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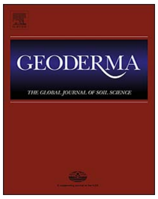

Moisture absorption by plant residue in soil

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ABSTRACT

Oil incorporated plant residues are an important source of carbon inputs and its decomposition defines magnitudes of many soil processes. While soil properties, especially soil moisture levels, influence decomposition rates, the moisture level of plant residue itself can differ from that of the surrounding soil due to the so called "sponge effect"-water absorption by plant residue from the surrounding soil. Our study explored whether water absorption by plant residue varies depending on soil moisture and matric potential levels; and how soil characteristics and characteristics of the plant residue itself affect the magnitude of this effect. We examined water retention of two types of plant residue materials, namely, corn and soybean leaves, in soil materials with three contrasting particle size distributions (PSD); and analyzed water distribution patterns in the soil adjacent to the residue using X-ray computed micro-tomography. The results demonstrated that the sponge effect was especially pronounced when soil moisture levels ranged from 0.15 to 0.40 cm^3 cm^{-3} (~30–80% water filled pore space). The leaves were fully saturated with gravimetric water content levels exceeding 2.0 g g^{-1} even when the soil moisture level was only 0.15 cm^3 cm^{-3}. Subsequent increase in residue moisture level was achieved due to vertical swelling of residue and reached 3.0–4.0 g g^{-1} at soil moisture levels $>$ 0.30 cm^3 cm^{-3}. The sponge effect was greater in the coarse textured soil materials with lower soil water retention than in the fine textured soil material with high water retention; it was greater in soybean than in corn, possibly due to greater porosity of soybean leaves. Our results indicate that plant residue fragments incorporated into soil likely create moisture microenvironments for microbial decomposers that differ from those of the surrounding soil; and which, in relatively dry soil, can be more beneficial for plant decomposition than what can be inferred from the information on moisture levels of the soil itself.

1. Introduction

Incorporation of plant residues in soil is an important contributor to soil fertility and sustainability. The use of agronomic practices that involve plant residue incorporation is continuously growing worldwide (Lal, 1997). Such practices, e.g., the use of green manures and cover crops, increase soil carbon sequestration, improve soil hydraulic properties, and reduce erosion (e.g. (Miguez and Bollero, 2005; Scholberg et al., 2010)), as well as potentially contribute to mitigation of greenhouse gas emissions (Liebig et al., 2012).

One of the key factors in defining C sequestration benefits as well as greenhouse gas emissions from soils subjected to plant residue incorporations is plant residue decomposition. Decomposition rates are affected by environmental factors, such as soil temperature, soil water content/potential, O_2 supply, pH, inorganic nutrients (Swift et al., 1979), by residue's size and contact with soil (Fruit et al., 1999; Garnier et al., 2008), and by properties of the residue, such as C:N ratio, lignin content, etc. (Gunnarsson et al., 2008).

The effect of soil moisture is of particular importance for plant residue decomposition as it affects production and activity of microbial extracellular enzymes (Sardans and Penuelas, 2005; Sardans et al., 2008; Alarcon-Gutierrez et al., 2010), which are the main drivers of decomposition processes (Sinsabaugh and Moorhead, 1994; Moorhead and Sinsabaugh, 2000; Smart and Jackson, 2009; Waring, 2013). Decomposition is typically the highest when soil moisture levels are within 50–60% of water filled pore space (WFPS), a condition known to be optimal for microbial growth and metabolic activity (Sommers et al., 1981). Lower decomposition rates are expected both in soils drier and wetter than the optimal WFPS range. However, despite an overall understanding of the mechanisms by which soil moisture influences plant residue decomposition (i.e. controlling motility, transport and activity of microorganisms, gas and nutrients fluxes in pore space, connectivity

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Abbreviations: WFPS, water filled pore space; PSD, particle size distribution

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between pores populated by microorganisms and residue location, etc.), published results on relationships between soil moisture levels and decomposition remain controversial. Some studies report no decomposition response to water additions (Steinberger et al., 1990; Li et al., 2016a), while others observe positive response (Strojan et al., 1987; Austin and Vitousek, 2000; Yahdjian et al., 2006; Setia and Marschner, 2013; Li et al., 2016b). Among proposed explanations for the discrepancies are differences in soil texture and structure of the studied soils (Adu and Oades, 1978; Gunnarsson et al., 2008), as well as masking effects of temperature, e.g. (Howard and Howard, 1979).

An additional emerging explanation is a possibility that moisture level of plant residue can differ from that of the surrounding soil. Kravchenko et al. (2017) recently brought attention to this phenomenon, reporting that plant residue located in soil with 30–45% WFPS had gravimetric moisture levels as high as 150–250%. The authors referred to the phenomenon as the “sponge effect” and explained it by the absorption of water by the residue from the surrounding soil. Such absorption is possible due to strong capillary forces generated by fine pores within the residue. Indeed, in an early study, Sommers et al. (1981) demonstrated that decomposition of various plant residues in the absence of soil might occur at water potentials considerably lower than those in soils, thus suggesting that the water retention properties of the residue itself may play an important role in its decomposition.

The possibility of water absorption by plant residue from the surrounding soil implies that conditions for decomposition within the residue might differ from those of the surrounding soil. This would explain only modest success in using soil moisture for predicting soil processes that relay on plant residue decomposition, including greenhouse gas emissions (Groffman et al., 2009; Ball, 2013). Understanding this phenomenon and possibly incorporating it in process-based models has the potential to improve the accuracy in predicting a number of soil processes important for both soil management decisions and for future climate assessments. However, at present this phenomenon remains largely unexplored. Questions to consider: (i) does water absorption by plant residues vary depending on soil moisture and matric potential levels; and (ii) how the soil characteristics and characteristics of the plant residue itself affect the magnitude of this effect.

