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Quantitative soil profile-scale assessment of the sustainability of long-term maize residue and tillage management

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ABSTRACT

Both surface and subsoil layers can be a significant source of soil moisture and nutrients for crop growth, but the changes in subsoil properties due to management are rarely assessed. This study was conducted to determine tillage and residue management effects on soil nutrient availability, as well as soil biological and physical conditions throughout soil layers ranging from 0 to 60 cm. We utilized an experiment with 40-year long continuous maize (*Zea mays* L.) cropping under crossed plow-till (PT) vs. no-till (NT) and residue removed (Harv) vs. residue returned (Ret) treatments on a silt loam soil in Chazy, NY. We assessed soil properties that are indicative of soil processes important for crop growth. Soil physical indicators (texture, bulk density (BD), water stable aggregation (WSA), available water capacity (AWC), and air-filled porosity (AFP)), soil biological indicators (soil organic matter (SOM), permanganate oxidizable carbon, mineralizable carbon, and soil protein), and soil chemical indicators (pH and plant available nutrients) were measured at five depth increments (0–6, 6–18, 18–30, 30–45, and 45- to 60-cm depth). A novel statistical approach of marginal R^2 (R^2m) was used to show percent variance of each measured soil indicator explained by tillage and residue management as well as the depth of soil sample. R^2m was higher for soil biological indicators ($0.66 < R^2m < 0.91$), compared to AWC and those nutrients that are not applied through fertilizer application ($0.11 < R^2m < 0.53$). NT-Ret showed the highest concentration of majority of the measured soil nutrients, and higher accumulation of SOM related properties across depths. This was partly explained by favorable soil physical conditions indicated by BD, WSA, and AFP at the transition layer (18- to 30-cm depth) that allowed for the vertical exchange of soil water, nutrients, and SOM related properties between the topsoil and the subsoil layers. The PT treatments showed the absence of SOM transfer across the transition layer, whereas NT-Harv showed nutrient depletion at the transition and subsoil layers. This study revealed significant alteration of soil biological, chemical, and physical indicators depending on the treatment combinations, which can be ignored if surface sampling is solely used. Benefits of residue return appear more significant when combined with no-till for 1) providing better soil physical conditions and 2) maintaining adequate nutrient availability across a soil profile especially when considering subsoil properties.

1. Introduction

The health of soils impacts their ability to perform critical functions, including the support of crop growth. In rainfed agriculture, limited or excessive amounts of soil moisture during critical growth stages are important regulators for yield levels and yield stability (Calviño et al., 2003), and subsoil layers (> 30 cm depth) have been identified as an important source of soil moisture (Ewing et al., 1991; Gaiser et al., 2012; Kirkegaard et al., 2007) and nutrients (Carter and Gregorich, 2010; Gransee and Merbach, 2000; Heming, 2004). Distinct soil microbial communities may also be present in subsoil layers compared to surface layers due to unique nutrient dynamics, soil physical properties, and redox potential (Fischer et al., 2013; Leininger et al., 2006), and can be a sink for a large amount of soil organic carbon (SOC; Batjes, 1996). However, limited attention has been paid to the effects of land management on subsoil soil properties even with this recognized importance of subsoil functions (Baker et al., 2007; Rumpel and Kögel-Knabner, 2010).

One such land management technique is the removal of crop residue. In recent years, the use of crop residue has been debated due to increasing demand for biofuel production (Lal and Pimentel, 2007), and a US-wide assessment indicating that less than 28% of maize (*Zea mays* L.) residue can be collected sustainably (Graham et al., 2007). Any management change in the amount of biomass and nutrient removal

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from a field needs to be evaluated carefully. Many of current evaluations are constrained by factors including i) the depth of soil sampling, and ii) particular focus on a narrow set of soil measurements. For fields under crop production, tillage practices are known to significantly affect the vertical distributions of SOC, and no-till (NT) showed to have higher SOC stocks in the surface layer (0–10 cm) while moldboard plow (PT) treatments have higher stocks in the deeper layers (20–40 cm) across eight sites of varying soil types in eastern Canada (Angers et al., 1997). The assessment of residue removal under NT solely in the topsoil may miss potential depletion of SOC in the subsoil layer, which have been found to rely on the exchanges to and from topsoil via plant root systems and soil fauna (Kautz et al., 2013), and dissolved SOM by preferential flow (Rumpel and Kögel-Knabner, 2010). Under PT systems, assessment of soil physical conditions at the interface between the plow layer (cultivated soil layer) and the subsoil may also be important to determine whether the vertical exchange of SOC is not restricted (Peigné et al., 2013).

Although SOC is a fundamental property related to numerous soil functions and an important component of global C cycle (Magdoff and van Es, 2009), it does not fully address the changes in soil conditions for plant growth, nor does higher SOC necessarily mean higher crop productivity (Sojka et al., 2003). There is a need to assess how the changes in the vertical distribution of SOC through residue removal impact the soil's biological, chemical, and physical conditions, important for crop production, across the soil profile. In recent years, combinations of soil measurements including i) soil biological assessment of total and labile components of soil organic matter (SOM), ii) soil physical assessment of water stable aggregation (WSA), available water capacity (AWC) and soil strength, and iii) soil nutrient and pH indicators have been shown to be important in determining yield constraints, and have been utilized as a soil health or soil quality test (Idowu et al., 2008; Karlen et al., 2001; Schindelbeck et al., 2008). Such a set of measurements has been successfully applied to detect aspects of soil degradation caused by tillage (Moebius-Clune et al., 2008; Van Eerd et al., 2014) and land use change (Moebius-Clune et al., 2011). Aziz et al. (2013) assessed the effects of 5 year tillage and crop rotation on soil quality and showed NT to have higher soil microbial biomass and activity, total C and N, permanganate oxidizable C (POXC), WSA, and particulate organic matter compared to PT in 0- to 30-cm depth on a silt loam soil. The evaluation of the interactions among soil biological, chemical, and physical properties also helps to determine the mechanisms behind the changes in soil conditions due to particular soil and crop management practices. Therefore, there is a need to utilize soil health test framework across the soil profile to thoroughly assess the effects of residue and tillage management.

