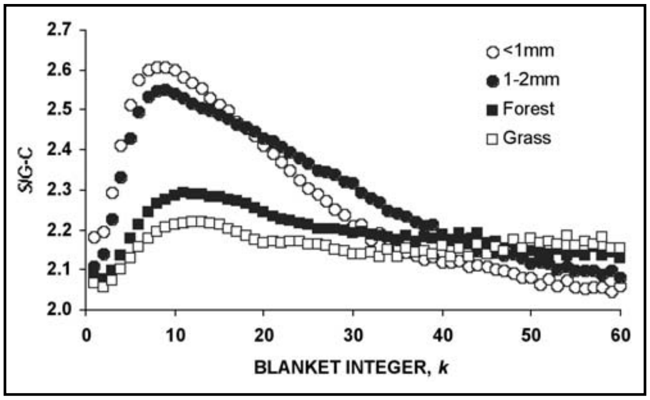

Figure 1.—*Average* SIG_C *signatures from MRB analysis used to detect the heterogeneity and hierarchical structure for intact forest and grass and packed soil cores.*

Figure 2 consists of two parts, a reproduced CT scan image, and a graph of the SIG_C vs. the blanket integer *k*. There were four replicated samples in each of the four groups. Variation among replicates in the < 1 mm packed core was the highest for the four treatments having a range in SIG_C of 0.17 at a blanket integer of 15 (fig. 2A). For the other three treatments, three of the four replicates had SIG_C values within 0.05 over the range of *k*. However, one sample replicate in each of these three treatments was more variable, having a variation value about 0.10 at a blanket integer of 15 (figs. 2B to 2D).

Soil aggregation may produce a fractal soil structure (Crawford and others 1993, Kozak and others 1996, Logsdon and others 1996). Soil densities measured by CT reflect the distribution of the soil aggregates. If aggregates are not fractal, their measured densities will not be fractal. Because packed cores have a smaller range in aggregate size relative to intact soil, these samples would be expected to be less fractal characteristics. This result agrees with the idea of Crawford and others (1993). They forward the idea that attempts to disintegrate aggregates sequentially through a clustered hierarchy, will not likely allow for a fractal model (packed soil). However, it is possible for intact soil to have a structure, which is fractal.

Lower Signature (SIG_L)

The average characteristic of the SIG_L was studied. Significant differences were found between graphs of the average SIG_L vs. blanket integer for soil cores from the four sources (fig. 3). The lower signature curve of packed soil looks like a bell, which increases sharply for short range distances (k < 9), then decreases more slowly at long range distance (k > 9).

The curve of the intact soil core, however, monotonically increases with a maximum value at the largest k = 40. The SIG_L value for the packed soil at high *k* was smaller. Peleg and others (1984) suggested that the SIG_L represents the shape and size of the aggregates and that the magnitude of the MRB signatures relates to the amount of details that are lost when the size of the measuring blanket passes *k*. Further, they suggest that high values of *MRB* signatures at small distance *k* result from significant high-frequency gray level variations while the high values for larger *k* result from significant low-frequency variations. Therefore, our results suggest that the aggregate sizes were smaller for the packed soil than for the intact forest or grass soil cores.

Upper Signature (SIG_U)

The shapes, but not the values of SIG_U, for the average upper signature SIG_U vs. blanket integer plots were similar for all four types of soil (fig. 4). The SIG_U reflects the shape and size of pores. The packed soil cores had high frequency variability across the lower range of blanket

Table 1.—*Average bulk density, multiple resolution blank signature values and fractal properties of soil from forest, grass, and packed cores*

Soil Core	Bulk Density Mgm^{-3}	slope of SIG_C	SIG_C MAX	SIG_C MIN	SIG_U MAX	SIG_U MIN	SIG_L MAX	SIG_L MIN	
<1mm packed	1.40	-0.017	2.61	2.02	2.59	2.03	2.62	2.04	non-fractal
1-2mmpacked	1.40	-0.012	2.55	2.06	2.55	2.06	2.55	2.09	non-fractal
Forest	1.10	-0.004	2.29	2.08	2.41	2.00	2.30	2.04	fractal
Grass	1.51	-0.003	2.22	2.05	2.37	2.00	2.39	2.02	fractal

Note: SIG values range from 2.00 to 3.00.

