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Development of a Soil Quality Index for the Chalmers Silty Clay Loam from the Midwest USA

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ABSTRACT

With the progressive degradation of agricultural soils, there is a new emphasis on using the concept of soil quality as a sensitive and dynamic way to document the conditions of soils, how they respond to management changes, and their resilience to stress. This study relates soil physical, chemical, and biological property changes under various long-term management systems. The study was conducted on an experimental field that had been under the same management systems for 16 years. There were 12 tillage and crop rotation combinations available for sampling. Sealing index, as a measure of aggregate stability, decreased with decreasing tillage intensity. However, infiltration rate was highest in the chisel plow system. Total C and N, microbial biomass C (MBC), particulate organic C (POC) and fluorescein released from enzyme activity, fluorescein diacetate (FDA) hydrolysis, were significantly greater in conservation systems as compared to conventional tillage practices. Tillage appeared to be the major contributor in the soil property changes with crop rotation effect being minor. Using soil erodibility as the baseline to develop a set of soil quality indicators, a standard scoring function enabled us to rate soil quality levels. Results showed that chisel plow system had higher quality level than no-till and moldboard plow while corn/soybean/wheat presented the lowest soil quality level among crop rotations. These results suggested that soil biochemical properties are potential indicators of soil quality with regard to soil erodibility.

INTRODUCTION

With the increasing degradation of agricultural soils, there is a great need for sustaining the soil resource base and enhancing soil quality. Soil quality can be defined as the degree of suitability to the specific functions that soils perform in a given system. In other words, soil quality is the capacity of the soil to promote the growth of plants; protect watersheds by regulating infiltration and partitioning of precipitation; and prevent water and air pollution by buffering potential pollutants (US National Research Council, 1992). The success of management in maintaining soil quality depends on our understanding of how soil responds to agricultural use and practice over time (Gregorich et al., 1994). Therefore, methods to quantify soil quality must assess changes in selected soil attributes over time. However, soil quality cannot be measured directly from the soil alone but is inferred from soil characteristics and behavior under defined conditions. Furthermore, there is no single measurement that can quantify soil quality (Stewart, 1992), but there are certain soil properties that when considered together can be good indicators. Some approaches to quantify soil quality are concerned with the characterization of different facets or attributes of quality (descriptive approach). Others are concerned with the identification of specific indicators or parameters that will assess the ability or capacity of an attribute to function in a desired manner (indicative approach). Quantifying soil quality requires that a data set be defined, comprising measures of various attributes or critical properties as key indicators (Larson and Pierce, 1991). To characterize soil quality over relatively short-time periods, these critical properties must be sensitive to changes in soil management, soil disturbances, and inputs into the soil system (Karlen and Stott, 1994).

The objectives of this study were to determine how the soil characteristics respond to long-term management and how could they be used as soil quality indicators.

MATERIALS AND METHODS

Description of the Site

The study was conducted in a long-term (16-yr) experiment (integrated pest management) field, located at the Agronomy Research Center at Purdue University, West Lafayette IN. The site was a 16.2 ha field of predominantly Chalmers silty clay loam (Fine-silty, mixed, superactive, mesic Typic Endoaquolls), with an initial pH of 6.4 and an OM content of 3.6%.

Management Practices

Three tillage systems were selected for a wide range of soil management. The most intensive was the conventional moldboard plowing, which completely inverted the top 15 to 18 cm of soil and left little crop residue on the surface. The intermediate tillage level was a fall chisel plowing that left approximately 30% cover of the previous crop residue on the soil surface. The third was a no-till system in which the crop was seeded directly into the previous crop residue with no soil preparation. This system left 90 to 95% cover of the previous crop residue on the surface. Row crops were cultivated once each season except in no-till. Tillage treatment for each whole plot always remained the same. The four rotation systems were continuous corn, continuous soybean, a two-year rotation between corn and soybean, with each crop grown each year, and a three-year rotation among corn, soybean and wheat, with each crop grown each

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year. The soil samples were collected after corn for corn/soybean and after wheat for corn/soybean/wheat rotations. Three levels of weed management were achieved by applying different amounts of herbicides. Only one weed management, the intermediate level, was considered in this study because it is the most typically used by farmers in the region.

