CHANGES IN SURFACE SOIL PHYSICAL, CHEMICAL AND BIOCHEMICAL PROPERTIES UNDER LONG-TERM MANAGEMENT PRACTICES ON A TEMPERATE MOLLISOL

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Abstract
With the progressive degradation of agricultural soils, there is a new emphasis on developing methods that are sensitive to changes in the condition of soils 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 a 16-year experimental field where several tillage and crop rotation combinations were available. The 16-ha field site was located in West Lafayette, Indiana, USA. The dominant soil was classified as a fine-silty, mixed, superactive, mesic Typic Endoaquoll. The climate is temperate, with a continental pattern of summer rains, averaging 970 mm/yr. The sealing index, as a measure of aggregate stability, decreased with decreasing tillage intensity, while soil penetrability increased. However, infiltration rate was highest in the chisel-disk system, with the no-till system exhibiting the lowest rates of infiltration. Total carbon and nitrogen, microbial biomass carbon, cold-water extractable dissolved organic carbon, and the enzyme activities were significantly greater in conservation systems as compared to conventional tillage practices. Enzyme activities measured, including β-glucosidase, arylsulfatase, and fluorescein diacetate hydrolase, were sensitive to both changes in tillage and in cropping management with strong correlations with the physical parameters measured. This research shows that soil enzyme activities should provide a quick, sensitive indication of changes occurring in the soil physical structure.

Additional Keywords: carbon, enzymes, infiltration, sealing index, tillage

Introduction
Erosion by water is still a major cause of soil degradation, yet most soil quality work is done with relation to soil productivity rather than factors relating to the ability of a soil to withstand erosive forces. With the increasing degradation of agricultural soils, there is a great need for sustaining the soil resource base and enhancing soil quality. Historically however, soil quality has been equated solely with the soil's ability to promote plant growth (Stott *et al*., 1999). Undoubtedly, many of the factors will be the same for both soil functions, however the patterns of change may differ.

Most research on the interactions of soil biological and biochemical characteristics with tillage and cropping systems has been conducted on soils shortly after tillage operations have been done in the spring or fall, highlighting the changes due to tillage management, or during the growing season, which highlights the changes in the soil to crop influences. Of particular interest to us was the condition of the soil in early spring, before spring tillage; a time when, in our climate, soils are frequently subjected to erosive rains with minimal ground cover present for protection.

The objective of this study was to compare surface biological, chemical, and physical properties of various tillage and cropping systems in order to determine which biological or biochemical characteristics would best follow the changes in the physical characteristics that have some impact on erosion rates.

Materials and Methods
Field site
The study was conducted in a long-term (16 yr) experimental field, located in West Lafayette, Indiana, USA. The site was a 16.2 ha field of predominantly Chalmers silty clay loam (fine-silty, mixed, superactive, mesic Typic Endoaquoll), with an initial pH of 6.4 and an organic matter content of 3.6%.

Management practices
Three tillage systems were selected for a wide range of soil management. The most intensive was the conventional mouldboard ploughing, 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 ploughing that left about 30% cover of the previous crop residue on the soil surface after the fall primary tillage. 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 90-95% cover of the previous crop residue on the surface after the fall harvest. Row crops were cultivated once each season except in no-till. The

tillage treatment for each 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 year. The soil samples were collected after corn for corn/soybean and after wheat for corn/soybean/wheat rotations.

Soil sampling and analysis
The soil samples were collected during the early spring, before seedbed preparation. From each plot, two opposite sampling points along a diagonal were used for infiltration rate measurement. 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 on ice for transport to the lab and then prepared as appropriate for analysis. The 0-7.5 cm depth was chosen as the surface layer because there was evidence of natural horizontal break in the soil profile in the no-till management plots, distinguishing this layer as the surface A_1 horizon. Although the tilled soils had the typical A_p horizon, the same sampling depth was maintained for comparison purposes.

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 fall velocity tube, and was expressed by the sealing index of a soil (Norton and Dontsova, 1998). 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 C and N were determined by dry combustion, using a LECO CHN-2000 (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 by Green *et al*. (2004, submitted).

Statistical design
The experimental design was a randomized block, with each block consisting of twelve treatment plots combining the four cropping systems and three tillages. There were three replicate blocks. For each treatment plot, there were two infiltration measurements taken, and eight soil cores were taken, 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 8.00. Duncan's multiple range test was used to determine rather or not means were statistically different. The analytical results from the four cores were associated with the nearby infiltration point for all statistical analyses.

Results and Discussion
For bulk density (Table 1 and 2), no significant differences in the mean values were observed among tillages or crop rotations. Despite differences in tillage, consolidation occurred during the winter months, resulting in similar bulk densities in the early spring before tillage. Soil resistance to penetration in no-till system (Table 1) was 92 and 148% greater than in chisel and mouldboard plough 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 plough system was 115% greater than in no-till and 32% greater than in mouldboard plough 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 mouldboard plough 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.

Table 1. Ranges of soil properties for a Chalmers silty clay loam sorted by tillage treatment.

