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Research paper

Impact of initial bulk density and matric suction on compressive properties of two Oxisols under no-till

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ABSTRACT

Compaction of the superficial soil layer can seriously jeopardise the sustainability of no-till systems. This study investigated how the compressive properties of two Oxisols under long-term no-till vary with initial bulk density (BD) and initial matric suction expressed as *p*F. Based on our experimental data, we then propose pedo-transfer functions for estimation of the compressive parameters *N* (intercept of the virgin compression line), λ (compression index) and κ (recompression index). Undisturbed samples were collected in the topsoil of two Oxisols with 220 (C_{220}) and 320 g kg^{-1} (C_{320}) of clay, and subjected to uniaxial compression tests at different initial *p*F. For both soils, *N*, λ and κ varied lineally with initial BD, whereas we found a quadratic relationship with initial *p*F, with a maximum *N*, λ and κ at intermediate matric suctions (*p*F = 2.4-2.7). The elastic rebound upon stress release, measured by κ, was high for our soils, and this was attributed to the high organic matter concentration that is typical for the superficial layer in no-till systems. The relationships between the compressive parameters (*N*, λ and κ) and initial conditions (BD, *p*F) were used to assess soil susceptibility to compaction. Simulations indicated that the susceptibility to compaction decreases with increasing initial *p*F for the C_{220} soil, but that the C_{320} soil is most susceptible to compaction at an initial *p*F of about 2.5. The functions for estimation of *N*, λ and κ from initial bulk density and initial matric suction proposed in this paper could be used in soil compaction models for prediction of soil compaction risks.

1. Introduction

The no-till system (NT) contemplates more than 100 million hectares in the world (Derpsch et al., 2010). It is referred to as the most important agricultural technology adopted in Brazil in the last fifty years (Giarola et al., 2013). NT follows three basic principles: minimizing soil disturbance, covering the soil with plant residues and rotational cropping (Giarola et al., 2013). Under no-till, the layer at around 0.07 to 0.20 m depth is typically rather compact, whereas the upper layer (0 to 0.07 m) should be characterized by low bulk density and low mechanical resistance, as this layer is highly important for early root growth and development (Reichert et al., 2009; Guedes Filho et al., 2013; Nunes et al., 2015). However, due to intense machinery traffic, compaction of the superficial layer is becoming an increasing problem, resulting in increasing soil bulk density and soil resistance and diminishing oxygen supply to plants and microorganisms (Reichert et al., 2009; Silva et al., 2012; Guedes Filho et al., 2013; Nunes et al., 2015).

Due to the compaction problem, many farmers abandon true no-till and use shallow tillage to mechanically loosen the compacted layer (Colonego and Rosolem, 2010; Guedes Filho et al., 2013; Nunes et al., 2015). The shift (back) from true no-till to shallow tillage is seen in many parts of the world (López-Garrido et al., 2014; Dang et al., 2015; Hongwei et al., 2016), but particularly prominent in Brazil (Guedes Filho et al., 2013; Nunes et al., 2015; Reichert et al., 2016a). However, the mechanical disturbance causes soil fragmentation and destroys

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continuous pores and aggregation, and makes the soil vulnerable to erosion (Reichert et al., 2009; Silva et al., 2012, 2014). Therefore, in order to minimize soil perturbation in this important layer, soil compaction needs to be avoided.

The impact of farm machinery on the soil can be estimated by means of soil compaction models. Such models are important tools for the development of recommendations of agricultural trafficability in order to minimize the risk of compaction (van den Akker, 2004; O'Sullivan et al., 1999; Défossez and Richard, 2002; Keller et al., 2007; Keller, 2005). Soil compaction models use stress-strain relationships to estimate the changes in soil volume as a function of the applied stress (e.g. Défossez and Richard, 2002). Hereby, volume change (expressed as bulk density, total porosity, void ratio or specific volume) is typically related to the logarithm of the applied stress. An example of such a stress-strain relationship was proposed by O'Sullivan and Robertson (1996), who relate the soil specific volume to the natural logarithm of the mean normal stress. This relationship can be described and parameterized by the soil mechanical parameters N (specific volume at mean normal stress $p = 1$ kPa), λ (compression index) and κ (recompression index) (O'Sullivan and Robertson, 1996), where N describes the intercept and λ the slope of the virgin compression line (VCL; plastic deformation), and κ the slope of the recompression line (elastic behaviour) (O'Sullivan and Robertson, 1996). The compression index is sometimes also termed compressibility coefficient, while the recompression index is also known as swelling index (e.g. Saffih-Hdadi et al., 2009; Keller et al., 2011). Note that different studies may use different stress components (e.g. mean normal stress, vertical stress), different logarithms (natural logarithm or logarithm to the base 10) and different measures of compactness (e.g. bulk density, void ratio, specific volume), which will result in different values for the compression and recompression indices (e.g. Gubiani et al., 2016). In addition, different methods and algorithms may be applied to obtain these indices, again resulting in slightly different values (e.g. Gubiani et al., 2016). Moreover, the recompression index can be obtained from the loading path, an unloading path or a reloading path, yielding slightly different values for the recompression index (Holtz and Kovacs, 1981; Braida et al., 2008; Keller et al., 2011). In this study, the recompression index was obtained from the loading path.

