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Selected soil physical properties and aggregate-associated carbon and nitrogen as influenced by gypsum, crop residue, and glucose

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ABSTRACT

Soil physical properties play an important role in maintaining proper soil conditions for sustainable plant growth and development. These properties can be improved through addition of soil amendments, but little information is available of the effect of gypsum applied alone or in combination with various C sources on selected soil properties. A greenhouse study was conducted involving two contrasting soil types (Wooster silt loam and Hoytville clay loam) from Ohio, USA to which were applied gypsum (8.9 and 26.9 Mg ha^{-1}), two contrasting C sources (i.e. crop residues at 13.4 Mg ha^{-1} and glucose at 4.5 Mg ha^{-1}), their combinations and an untreated control. Response variables included soil bulk density, porosity, water stable aggregates, and aggregated-associated total C and N. A significant ($P < 0.10$) reduction in soil bulk density and increased porosity by glucose as compared to the control was observed. Crop residue addition also decreased bulk density. There was no significant effect on bulk density due to gypsum. Addition of glucose combined with gypsum (26.9 Mg ha^{-1}) or crop residue resulted in more water stable aggregates (WSA), greater mean weight diameter (MWD), and greater geometric mean diameter (GMD) as compared to other treatments. The differences were attributed to multiple factors such as the gluing activity of the polysaccharides promoted by glucose, and the inorganic binding/stabilizing activity brought about by Ca^{2+} in the gypsum. Addition of C amendments increased aggregate formation and lowered soil bulk density. It also caused a C increase within aggregates. Both, highly labile C (i.e. glucose) and more stable C in the form of plant residues provided benefit by improving soil physical properties. These benefits were also enhanced in some instances when gypsum was applied in combination with the C amendments.

1. Introduction

Maintenance of optimum soil physical conditions is important for sustaining plant growth and other living organisms in soils. Poor soil structure results in poor water and aeration conditions that restrict root growth, thus limiting efficient utilization of nutrients and water by plants. Soil structure is a dynamic fabric that affects the strength and stability of the soil. Soil structure, in addition to its effect on plant growth, also affects storage of soil organic carbon (SOC) (Blanco-Canqui and Lal, 2004). Soil properties such as bulk density, soil aggregation, and aggregate stability are also affected by the amount of organic C present and the composition of the organic matter (Martin, 1971; Dormaar, 1983).

Residues applied to soil can increase the size of the SOC pool (Lal, 2008a, 2008b) and also impact structure by creating stable soil aggregates which are the basic units of soil structure (Kononova, 1961). The longevity of the changes in soil properties due to crop residue addition is related to their rate of decomposition. In general, materials that are quickly decomposed, such as glucose, exert a rapid stabilization effect which is transient (Griffiths and Burns, 1972) because the glues formed can be readily decomposed (Tisdall and Oades, 1982). The polysaccharides bind together clay-sized particles into aggregates that are of the order of 10 μm diameter. These polysaccharides form an association with fine clay particles that can be seen using an electron microscopy (Foster, 1978; Tisdall and Oades, 1979). However, materials that are slower to decompose, such as cellulose, require a longer time for maximum aggregation to occur, but their aggregation effects continue for a longer period (Martin and Waksman, 1941; Martin, 1942; Tisdall and Oades, 1982).

Crop residues returned to the soil also improve soil quality and productivity due to their effect on total SOC concentration and content (Havlin et al., 1990; Paustian et al., 1997). The amount, chemical

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composition, and decomposition rate of crop residues have varying influences on aggregation and on SOC content, depending on the crop species (Martens, 2000). However, the maximum soil C pool is also determined by other factors such as climate, parent material, physiography, drainage, management practices, and soil properties including clay content, minerals and nutrient reserves (Lal, 2008a, 2008b).

Gypsum (calcium sulfate dihydrate, $CaSO_4 \cdot 2H_2O$) is an excellent source of Ca and S, two essential macro-elements needed for plant nutrition (Shainberg et al., 1989). Chan and Heenan (1998, 1999) reported that additions of Ca to field soils, in the form of lime or gypsum, increased the aggregation level by approximately 10%. Calcium also binds organic matter to clays which enhances seedling emergence and subsequent crop growth (Shainberg et al., 1989; Chen et al., 2005). Calcium is accepted as a critical element for the stabilization of organic matter, and aggregates with its role associated with formation of clay–polyvalent cation–organic matter complexes (Clough and Skjemstad, 2000).

Gypsum is readily available throughout the world and is mined in 80 countries. In the United States, the Clean Air Act Amendments of 1990 mandated that electricity-producing utilities install systems for removal of flue gas S (e.g. SO_2) that is generated during the burning of coal. The resulting material that is formed during this removal is called flue gas desulfurization (FGD) gypsum. This product is available for drywall manufacturing or for agricultural applications. A total of about 33 million tons of FGD gypsum was produced by utilities in the United States in 2015 (American Coal Ash Association, 2016). FGD gypsum, like other sources of gypsum, has the potential to improve soil quality when applied to agricultural land. This can both directly and indirectly increase agricultural productivity (Chen et al., 2001; Dick et al., 2006).

