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Soil structural stability assessment with the fluidized bed, aggregate stability, and rainfall simulation on long-term tillage and crop rotation systems

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ABSTRACT

The establishment of long-term tillage and crop rotations studies helps to investigate the cumulative effect and the long-term effect of management practices on soil properties, including those affecting soil health and water quality. In this study, a suite of techniques was used to evaluate the impact of a 28-year long-term tillage and crop rotations on soil structural stability parameters including soil cohesion, aggregate stability, and sediment loss. Fluidized bed experiments to estimate soil cohesion and aggregate stability tests were performed on samples collected from plots managed under chisel tillage (CT) and no-till practice (NT) and four rotations (continuous corn [*Zea mays*], CC; continuous soybean [*Glycine max*], BB; corn-soybean, CB; and soybean-corn, BC). At the same site, rainfall simulation experiments were conducted and sediment loss was correlated to fluidized bed and aggregate stability measurements. No-till practice had a positive effect on soil cohesion in the 0–15 cm soil layer; average pressure drop at fluidization (ΔP_f) values were 30.8 Pa for NT and 17.0 Pa for CT and a higher proportion of stable macroaggregates was present under NT practice (51.4% vs. 28.9%). In the 15–30 cm soil layer, aggregate stability measurements mimicked those of the surface layer for each tillage practice and crop rotation. In this study, we found no correlation between fluidized bed results and aggregate stability tests. The soil organic carbon content correlated to macroaggregates ($R^2 = 0.56$) and magnitude of cohesion ($R^2 = 0.51$). Corn residues were associated with improved aggregation in both surface and lower soil layers with respectively 18% and 13% more aggregates than soybean residues. Rainfall simulation experiments conducted on the sample sites revealed tillage effect on sediment loss patterns consistent with aggregate stability and fluidized bed measurement results. Chisel-tilled fields yielded 20 times more sediment loss than no-till fields. The effect of corn residue on aggregate stability resulted in 380 and 6.7 kg ha^{-1} less sediment loss under conventional and no-till practices, respectively.

1. Introduction

Through the U.S. Farm Bill, the implementation of conservation practices is encouraged to help the farmer while preserving the natural resources. The U.S. Department of Agriculture (USDA) Conservation Effects Assessment Project (CEAP) is a multi-agency endeavor to assess the implementation of conservation practices and programs and to develop new science-based conservation practices to improve soil health and water quality. Thus, the establishment of long-term tillage and crop rotations studies helps to investigate the cumulative effect and the long-term effect of treatments on specific soil properties, including those affecting soil health and water quality.

Conservation practices that improve soil health have been implemented in the U.S. Midwest for decades. These management practices are often evaluated through their influence on soil physiochemical properties. Tillage or the degree thereof has been extensively investigated for its influence on soil aggregation and resistance to erosion. Reduced tillage has been linked to improved aggregate stability, water storage, and soil organic carbon (Beare and Bruce, 1993; Khakural et al., 1992; Kladivko et al., 1986; Kushwaha et al., 2001). No-till farming practice has been linked to decreased soil erosion but much of the reduction has been attributed to the protection of plant residues on soil surface (Knapen et al., 2007). It is, however, implied that the benefit of no-till practice on soil properties such as soil organic carbon,

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aggregate stability, and soil moisture may increase soil erosion resistance (West et al., 1992). Crop rotation, as a conservation practice, is implemented to manage soil fertility and reduce soil borne diseases. Furthermore, crop rotations, through quantity and quality of plant residues, affect soil processes, including soil erosion (Schroeder, 1986), soil organic matter transformations, and aggregate stability (Martens, 2000).

In wet soils, the main forces keeping particles together are attributed to the surface tension at the air and water interface and cohesion (Kemper and Rosenau, 1986). If aggregates are dry and exposed to a fast-wet process, the aggregates' entrapped air is compressed, causing the disintegration of the aggregates (Barthès and Roose, 2002). Aggregate stability is influenced by several factors, including soil organic matter (e.g., Bird et al., 2002; Chenu et al., 2000; Igwe et al., 1995; Marinissen and Hillenaar, 1997) and soil particle size. Most studies found a beneficial effect of no-till agriculture on soil aggregate stability (e.g., Beare et al., 1994; Kladivko et al., 1986; Kumar et al., 2012; Pikul et al., 2009; Zuber et al., 2015). Some authors (e.g., Fernandez et al., 2015) have, however, found no statistical difference between no-till and strip-till practices on soil aggregate stability. When contact between particles increases, soil cohesion develops rapidly (Nouwakpo et al., 2014). The mechanical disruption of the soil during tillage practices may reduce bulk density and the effective contact between soil particles and aggregates, leading to lessened aggregate stability, of which may be used as assessment tool indicator for soil erosion susceptibility and represent erodibility in soil erosion modeling (Barthès and Roose, 2002), and in conjunction with soil organic carbon, as assessment tool indicators for land use sustainability (Carter, 2002).