In order to apply soil compaction models and estimate compaction risks, knowledge of the soil compressive properties (e.g. N, λ and κ) is needed. These properties vary with soil texture, and are affected by soil compactness and soil moisture. The impact of soil texture and other soil state variables (initial density expressed in terms of initial bulk density, initial void ratio or initial specific volume; and initial soil moisture expressed as initial water content, initial matric suction or initial degree of saturation) on the mechanical parameters in unsaturated soils were investigated by Leeson and Campbell (1983), Hettiaratchi and O'Callaghan (1985), Hettiaratchi (1987), Petersen (1993), O'Sullivan et al. (1994) and Défossez et al. (2003). These studies aimed at establishing (i) relationships among the mechanical parameters and (ii) investigating how they vary as a function of clay content, specific volume, gravimetric water content and degree of saturation. However, they were developed considering a limited textural range, as well as specific mineralogy, and therefore, may only be valid for the investigated soils. In addition, these studies used remoulded soil. While this may be appropriate for regularly tilled soil, undisturbed soil samples should be used to properly characterize soil under NT. Besides that, the effect of soil moisture was studied using water content, while it could be argued that matric suction might be more relevant from a mechanical point of view (Larson and Gupta, 1980; Fazekas and Horn, 2005; Cui et al., 2010; Peth et al., 2010).

Estimating soil mechanical parameters as a function of soil texture, initial bulk density and matric suction would be practically useful for compaction risk assessment because the data could be relatively easily obtained at the field scale (using soil maps and tensiometers, for example). For example, soil texture and matric suction are used in the web-based decision support model Terranimo® (Stettler et al., 2014) for estimation of soil precompression stress and prediction of the risk of soil compaction due to agricultural field traffic, in the methodology to assess compaction risks proposed by Horn and Fleige (2009), as well as in the approaches given by Ajayi et al. (2009), Ajayi et al. (2010) and Severiano et al. (2013) for calculation of soil strength (using precompression stress) in Brazilian Oxisols. Few studies (e.g. Sullivan et al., 1994; Défossez et al., 2003; Keller and Arvidsson, 2007) have characterized all the three compressive parameters necessary to describe the compression curve (N, λ and κ). For Oxisols, the majority of studies have focused on precompression stress (Imhoff et al., 2004; Veiga et al., 2007; Severiano et al., 2013), some studies have investigated the compression index (Silva et al., 2002; Imhoff et al., 2004), and only few studies are concerned with the recompression index (e.g. Braida et al., 2008). To the best of our knowledge, there are no data on N for Oxisols under NT. Hence, a comprehensive characterization of the compressive behaviour of Oxisols managed under NT is lacking.

Knowledge of compressive properties of soil under no-till is particularly important: although reducing the risk of soil compaction is good management practice in any tillage system, the lack of mechanical loosening in no-till makes avoidance of soil compaction a top priority in NT. Hence, characterization of the compressive could be useful for minimizing (topsoil) compaction in NT, reducing the need for shallow tillage in NT. Soil structure affects the relationship between intensity properties (also referred to as functional properties; e.g. compression indices) and capacity properties (also referred to as compositional properties; e.g. bulk density) (Horn and Kutilek, 2009; Reichert et al., 2016b). Reichert et al. (2016b) have shown that intensity and capacity properties evolve at different rates. This implies that the relationship between intensity and capacity parameters changes from the time of adoption of no-till until a quasi steady-state no-till system has established. Consequently, pedo-transfer functions developed based on remoulded soil cannot be applied to predict intensity properties of soil under no-till.

In this study, we investigated how the compressive properties of two Oxisols under long-term no-till vary with initial bulk density and initial matric suction, and discuss the soil susceptibility to compaction of these two soils. Based on our experimental data, we propose pedo-transfer functions for estimation of the compressive parameters N, λ and κ from initial bulk density and initial matric suction. These functions could be used in soil compaction models for estimation of compaction risks of field operations.

2. Materials and methods

2.1. Site location

The soils were sampled in Ponta Grossa, Paraná State, Brazil (25° 05′ 52″ S and 50° 02′ 43″ W), at an average altitude of 1080 m. Ponta Grossa has an annual mean rainfall of 1545 mm and an annual mean temperature of 18.7 °C (IAPAR, 2000). Two experimental fields with distinctly different soil texture that are located in close vicinity (within a few hundred metres) were selected for this study: a soil with approximately 320 g kg^{-1} clay and a soil with *c.* 220 g kg^{-1} clay. Both sites have been cultivated under no-till for around 20 consecutive years with the following crop rotation: maize (*Zea mays* L.) and soybean (*Glycinemax* L.) in spring/summer; wheat (*Triticum aestivum* L.) intercropped with black oat (*Avena strigosa Schreb*) + vetch (*Vicia sativa* L.) in autumn/winter.

2.2. Soils characterization

The two studied soils have a sandy loam and a sandy clay loam texture, respectively (Table 1). The soils were classified as Haplorthox according to the USA Soil Taxonomy (Soil Survey Staff, 2010) and as