In addition to gypsum production in the United States, enormous amounts of crop residues are also produced annually by agriculture and reapplied back to the land. There is an effort to remove crop residues from fields to serve as a feedstock for biofuels (Kim and Dale, 2004). However, information is needed to assess how different C (highly labile and slowly degradable) sources, acting alone or in combination with gypsum, can best be used to maintain sustainable soil quality. Therefore, we evaluated the effect of Ca in gypsum with a rapidly available C source (i.e. glucose) that was considered the optimum treatment to promote beneficial soil physical properties, and compared these results to the more slowly released C source that is derived from plant residues applied in conjunction with gypsum. Response variables measured in two contrasting soil types in Ohio, USA were soil bulk density, porosity, aggregate stability and aggregate-associated C and N.

2. Materials and methods

2.1. Experimental setup

A greenhouse experiment was conducted at The Ohio Agricultural Research and Development Centre of The Ohio State University, Wooster, Ohio, USA. A Wooster silt loam soil (fine-loamy, mixed, mesic Typic Fragiudalfs) and a Hoytville clay loam soil (fine, illitic, mesic Mollic Epiaqualfs) representing two contrasting soil types, were collected from university farms located near Wooster and Custar, Ohio, USA, respectively. Soils were collected from the top 30 cm in the summer of 2013.

Each soil sample was screened through a 2-mm sieve, and then mixed thoroughly before selected soil properties were measured just before start of the experiment (Table 1) (Walia, 2015; Walia and Dick, 2016). The properties measured were soil pH using a 1:1 ratio of soil:deionized water (Watson and Brown, 1998), texture by the hydrometer method (Day, 1965), total C and N using high temperature combustion (Nelson and Sommers, 1996), Bray P-1 by the method of Frank et al. (1998), and exchangeable bases (Ca, K, and Mg) by extraction with 1 M NH_4OAC (Warncke and Brown, 1998). The materials applied as soil treatments were crop (corn) residues, gypsum, and glucose. Corn residues were collected from the field and dried in an oven at 60 °C before being ground to pass a 2-mm mesh sieve. Glucose and gypsum were obtained from Fisher Scientific. Details on the experimental materials and soil fertility have been reported previously (Walia, 2015; Walia and Dick, 2016).

Table 1
Selected soil chemical characteristics before application of treatments (Walia and Dick, 2016).

Parameter	Soil	
	Wooster	Hoytville
pH	6.15	6.80
Texture Classification	Silt loam	Clay loam
Sand (%)	16	22
Silt (%)	59	30
Clay (%)	25	48
Carbon (%)	0.72	2.14
Nitrogen (%)	0.09	0.24
Bray P-1 (mg/kg)	6.5	22.2
NH_4OAc Extracted (mg/kg)		
Ca^{2+}	1140	2730
Mg^{2+}	184	365
K^+	72.9	254
CEC (cmol(+)/kg)[a]	7.4	19.2

[a] CEC = cation exchange capacity.

Soil columns (dimensions 60 cm long, and 20 cm diameter) were made from polyvinyl chloride pipe as described in Walia and Dick (2016). Each soil was thoroughly mixed to provide a uniform material. The columns were filled first with a 5-cm layer of gravel. Over the gravel, the homogenized soil was placed to a depth of 35 cm, except for the control/untreated columns that were filled to a depth of 55 cm. All columns were filled manually, and in the exact same way by simply allowing gravity to compact the columns.

The top 20 cm layer of the treated columns consisted of soil treated with corn residues (0 and 13.4 Mg ha^{-1}), gypsum (0, 8.90, and 26.9 Mg ha^{-1}), and glucose (0 and 4.5 Mg ha^{-1}) and their combinations. The lower rate of gypsum (8.90 Mg ha^{-1}) was presumed optimal to affect soil properties, although it is about double the recommended rate for soils with a cation exchange capacity of > 15 cmol$_c$/kg soil (USDA-NRCS, 2015). The high rates of gypsum and other C amendments (residue 13.4 Mg ha^{-1}, gypsum 26.9 Mg ha^{-1}, and glucose 4.5 Mg ha^{-1}) were set to increase the likelihood of producing measurable effects on soils or crops. The residue rate applied is approximately that produced by a high-yielding corn crop.

The corn residues were mixed into the soil at the time the columns were filled with soil. The gypsum was surface applied in four equal applications of 2.23 Mg ha^{-1} for the low rate, and 6.73 Mg ha^{-1} for the high rate. The first application was at the time the columns were filled with soil. The second, third, and fourth applications of gypsum were applied on the soil surface one, three and five months after ryegrass was sown. Similarly, glucose was initially surface applied at a rate of 2.25 Mg ha^{-1} at the time the soil columns were filled, and then a second equal application was made onto the soil surface three months after ryegrass was sown. A control with no soil amendments was considered as a control. There were four replicates of each treatment or treatment combination. The total number of treatments yielded a total of 96 experimental units (2 soil × 2 residue rates × 3 gypsum rates × 2 glucose rates × 4 replications). The experiment was a complete block factorial design.

All soil columns were seeded in September with perennial ryegrass (*Lolium perenne*) at the rate of 27 kg ha^{-1}. Perennial ryegrass (*Lolium perenne*) was selected due to its rapid growth and fibrous root system. Fertilizers P (single super phosphate) and K (muriate of potash) were mixed into the soil and applied at rates of 25 and 75 kg ha^{-1} at planting. Nitrogen (urea) was surface applied in three equal doses