Sediment loss measurement in the field is the most direct method of erosion resistance evaluation. Nevertheless, soil erosion measured insitu depends on field conditions prevailing at the time of measurement. Factors such as subsurface hydraulic gradient (e.g., Huang and Laflen, 1996; Romkens et al., 2001; Zheng et al., 2000), water quality and wetting rate (e.g., Shainberg et al., 2003), and initial moisture content (e.g., Mamedov et al., 2006) have been shown to directly affect measured erodibility. Rainfall simulation is an alternative technique to avert some of the above issues. In addition, this technique allows implementing treatments before the rainfall simulations, e.g. applications of fertilizers and pesticides.

The fluidized bed method for soil cohesion estimation (Nouwakpo et al., 2010) was developed to overcome the dependence of field erodibility measurement on extrinsic factors. The technique is based on the principle that soil erodibility has a fixed component that is a function of soil intrinsic properties and a variable component that fluctuates with field conditions (Nouwakpo et al., 2010). The technique has the potential to mechanistically link aggregate cohesion estimation to soil hydraulic properties such as the critical shear stress (Nouwakpo and Huang, 2012) and has been used to quantify cohesion development from aging and drainage conditions (Nouwakpo et al., 2014). In this paper, the fluidized bed, aggregate stability, and determination of sediment losses by rainfall simulations were used to estimate the effect of tillage and plant residue type on the soil cohesion. We hypothesized that type of tillage and crop residue affect soil structural stability and that both the fluidized bed and the aggregate stability methods gives similar results.

2. Material and methods

2.1. Site description

Soils used in this study were from long-term erosion plots (LTEP), located at the Throckmorton Purdue Agricultural Center, Purdue University, West Lafayette, IN, USA. The LTEP were established in 1983 to investigate the effect of tillage and residue type on soil erosion (Schroeder, 1986). In 1998, two of the tillage systems (ridge and moldboard tillage) were discontinued and these plots were converted to no-till and chisel tillage. With this new experimental design, each treatment has a duplicate: 2 tillage systems (no-till, NT and chisel tillage, CT) × 4 crop rotations (continuous corn, CC; continuous soybean, BB; corn-soybean, CB; and soybean-corn, BC) × 2 reps. In the U.S. Midwest, corn and soybean rotations are typical; i.e. CB (corn followed by soybean) or BC (soybean followed by corn); hence, the inclusion of these rotations in this study. However, the monocropping systems (continuous corn or soybean) are less common. Results in this paper are presented to show both the effect of crop sequence in a rotation (i.e. CC, BB, CB, BC) and that of short term crop residue prevailing at the time of sampling by combining CC and BC as corn residue and BB and CB as soybean residue.

The soils in these plots are associations of Mellot silt loam (Fine-silty, mixed, superactive, mesic Mollic Hapludalfs), Throckmorton silt loam (Fine-silty, mixed, superactive, mesic Mollic Oxyaquic Hapludalfs) and Octagon silt loam (Fine-loamy, mixed, active, mesic Mollic Oxyaquic Hapludalfs).

2.2. Soil samples

On May 22, 2014, soil samples were collected from each plot (~4.5 m wide × ~64 m long). To represent the zones where most root activity and nutrient uptake occur, about 10 soil cores were collected at 0–15 and 15–30 cm depths and composited to yield 16 composited samples (2 tillage × 4 crop rotations × 2 depths). Each composite sample was divided into two sub-sample sets; one set was air-dried, passed through a 2-mm sieve, and used for the fluidized bed study and chemical analysis. The other set of sub-samples was gently broken up and passed through an 8-mm sieve, and air-dried for the aggregate stability study. Soil properties and parameters determined in these soils are listed in Table 1.

2.3. Fluidized bed

Soil cohesion was determined by the fluidized bed procedure (Nouwakpo et al., 2014). Soil samples were sieved to 2 mm and packed into the fluidization chamber to a thickness of 50 mm. The packed soil was subjected to a pressure drop controlled by a water reservoir which was gradually increased at 4 mm increments throughout the experiment. The pressure drop within the packed soil sample was monitored with a differential pressure transducer. At each increase in pressure drop, the corresponding flow discharge was measured. Pressure head was incrementally increased until fluidization occurred. At bed fluidization, a sudden decrease in pressure drop (soil resistance) was observed which indicated the end of the experiment. The fluidization measurement was replicated three times for each composite sample.

2.4. Wet aggregate stability

Wet aggregate stability was determined by wet sieving 25 g of 8-mm sieved soil on four-nested sieves as described by Kemper and Rosenau (1986). In this study, macroaggregates were expressed as the fraction remaining > 0.25 mm after sieving; whereas the microaggregates were defined as the fraction passing the 0.25 mm sieve. Two duplicates were measure per composite sample.

2.5. Rainfall simulation study

Programmable, variable intensity rainfall simulations were performed to the 16 plots from the LTEP following the procedure used by Warnemuende et al. (2007). Briefly, two 2 m long × 0.75 m wide sub-plots were created and a runoff collection trough was installed at the down slope end of each sub-plot. The sub-plots had a mean slope of 1%. The rainfall intensity sequence (75, 25, and 100 mm h^{-1}) was designed to allow steady state of runoff to be achieved at several runoff rates and to represent a 200-year return period storm for the region.