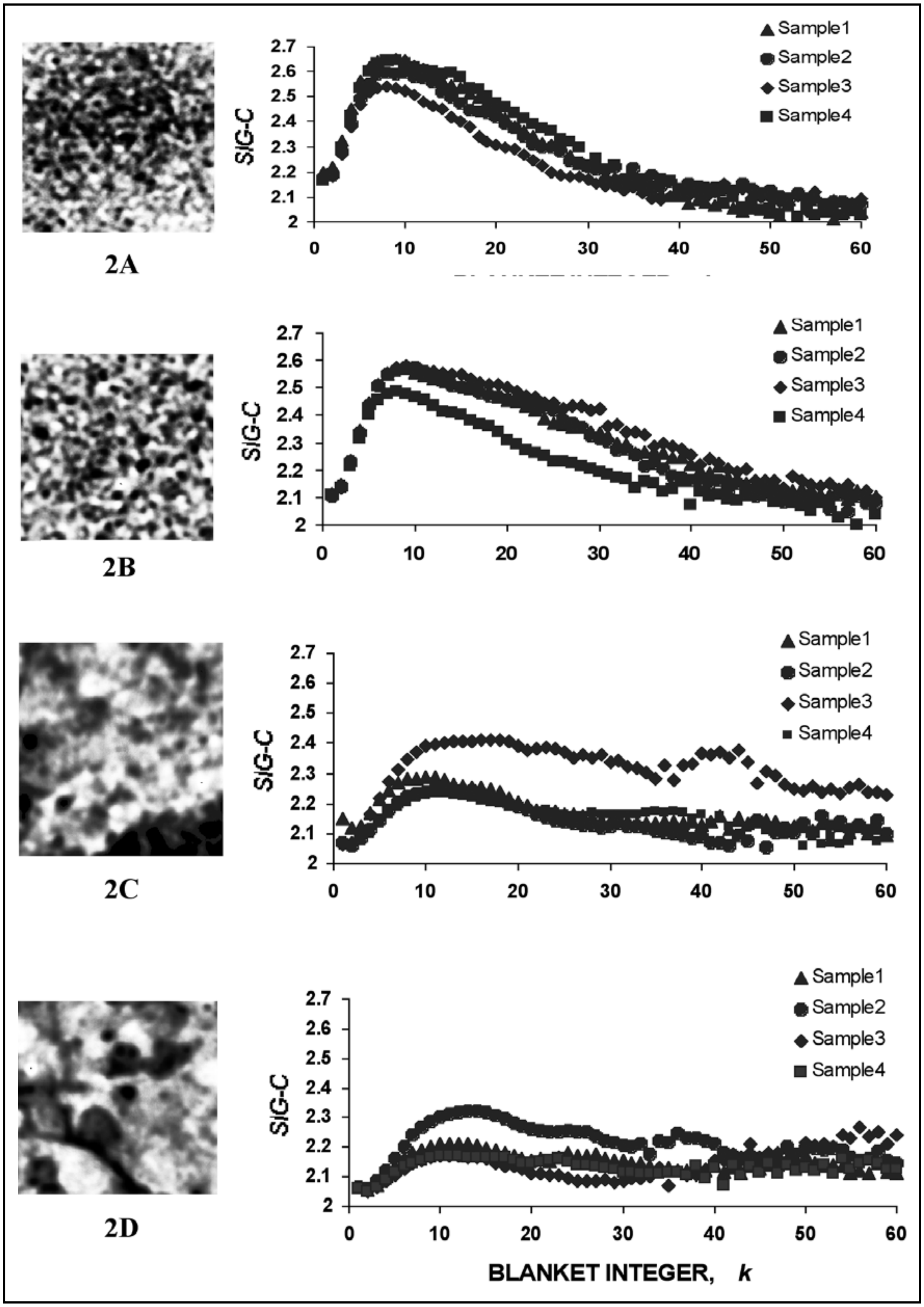

Figure 2.—*Average gray scale image and individual soil core* SIG_C *signature from MRB analysis of 256 by 256 pixel CT-images from packed soil cores (2A and 2B) and four intact forest (2C) and grass cores (2D).*

integer, indicating that the pore sizes in packed soil were smaller than pore sizes for intact soil.

Our results agree with results reported by Zeng and others (1996), indicating that the CT–measured soil density surfaces for the packed cores had peaks and valleys that are of high frequency. The intact soil cores had peaks and valleys that are of lower frequency. The average signature curve of grass and forest soil cores are almost overlapping, as are the signature curves for the two packed soil cores. These results suggest that the pore shape and size were different between classes (intact vs. disturbed soil) but similar within classes.

Soil Structure Difference Analysis

Calculated soil structure differences between the MRB signatures clearly separate the soil cores into groups for packed and intact soils (table 2). The only incorrectly classified image is the third replication for the forest soil cores, which fell into the packed 1 to 2 mm soil group. This misclassification may have been due to the high variability found in soils under forest management.

For each soil treatment, the three cores with the smallest soil structure difference occurred within the correct soil treatment only 50 percent of the time for < 1 mm soil cores, 58 percent of the time for 1 to 2 mm soil cores, 58 percent of the time for forest soil cores, and 42 percent of the time for grass soil cores. Therefore, this method is not suited for analyzing soil structure classification using CT images for similar classed soil structure. However, it still does a good job of separation between classes (disturbed vs. intact).