This study was conducted on 40-year continuous maize experimental plots with tillage and maize residue management treatments. Our hypothesis is that PT creates a root growth-restricting layer that does not allow the effective movement of residue-derived organic materials and nutrients through the subsoil. Also, we hypothesize that the absence of residue return causes unfertilized nutrients to become depleted, especially from the deeper soil layers where the amount of root residue is lower.

The objective of this study was to investigate the degree of impacts of surface tillage and crop residue management on surface as well as subsurface layer soil conditions using soil physical, chemical, and biological indicators.

2. Materials and methods

2.1. Study site

The study site is located in Chazy, NY (44°53′N, 73°28′W) to test the effects of tillage (PT vs. NT) and residue management (residue returned (Ret) vs. residue harvested (Harv)) in two by two factorial design. Each plot (6 by 15.2 m) was arrayed in randomized complete block design with four replicated plots for each treatment combination.

The experiment was established in 1973 after many years of continuous mixed grass sod (SOD) while the periphery was maintained as SOD. Continuous maize cropping was maintained during the experiment, and a maize hybrid with maturity class of 85–90 days was planted. Fertilizer management consisted of banded application of 17 kg N ha^{-1}, 67 kg P_2O_5 ha^{-1}, and 67 kg K_2O ha^{-1} at the time of planting. In addition, a side-dress application of 140 kg N ha^{-1} was added when the maize plants were between V5 and V7. Weed management in the recent years consisted of pre-emergence herbicide applications of an S-metolachlor, atrazine, and mesotrione mixture followed by glyphosate early in the growing season depending on the level of weed pressure. The PT plots were moldboard plowed at a depth of 15–20 cm (Ramsey, 1984) and disked annually in the fall, and maize was planted in the spring; while the NT plots were not tilled and planted with a NT planter (Idowu et al., 2009).

All the experimental plots share one soil series: Roundabout silt loam (Aeric Endoaquept: coarse-silty, mixed, active, nonacid, frigid; Soil Survey Staff, 2015). The soil was formed from medium-textured glaciolacustrine and glaciomarine deposits of Wisconsin Age on the Lake Champlain Plain, near Plattsburgh, NY. According to the Official Series Description, surface 18 cm is in Ap horizon, 18–43 cm in Bw, 43–66 cm in Bg, 66–76 cm in BCg, and 76–165 cm in C horizon (Soil Survey Staff, 2015). The soil is poorly to somewhat poorly drained, and the plots are tile drained to the depth of 100 cm at the spacing of 15.24 m.

2.2. Soil sampling

Soil sampling was undertaken in July 2013 with two subsamples at two locations within each experimental plot in non-traffic inter-rows of maize away from field edges. A soil sampling probe (ST-104, Giddings Machine Company Inc., Windsor, CO) was used, which provided the actual soil sample, 3.81-cm in diameter. The soil sampling probe was inserted to the soil continuously to 60-cm depth using a tractor-mount hydraulic powered soil sampler (GSRTS; Giddings Machine Company Inc., Windsor, CO) while making sure that no soil compaction occurred by visually checking the soil surface through the view slots of the sampling tube. The collected soil samples were cut in 0–6, 6–18, 18–30, 30–45, and 45- to 60-cm increments and subsamples were mixed thoroughly. The first two increments were generally in the Ap horizon, the third and the fourth in the Bw horizon, and the last increment in the Bg horizon. Five additional samples were taken in SOD using the same equipment, which was in the periphery of the experimental plots and was trafficked by farm machineries regularly. The soil samples were kept at 4 °C until analysis.

2.3. Soil analysis

Whole soil samples were weighed to estimate percent field soil moisture content and a subsample was subsequently weighed again, after being oven-dried at 105 °C, to determine dry sample weight. Dry soil bulk density (BD) was determined based on the volume of sample, dry sample weight, as well as calculated volume of rock fragments (> 2 mm), which were sieved from the whole soil sample and converted from mass to volume based on standard rock density (2.65 g cm^{-3}). Soil texture was assessed using a rapid quantitative method developed by Kettler et al. (2001). The soil sample was dispersed with 3% sodium hexametaphosphate ($(NaPO_3)_n$). A combination of sieving and sedimentation steps was used to separate size fractions. WSA was assessed using soil samples that were dried at 40 °C. A rainfall simulator (Ogden et al., 1997) that allows the soil particles to receive the impacts of known rainfall energy was utilized, applying 2.5 J of energy for 300 s on aggregates (0.25–2 mm) placed on a 0.25-mm mesh sieve. The fraction of soil aggregates remaining on the sieve, corrected for stones > 0.25 mm, was regarded as the percent WSA after drying at