Soil Sampling and Determination of the Soil Properties

The soil samples were collected during the early spring of 1995, prior to seedbed preparation. From each plot, two opposite sampling points along one diagonal were used for infiltration rate measurement. Each point was equidistant between one corner and the center of a plot. Around each infiltration point, four cores (0 to 7.5 cm depth) were taken using a soil probe for biochemical analyses, as well as four soil cores using a brass ring for bulk density measurement at the 0 to 7.5 cm depth, and four soil samples at the soil surface (0 to 5 cm depth) for aggregate stability. The soil samples collected were stored in an ice chest with ice and later, prepared as appropriate for analysis.

The infiltration rate was measured by water ponding method, using a 1 m^2 galvanized box with a 15 cm height. Measurements were taken over a two-hour period at increments of 2.5 or 5 min for the first 50 min and 10 min thereafter. Steady-state infiltration rates were calculated from the last five readings.

The soil resistance to penetration was determined in the field by a static penetration method using a cone penetrometer (Bradford, 1986). Like the soil sample collection, the soil penetrability was measured at each of the four sides of the infiltration points. The readings were done at 7.5 cm depth. The targeted positions were the row axes and the upper interrow shoulders while discernible wheel tracks were avoided.

The bulk density of the soil was measured to a 7.5 cm depth by the core method (Blake et al., 1986).

Soil aggregate stability was measured on wet and dry samples, using a Griffith fall velocity tube (Hairsine and McTainsh, 1986) as modified by Stott (1996). Soil aggregate stability was expressed by the sealing index of a soil. The sealing index (SI) is defined as the ratio of the wet to dry fall velocity at 50% mass (V_{50}) of the soil sample. The closer to 1 the sealing index, the more stable the soil aggregates. As the sealing index increases ($SI > 1$), the susceptibility of the soil to undergo surface sealing or slaking increases.

Total carbon and nitrogen were determined by dry combustion, using a LECO CHN-600 (Leco Corp., St Joseph, MI). Before analysis, presence of $CaCO_3$ in the soil was tested with HCl and there was none. Dissolved organic carbon (DOC) was measured using a Dohrmann DC-190. Particulate organic C was determined from the light-fraction and macro-organic matter of the soil (Strickland and Sollins, 1987). Microbial biomass C (MBC) was determined using the chloroform fumigation-incubation method (Horwath and Paul, 1994).

Fluorescein diacetate (FDA) hydrolysis was assayed as described (Schrüner and Rosswall, 1982; Diack et al., 1997)

The experimental design was a completely randomized block, in which the twelve treatment combinations were composed of four cropping systems and three tillages. Three field replicates were used as blocks, and in each block, we did two measurements for infiltration rates and eight measurements (four around each infiltration point) for the other soil properties.

Analysis of variance was run on the data to determine differences among treatments using the PC-SAS, Version 6.09.

Description of the Soil Quality Model

The model used to determine soil quality was primarily from Karlen and Stott (1994). To develop the model and rating of quality, they used the following approach for initiating the development of a soil quality index:

1. Set goals for high-quality soil;
2. Set criteria for high-quality soil in order to determine soil quality indices;
3. Rank criteria according to goals and definition of soil quality;
4. Give a weight to each parameter according to the rank of criteria;
5. Add up all weighted parameters to obtain a numerical value for a given soil.

The model has been modified as follows:

$$Q = q_{we}w_{we}+q_{wt}w_{wt}+q_{rpd}w_{rpd}+q_{rbd}w_{rbd}+q_{spg}w_{spg} \quad (1)$$

Where Q is the soil quality, q_{we} is the rating for accommodating water entry, q_{wt} is the rating for water transport and absorption, q_{rpd} is the rating for resisting physical degradation, q_{rbd} is the rating for resisting biochemical degradation, q_{spg} is the rating for sustaining plant growth, and w is the weighing factor for each function.