	Tillage means		
Variable	**Mouldboard Plough**	**Chisel Plough**	**No-Till**
Bulk density (g cm^{-1})	1.41 ± 0.1 a	1.40 ± 0.1 a	1.38 ± 0.1 a
Soil penetrability at 7.5 cm (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} soil)	23.0 ± 0.6 a	24.4 ± 0.3 ab	26.0 ± 0.4 ab
Total N (g kg^{-1} soil)	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, (μg fluorescein g_{soil}^{-1} h^{-1})	76.4 ± 16.6 a	89.7 ± 23.3 b	103.1 ± 17.0 c
Arylsulfatase (μg p-nitrophenol g_{soil}^{-1} h^{-1})	34.5 ± 2.4 a	45.8 ± 6.7 b	59.4 ± 4.2 c
β-Glucosidase (μg p-nitrophenol g_{soil}^{-1} h^{-1})	52.0 ± 3.3 a	66.0 ± 4.4 b	89.2 ± 4.9 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 Duncan's multiple range test at P=0.05.

Table 2. Ranges of soil properties for a Chalmers silty clay loam sorted by crop rotation.

	Crop Rotation means			
Variable	**Corn/Corn**	**Soybean/Soybean**	**Corn/Soybean**	**Corn/Soy/Wheat**
Bulk density (g cm^{-1})	1.38 ± 0.7 a	1.41 ± 0.1 a	1.38 ± 0.1 a	1.40 ± 0.1 a
Soil penetrability at 7.5 cm (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	1.50 ± 0.2 a
Total C (g kg $soil^{-1}$)	24.5 ± 0.3 a	23.4 ± 0.6 a	25.1 ± 0.4 a	24.9 ± 0.4 a
Total N (g kg $soil^{-1}$)	2.7 ± 0.1 a	3.7 ± 0.1 c	3.2 ± 0.1 b	2.8 ± 0.1 b
Dissolved 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
Microbial biomass C (mg kg^{-1})	614.5 ± 336.7 a	685.9 ± 314.7 a	808.5 ± 251.1 b	628.2 ± 338.7 a
Fluorescein diacetate activity (μg fluorescein g_{soil}^{-1} h^{-1})	96.7 ± 22.9 b	96.4 ± 28.6 b	83.1 ± 17.3 a	83.2 ± 14.6 a
Arylsulfatase (μg p-nitrophenol g_{soil}^{-1} h^{-1})	42.5 ± 6.8 a	53.3 ± 5.4 a	42.8 ± 6.9 a	47.6 ± 6.6 a
β-Glucosidase (μg p-nitrophenol g_{soil}^{-1} h^{-1})	50.3 ± 3.1 a	61.2 ± 4.2 a	79.6 ± 4.5 b	85.1 ± 4.6 b
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 Duncan's multiple range test at P=0.05.

The mean concentrations for total C were not significantly different among the crop rotations (Table 2), however, mouldboard was significantly lower in C than the no-till treatments, with the chisel-Disk system falling into an intermediate position (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 observed. Mean values for DOC in no-till were 40% greater than in chisel plough and 44% greater in mouldboard plough. 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 mouldboard plough and chisel plough 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 FDA hydrolase activity in no-till (Table 1) were 14 and 30% greater than in chisel and mouldboard plough systems respectively. In crop rotations systems (Table 2), FDA hydrolase activity in continuous soybean were not significantly different from that in continuous corn, but was 18% lower than both corn/soybean and corn/soybean/wheat rotations. When a step-wise regression analysis was run using infiltration as the dependent variable, FDA, along with total C and microbial biomass C, were the most significant variables. β-Glucosidase activity was significantly different in each of the tillage treatments, with the no-till being 72% and 35% greater than mouldboard and chisel-disk, respectively. These last two enzymes followed the changes in soil penetrability and Differences were also apparent in the cropping rotations, with the mono-cropping systems experiencing lower levels of β-Glucosidase activity than the two and three crop rotation systems. Similarly, arylsulfatase activity was found to be significantly different between the tillage treatments, with no-till being 72% and 30% greater than mouldboard and chisel-disk, respectively, while there were no significant differences between the rotations. Clearly the FDA, as an indicator of overall microbial activity, and β-Glucosidase as an indicator of the C-cycle, showed the ability to distinguish between tillage managements and to some extent, cropping systems.

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 mouldboard plough 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.

Conclusions

Tillage was the overriding factor in changes in surface properties, with more significant differences in surface characteristics than could be found between the cropping systems. In a step-wise regression, total C, FDA, and microbial biomass C were most strongly related to the changes in infiltration rate across all treatments. Clearly the FDA, as an indicator of overall microbial activity, and β-Glucosidase as an indicator of the C-cycle, showed the ability to distinguish between tillage managements and to some extent, cropping systems and are related to changes in some of the physical characteristics related to soil erodibility. While FDA followed changes in the infiltration rate, β-Glucosidase followed changes in soil penetrability.

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