MRB vs. Box-Counting Method

Zeng and others (1996) used a box-counting method to estimate the fractal dimension (*D*) and lacunarity *C(L)* of the same images used in this study. They also used these parameters to evaluate soil density distribution of different soil groups. The box-counting method indicated that cores of all soil groups were fractal, when in fact, only the intact cores were found fractal with the MRB method. Plotting the fractal dimension against lacunarity *C(L)* using the box-counting method did not resolve soil cores into unique groupings (fig. 5).

Plotting the MRB signature values for SIG_C when k = 10 against the slope (change in SIG_C divided by change in k) clearly separated packed soil from intact soil (fig. 6). Good separation of intact cores from forest and grass soils is also achieved. This figure provides for an approximate graphical method of determining if the groups are distinct. As can be seen, the forest and grass soil and the packed soil are completely separated. Comparison with the classification using lacunarity and fractal *D* shows that the box-counting method is not as powerful as the MRB method (figs. 5 and 6).

CONCLUSIONS

Soil density of cores packed by single sized aggregates was found to be non-fractal, while intact soils show a fractal density distribution. The differences between soil structures with different treatments are caused by the aggregation size and shape differences. The structural difference measurement allows us to group soil samples that are similar. The MRB signatures are better able to separate treatment differences

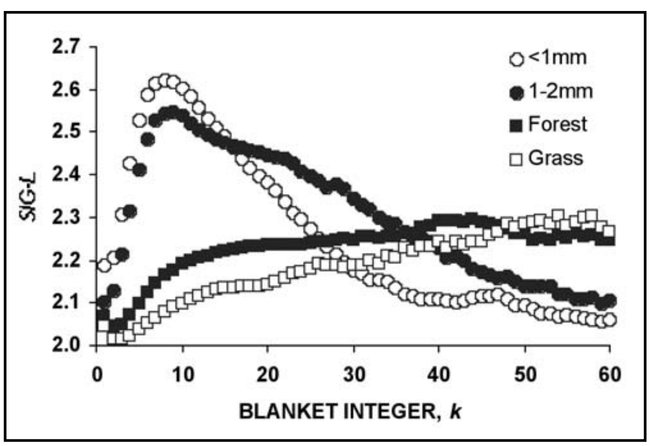

Figure 3.—*Average* SIG_L *signatures from MRB analysis used to describe the shape and size of aggregates for intact forest and grass and packed soil cores.*

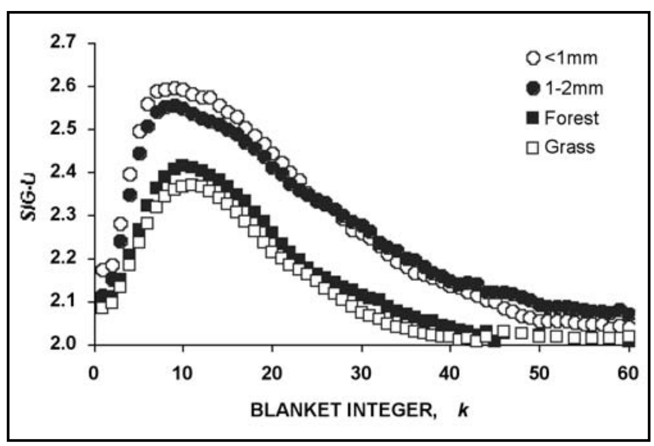

Figure 4.—*Average* SIG_U *signatures from MRB analysis used to describe the shape and size of pores for intact forest and grass and packed soil cores.*

Table 2.—*Calculated* MRB *soil structure distance between each soil core using SIG*$_C$ *for k = 10 to 40. Values for the three cores most similar to the sample core are underlined within each row.*