The criteria for a high-quality soil were based on the ability of the soil to partition water and regulate infiltration thus decreasing soil erodibility. The functions chosen for the soil quality indices were derived from the sensitivity analysis of the Water Erosion Prediction Project (Nearing et al., 1990b). A systems engineering technique was applied by Karlen and Stott (1994) to define a soil quality rating with regard to erosion by water, to provide a mechanism for assigning relative weights to each function. Potential indicators were assigned a priority or weight that reflects its relative importance. It has been suggested that the primary function of soil with high quality, relative to water erodibility, is to accommodate entry of the water into the soil matrix through the infiltration rate and capacity (Karlen and Stott, 1994). If the water can enter the soil, it will not run off, and thus will not initiate the erosion process. Based on this rationale, we suggest that this function be given a weight of 0.4. For water to be able to enter the soil matrix, facilitating its transport downward, away from the surface and absorption is assumed to be complementing the first function, with a weight of 0.1. The next most critical function, which is resisting physical degradation, has been assigned a weight of 0.25. The remaining 0.25 is assigned to the functions of resisting biochemical degradation at the soil surface (0.20), functions that can interact with sustaining plant growth (0.1). In this definition of soil quality, the ability of the soil to sustain plant growth is assumed to be less important than the process contributing to water entry and transport or to aggregate formation and stability.

After assigning relative weights to the functions necessary for a soil to resist water erosion, physical, chemical, and biological potential indicators, useful for evaluating those functions, are defined and prioritized. To quantify soil quality relative to the function of accommodating water entry into a soil, we use a direct measure of infiltration rate as the first function. With regard to facilitating water transport and absorption as a second function, bulk density and soil penetrability are used as indicators. The third and fourth functions, relative to decreasing crusting and resisting structural degradation, respectively, are closely related. While the third function is measured by the sealing index, the fourth one is measured by total carbon, dissolved organic carbon, soil carbohydrates, microbial biomass C and enzyme activity (FDA). The fifth function, as the ability of the soil to sustain plant growth, is much more dependent on the root system development through soil nitrogen and on reducing soil erodibility.

The standard scoring functions, used to combine the distinctly different functions and indicators were developed for solving systems engineering problems (Wymore, 1993). From the four most common shapes for scoring functions, we chose «more is better» as a goal for the soil quality level among tillages and among crop rotations.

Converting Soil Data to a 0-1 Scale

Soil data, to be used in scaling functions, needs to be converted to a zero to one scale. The converted soil data needs to be consistent with the statistical analysis obtained from the ANOVA, thus the procedure (Wymore, 1993) has been modified.

The set of scoring functions for the function f is defined as follows:

$$SFS(f) = FNS(RNG(f), RLS[0,1]) \qquad (1)$$

where SFS is the set of scoring functions for a given function, FNS is the set of functions, RNG is the range of functions, and RLS is the set of real numbers.

If A is a set of soil property data,

$\{s,t\} \subseteq RLS$ such that $s < t$, and

$f \in FNS\ (A,\ ONTO,\ RLS[s,t])$, then

$$g=\{(x,y): x\in RLS(s,t);\ y\in RLS[0,1];\ \ y=(x-s)/(t-s)\} \qquad (2)$$

therefore, for «more is better»,

$$y = (x - s) / (t - s), \qquad (3)$$

whereas, for «less is better»,

$$y = 1 - [(x - s) / (t - s)],\ for\ every\ x \in A. \qquad (4)$$

To be consistent with our approach and for the conversion of these soil data into a 0 to 1 scale, we used equation (3) i.e. «more is better» standard scoring function, for final infiltration rate, total C, dissolved organic C, total N, particulate organic C, microbial biomass C and enzyme activity. For bulk density, soil resistance to penetration, and the sealing index, the «less is better» scoring function was used with equation (4).

Using equation (3), $y = (x - s) / (t - s)$, where x and y are values of soil property converted into a 0 to 1; scale, s and t are real numbers chosen such that $s < x < t$.

To choose s and t values as real numbers, we have decided that s equal 0, the lowest possible value of the soil data and t be the highest soil property value among tillages or among crop rotations, plus 10% of that value. Therefore, equation (3) becomes