The main hypothesis of the present study is that the water retention capacity of the plant residue incorporated into soil is greater than the water retention of the soil, leading to a sponge effect - water absorption by the residue from the surrounding soil. Our objectives are 1) to examine water retention of two types of plant residue materials, namely, corn and soybean leaves in soil materials with three contrasting particle size distributions (PSD), and 2) to explore water distribution patterns in the soil adjacent to the residue using X-ray computed micro-tomography (μCT).

2. Materials and methods

2.1. Soil and plant residue sampling and analysis

Soil samples were taken in September 2016 from the Long Term Ecological Research (LTER) site located at Kellogg Biological Station in southwest Michigan, USA (85°24′ W, 42°24′ N). The soil of the experimental site is fine-loamy, mixed, mesic Typic Hapludalf (Kalamazoo series) developed on glacial outwash. We sampled plots of the LTER's biologically-based agronomic treatment from three blocks of the LTER experiment. The treatment is in corn-soybean-winter wheat rotation with cereal rye (*Secale cereal* L.) and clover (*Trifolium pretense* L.) cover crops. The treatment does not receive any chemical inputs. Rye cover crop is planted after corn harvest in fall, red clover is frost seeded into wheat in late winter. Cover crops are terminated and their residues are incorporated in soil by chisel plowing prior to main crop planting in spring. Additional details on soil, climatic, and management characteristics of the experimental site can be found in Robertson and Hamilton (2015). The biologically-based agronomic treatment was selected for this study since it receives substantial amounts of plant residues in the course of the rotation and, thus, relies on the decomposition of the residue of the legume cover crop for its main nutrient input and soil C sequestration (Syswerda et al., 2011).

Soil samples were collected from 0 to 15 cm depth and air-dried. Air-dry soil was mechanically crashed and sieved with RO-TAP test sieve shaker (Model RX-29, OH, USA) for 1 min to obtain three soil fractions with < 0.05, 0.10–0.50 and 1.00–2.00 mm size ranges. We will refer to these fractions as fine, medium and coarse fractions, respectively. Particle size distributions were measured in the three soil fractions using the pipet method (Gee and Or, 2002), after dispersion in 5% sodium hexametaphosphate solution. For each fraction, three lab replicates were analyzed for data from each of the three LTER plots for a total of 9 measurements per fraction. Particle diameter groups were < 0.002, 0.002–0.005, 0.005–0.01, 0.01–0.022, 0.022–0.05, 0.05–0.1, 0.1–0.25, 0.25–0.5, 0.5–1.0, and 1.0–2.0 mm.

Leaves of corn and soybean plants were collected from experimental fields in summer of 2016. The leaves were dried in a herbarium press; then, 8 mm and 22 mm diameter disks were cut from the leaves with a puncher for subsequent water retention and X-ray computed micro-tomography (μCT) experiments.

2.2. Soil water retention

Water retention was measured in the three soil fractions using a 15 Bar ceramic pressure plate extractor (Model CAT.#1500, Soilmoisture Equipment Corp, Santa Barbara, CA). For each fraction, three lab replicates were analyzed for data from each of the three LTER plots for a total of 9 measurements per fraction. The soil was placed into metal rings (10 mm height, 39 mm ID) and gradually saturated from the bottom overnight. The water retention was measured at saturation and at the pressure head levels of -56, -102, -336, -1020, -3060, -5608, $-10{,}200$ and $-14{,}080$ cm. Additional measurements were conducted using controlled vapor pressure method (Nimmo and Winfield, 2002) in a desiccator with saturated solutions of $CaCl_2$ to obtain soil water content at a pressure head level of $-1.05 \cdot 10^6$ cm. We express pressure head levels as pF, which is a $\log_{10}$ of water pressure head in centimeters.

2.3. Leaf water retention experiment

Leaf water retention was measured in soybean and corn leaves at six levels of WFPS, roughly corresponding 10%, 20%, 40%, 50%, 60% and 80%, as determined for each respective soil fraction based on its full saturation. Note that since the total soil volume decreases as soil dries during water retention experiment, it is not possible to precisely determine WFPS of each sample corresponding to each pressure head level. Thus, water retention results are reported in terms of soil water content levels, and approximate WFPS are only mentioned when discussing the results, in order to place the findings in perspective of this commonly used metric.

For the measurements, we prepared soil columns with 22 mm diameter and 20 mm height. In each column, an air-dry leaf disk (22 mm in diameter) was placed between two soil layers, each layer 10 mm thick. Prior to leaf placement the soil layers were brought to the specified soil water content. The prepared samples were left overnight to reach an equilibrium between the moisture in the soil and in the leaves. Then, the leaves were separated from the soil, and gravimetric water content of the leaves was determined from the weights of wet leaves and after drying them for 48 h at 60 °C. In addition, after drying, the leaves were ashed at 500 °C. The mass of ashed leaves was used to correct the leaf water content measurements for occasional soil particles attached to leaf surfaces (Blair, 1988). We report the resulting relationships between leaf gravimetric water contents and soil volumetric water contents, as well as relationships between leaf gravimetric water contents and pF. We used soil water retention curves measured individually for