		TREATMENT															
Treat-		<1 mm Packed				1 - 2 mm Packed				Forest Intact Cores				Grassland Intact Cores			
ment	Smpl.	No.1	No. 2	No. 3	No. 4	No. 1	No. 2	No. 3	No. 4	No. 1	No. 2	No. 3	No. 4	No. 1	No. 2	No. 3	No. 4
<1mm	1	0.000	0.004	0.025	0.002	0.010	0.011	0.014	0.042	0.176	0.224	0.091	0.238	0.257	0.160	0.316	0.300
	2	0.004	0.000	0.010	0.007	0.005	0.005	0.011	0.021	0.128	0.170	0.060	0.182	0.198	0.114	0.250	0.236
	3	0.025	0.010	0.000	0.033	0.017	0.018	0.032	0.004	0.074	0.107	0.042	0.118	0.130	0.070	0.170	0.160
	4	0.002	0.007	0.033	0.000	0.009	0.009	0.009	0.049	0.188	0.237	0.090	0.250	0.269	0.167	0.332	0.314
1 - 2mm	1	0.010	0.005	0.017	0.009	0.000	0.000	0.003	0.023	0.124	0.164	0.044	0.173	0.189	0.104	0.244	0.226
	2	0.011	0.005	0.018	0.009	0.000	0.000	0.002	0.024	0.126	0.166	0.044	0.175	0.191	0.105	0.246	0.228
	3	0.014	0.011	0.032	0.009	0.003	0.002	0.000	0.038	0.151	0.194	0.053	0.202	0.220	0.125	0.281	0.260
	4	0.042	0.021	0.004	0.049	0.023	0.024	0.038	0.000	0.047	0.074	0.024	0.082	0.093	0.043	0.128	0.119
Forest	1	0.176	0.128	0.074	0.188	0.124	0.126	0.151	0.047	0.000	0.003	0.037	0.005	0.008	0.005	0.020	0.017
	2	0.224	0.170	0.107	0.237	0.164	0.166	0.194	0.074	0.003	0.000	0.054	0.001	0.002	0.009	0.008	0.006
	3	0.091	0.060	0.042	0.090	0.044	0.044	0.053	0.024	0.037	0.054	0.000	0.056	0.066	0.019	0.102	0.088
	4	0.238	0.182	0.118	0.250	0.173	0.175	0.202	0.082	0.005	0.001	0.056	0.000	0.001	0.011	0.007	0.004
Grass	1	0.257	0.198	0.130	0.269	0.189	0.191	0.220	0.093	0.008	0.002	0.066	0.001	0.000	0.015	0.004	0.002
	2	0.160	0.114	0.070	0.167	0.104	0.105	0.125	0.043	0.005	0.009	0.019	0.011	0.015	0.000	0.034	0.026
	3	0.316	0.250	0.170	0.332	0.244	0.246	0.281	0.128	0.020	0.008	0.102	0.007	0.004	0.034	0.000	0.001
	4	0.300	0.236	0.160	0.314	0.226	0.228	0.260	0.119	0.017	0.006	0.088	0.004	0.002	0.026	0.001	0.000

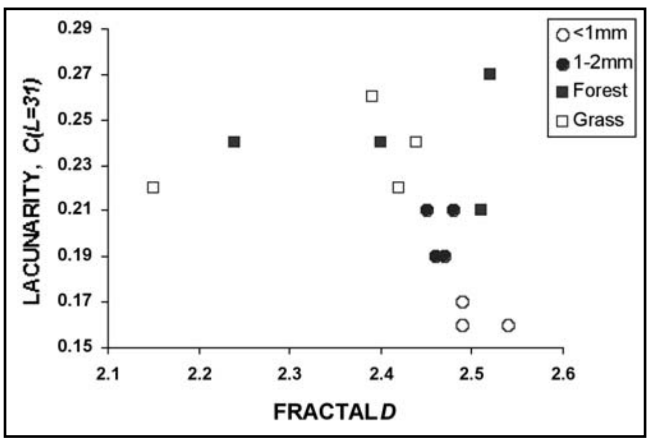

Figure 5.— *Fractal lacunarity, C(L), vs. fractal dimension,* D, *from intact forest and grass and packed soil cores (after Zeng 1996).*

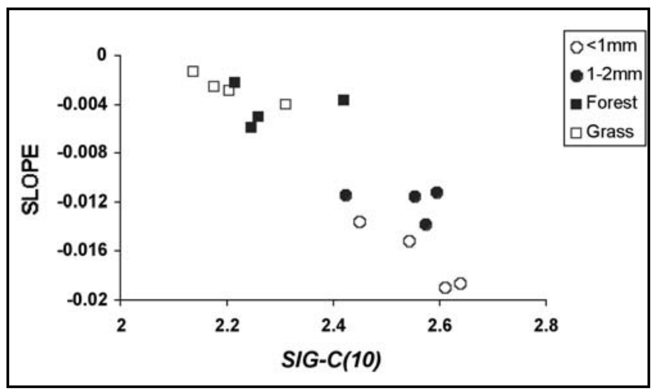

Figure 6.— *Slope of* SIG$_C$ *for blanket integer ranging from 10 to 40 vs.* SIG$_C$ *(10) value by* MRB *method from four groups of soil samples.*

than the box-counting method using graphical techniques. The MRB method showed greater discrimination between intact and sieved soil compared to the box-counting method.

The MRB parameters also provide additional information about soil structure. These parameters are related to size and distribution of aggregates and pores. This method can be used for both fractal and non-fractal images. Two different measures can be obtained, the upper and lower signatures, which provide measurement information on both the arrangement and the distribution of pores and solids. These measures appear to provide more information than the fractal *D* and lacunarity together (Albregtsen and others 1992, Talibuddin and others 1994, Zeng and others 1996). Future work is suggested for using these techniques in comparing the effects of forest management systems on soil structure.

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