$$y = (x - s) / ([t + t/10] - s) = (x - s) / (1.1t - s) \qquad (3')$$

whereas, for equation (4),

$$y=1-\{(x-s)/([t+t/10]-s)\} = 1-\{(x-s)/(1.1t-s)\} \qquad (4')$$

RESULTS

Changes in Soil Properties

For bulk density (Tables 1 and 2), no significant differences in the mean values were observed among tillages or crop rotations. Soil resistance to penetration in no-till system (Table 1) was 92 and 148% greater than in chisel and moldboard plow systems respectively. Among crop rotations (Table 2), there was no significant difference in soil penetrability. The mean values for final infiltration rates were significantly different among tillages (Table 1) as well as among crop rotations (Table 2). Steady-state infiltration rate in chisel plow system was 115% greater than in no-till and 32% greater than in moldboard plow system. In crop rotation systems, final infiltration rates in continuous corn increased 20% over both continuous soybean and corn/soybean, and 56% over corn/soybean/wheat. Mean sealing index among tillage treatments (Table 1) was significantly different. In no-till, sealing index was 24% and 44% lower than in chisel and moldboard plow respectively. For continuous soybean, sealing index had 15, 21, and 24% decrease over corn/soybean/wheat, corn/soybean, and continuous corn respectively (Table 2), but the differences were significant only for the continuous soybean compared to other crop rotation treatments.

The mean concentrations for total C were not significantly different among tillage (Table 1) or crop rotation systems (Table 2). In no-till system, total C was only 13% greater than in moldboard plow and 7% greater than in chisel plow. In crop rotation systems, corn/soybean had mean concentrations for total C almost equal to that for corn/soybean/wheat rotation and continuous corn, and 7% higher than that for continuous soybean. Total N was significantly different among crop rotations (Table 2), but not in tillage systems (Table 1). For continuous soybean, total N was 15, 32, and 37% greater than for corn/soybean, corn/soybean/wheat, and continuous corn rotations respectively. Highly significant differences for dissolved organic carbon (DOC) among tillages (Table 1) and among crop rotations (Table 2) were obtained. Mean values for DOC in no-till were 40% greater than in chisel plow and 44% greater in moldboard plow. In crop rotations, DOC for corn/soybean/wheat was 27, 22, and 5% higher than corn/soybean, continuous soybean, and continuous corn respectively.

Microbial biomass C (MBC) has mean concentrations significantly different among tillage systems (Table 1) as well as among crop rotations (Table 2). MBC in no-till was 151 and 57% greater than in moldboard plow and chisel plow respectively. In crop rotations, MBC for corn/soybean were 18, 29, and 32% greater than continuous soybean, corn/soybean/wheat, and continuous corn respectively. Differences in mean values for fluorescein released from FDA hydrolysis were highly significant from one tillage system to another. Mean values of fluorescein released in no-till (Table 1) were 14 and 30% greater than in chisel and moldboard plow systems respectively. In crop rotations systems (Table 2), FDA hydrolytic activity in continuous soybean were not significantly different from that in continuous corn, but was 18% higher than both corn/soybean and corn/soybean/wheat rotations. Mean concentrations for particulate organic carbon (POC) were also significantly different among tillages (Table 1) as well as among crop rotations (Table2). In no-till, POC was 117 and 135% greater than in chisel and moldboard plow systems respectively. As for crop rotations, POC for continuous soybean was 64, 25, and 34% higher than continuous corn, corn/soybean, and corn/soybean/wheat rotations respectively.

Evaluation Mechanics of the Model

Within the same function (Tables 3 and 4), the sum of weighted indicators determines the level of that function. The sum of these functions indicates the level of soil quality. These results show that after such 16 years of management, chisel plow as tillage system with 62% level of quality, presents globally better conditions for the soil to resist erosion by water than no-till (50%) and moldboard plow (49%). As for crop rotations, continuous soybean (60%) and continuous corn (59%) seem to be more suitable practices than corn/soybean rotation (54%) and corn/soybean/wheat (48%) for the soil against erosion by water.

DISCUSSION

Except for bulk density and total C (Table 1) and bulk density and soil penetrability (Table 2), all other variables have shown significant changes under tillage and crop rotation systems. Final infiltration rate did make a big

Table 1. Ranges of soil properties for a Chalmers silty clay loam (West Lafayette, Indiana, USA) sorted by tillage treatment.

	Tillage mean		
Variable	**Moldboard Plow**	**Chisel Plow**	**No-Till**
Bulk density, g cm^{3}	1.41 ± 0.1 a	1.40 ± 0.1 a	1.38 ± 0.1 a
Soil penetrability, kgf cm^{-2}	1.24 ± 0.5 a	1.61 ± 0.6 b	3.08 ± 1.2 c
Final infiltration, cm hr^{-1}	2.06 ± 0.9 b	2.71 ± 1.3 c	1.26 ± 0.6 a
Sealing index	1.77 ± 0.4 a	1.52 ± 0.3 ab	1.23 ± 0.2 bc
Total C, g kg^{-1}	23.0 ± 0.6 a	24.4 ± 0.3 a	26.0 ± 0.4 a
Total N, g kg^{-1}	3.1 ± 0.1 a	3.0 ± 0.1 a	3.3 ± 0.1 b
Dissolved organic C, mg kg^{-1}	57.0 ± 16.1 a	58.6 ± 12.9 a	82.3 ± 16.2 b
Microbial biomass C, mg kg^{-1}	400.9 ± 121.0 a	643.9 ± 273.7 b	1008.0 ± 148.9 c
Fluorescein diacetate activity, µmol fluorescein g^{-1}h^{-1}	0.23 ± 0.05 a	0.27 ± 0.07 b	0.31 ± 0.05 c
Particulate organic C, g kg^{-1}	18.4 ± 0.4 a	20.0 ± 0.4 a	43.3 ± 1.4 b

Values within each row, followed by the same letter, are not significantly different, by Student-Newman-Keuls range test at *P* = 0.05.

Table 2. Ranges of soil properties for a Chalmers silty clay loam (West Lafayette, Indiana, USA) sorted by crop rotation.

	Crop Rotation means			
Variable	**Corn/Corn**	**Soybean/Soybean**	**Corn/Soybean**	**Corn/Soy/Wheat**
Bulk density, g cm^{3}	1.38 ± 0.7 a	1.41 ± 0.1 a	1.38 ± 0.1 a	1.40 ± 0.1 a
Soil penetrability, kgf cm^{-2}	2.08 ± 1.1 a	1.78 ± 0.7 a	2.16 ± 1.6 a	1.88 ± 0.8 a
Final infiltration, cm hr^{-1}	2.43 ± 0.9 b	2.03 ± 1.6 a	2.03 ± 1.0 a	1.56 ± 0.8 a
Sealing index	1.62 ± 0.3 a	1.31 ± 0.1 ab	1.58 ± 0.2 a	1.5/0 ± 0.2 a
Total C, g kg^{-1}	24.5 ± 0.3 b	23.4 ± 0.6 ab	25.1 ± 0.4 b	24.9 ± 0.4 b
Total N, g kg^{-1}	2.7 ± 0.1 a	3.7 ± 0.1 c	3.2 ± 0.1 b	2.8 ± 0.1 b
Dis. Organic C, mg kg^{-1}	70.51 ± 12.9 b	60.68 ± 14.2 a	58.43 ± 19.9 a	74.27 ± 23.3 bc
Microb. biomass C, mg kg^{-1}	614.46 ± 336.7 a	685.89 ± 314.7 a	808.46 ± 251.1 b	628.24 ± 338.7 a
Fluorescein diacetate activ., µmol fluorscein g^{-1}h^{-1}	0.29 ± 0.07 b	0.29 ± 0.09 b	0.25 ± 0.05 a	0.25 ± 0.04 a
Particulate organic C, g kg^{-1}	21.0 ± 0.7 a	34.5 ± 2.3 c	27.6 ± 1.1 b	25.8 ± 0.6 ab

Values within each row, followed by the same letter, are not significantly different, by Student-Newman-Keuls range test at *P* = 0.05.

Table 3. Soil quality functions, indicators, and ratings related to soil erodibility for a Chalmers silty clay loam (West Lafayette, Indiana, USA) sorted by tillage systems.

Functions	Indicators	Weights	Score		
			No-Till	Chisel Plow	Moldboard Plow
Accommodate water entry	Final infiltration rate	0.40	0.169	0.364	0.276
Facilitate water transport and absorption	Bulk density	0.05	0.005	0.005	0.005
	Soil penetrability	0.05	0.005	0.026	0.032
Resist physical degradation	Sealing index	0.25	0.092	0.055	0.023
Resist biochemical degradation	Total organic C	0.04	0.036	0.034	0.032
	Particulate organic C	0.04	0.036	0.017	0.015
	Dissolved organic C	0.04	0.036	0.026	0.025
	Microbial Biomass C	0.04	0.036	0.023	0.014
	Enzyme activity (FDA)	0.04	0.036	0.032	0.027
Sustain plant growth	Total N	0.05	0.045	0.041	0.043
	Total score	1.00	0.50	0.62	0.49

Table 4. Soil quality functions, indicators, and ratings related to soil erodibility for a Chalmers silty clay loam (West Lafayette, Indiana, USA) sorted by crop rotations.

Functions	Indicators	Wts	Score			
			C/C	S/S	C/S	C/S/W
Accommodate water entry	Final infiltration rate	0.40	0.364	0.304	0.304	0.234
Facilitate water transport and absorption	Bulk density	0.05	0.005	0.005	0.005	0.005
	Soil penetrability	0.05	0.006	0.013	0.005	0.011
Resist physical degradation	Sealing index	0.25	0.023	0.066	0.028	0.040
Resist biochemical degradation	Total organic C	0.04	0.035	0.034	0.036	0.036
	Particulate org. C	0.04	0.022	0.036	0.029	0.027
	Dissolved organic C	0.04	0.035	0.030	0.029	0.036
	Microb. Biomass C	0.04	0.028	0.031	0.036	0.028
	FDA activity	0.04	0.036	0.036	0.031	0.031
Sustain plant growth	Total N	0.05	0.033	0.045	0.039	0.034
	Total score	1.00	0.59	0.60	0.54	0.48

C/C = continuous corn; S/S = continuous soybean; C/S = corn/soybean; C/S/W = corn/soybean/wheat.

difference in the soil quality rating among tillage systems (Table 1). Furthermore, dynamic C variables such as MBC, DOC, FDA hydrolysis, and POC presented highly significant differences among tillages and to a lesser extent among crop rotations. Collins et al., (1992), found more than four times more MBC under grass pasture soil than wheat-fallow soil and Burke et al., (1995) found native grassland to have almost twice the microbial biomass pool as an adjacent cultivated field. Both of these observations were from long-term studies of 50 yr or more where there were significant differences in soil organic matter. These significant differences constituted the backbone for the sensitivity to these soil management practices and thereby for different levels of soil quality indicators. As microbial biomass C is strongly influenced by management practices and system perturbations (Smith and Paul, 1990), it provides an indication of a soils' ability to store and recycle nutrients and energy. MBC also serves as a sensitive indicator of change and of future trends in organic matter levels and equilibria (Gregorich et al., 1994). Due its dynamic nature, microbial biomass quickly responds to changes in soil management and soil perturbations (Carter, 1986) and to soil environment (Insam et al., 1989; Skopp et al., 1990; Duxbury and Nkambule, 1994). Studies using the MBC to total C ratio have demonstrated the utility of this index to monitor organic matter changes in agricultural systems (Carter, 1991; Sparling, 1992). The MBC to total C ratios of 2.6 in chisel plow and 3.9% in no-till fall in the high end of the expected range of 2 to 5% (Jenkinson and Ladd, 1981; Smith and Paul, 1990). However, for moldboard plow, the ratio (1.7%) is at the lower limit of the range. Although soil biological parameters are strongly affected by temporal variability, they may be most useful when comparing different management systems at one time period.

Usually, tillage is thought to decrease soil quality by promoting oxidation of organic matter, destroying soil structure and reducing biological activity even though no soil management is possible without some disturbance to soil. Indeed, the shift in management practices from conventional to conservation tillages combined with crop rotation has given the opportunity to evaluate changes in physical, chemical, and biological soil parameters for changes in soil quality. There is adequate knowledge of several critical soil processes, and the way soil cultural practices can alter them in order to make sensible decisions about improving management. However, we need to go further to explain in quantitative terms the impact of soil disturbance on soil quality, in the long term, so that the level of the management decisions can be upgraded. In other words, indicators of soil quality should respond in a quantitative way to the impacts of soil management practices, whether there are positive or negative.

CONCLUSION

The model developed has shown that by defining the potential indicators and assigning weights accordingly, one can quantify the level of soil quality under defined management practices. As tillage systems appeared to be the major contributor to the soil property changes, as compared to crop rotations, quantified responses of the soil in terms of quality to management practices were more significant with tillages than with crop rotations. The model has also demonstrated that with regard to tillage practices, chisel plowing this soil type seems to be the most appropriate system for long-term management because it developed the optimum equilibrium between soil organic matter accumulation, transformation and tillage intensity of the systems studied. This was in line with the problems with excess water observed in the no-till areas. Due to their greater and significant responses to different management practices, soil biochemical properties seem to be good indicators of soil quality with regard to soil erodibility.

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