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Age-hardening phenomena in an oxisol from the subtropical region of Brazil

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ABSTRACT

Soil strength is not only affected by water content and bulk density, but also by the age-hardening phenomena, which plays a key role in increasing the soil strength as a function of time. It has been demonstrated that soil penetration resistance in no-tillage is higher when compared with other tillage systems at the same bulk density and water content. The objectives of this study was to investigate the effects of the age-hardening phenomena on soil penetration resistance in a long-term soil management system, running since 1988 in a very clayey Oxisol, in southern Brazil. Soil samples were collected from three soil layers (0.0–0.10 m; 0.10–0.20 m and 0.20–0.30 m) and five soil tillage systems: conventional tillage; minimum tillage with chiselling performed every year or every three years; and no-tillage for 11 or 24 years. Age-hardening was investigated using soil penetration resistance analysis and modelling. We used the area under the soil resistance to penetration curve to compare the age-hardening phenomena under the different tillage systems. For the same bulk density and water content, the soil resistance to penetration increased with time under no-tillage or without soil chiselling. For the same bulk density, no differences were found for macroporosity and microporosity among the tillage systems. Higher soil penetration resistance values in long-term no-tillage at the same soil bulk density and water content were attributed to the age-hardening phenomena, which increased the number and strength of bonds among soil particles, leading to higher soil cohesion. It is necessary to establish critical limits of soil penetration resistance as a function of the soil tillage system, and the time without soil chiselling or under no-tillage system.

1. Introduction

Soil penetration resistance (SPR) is widely known to change as a function of water content and soil bulk density (Moraes et al., 2012). Therefore, the soil water content dependency may influence the interpretation of the soil's compaction level when using SPR as a quantitative indicator. This problem may be circumvented by measuring the SPR in a drying soil at different bulk density values, either in the laboratory using undisturbed soil samples, or directly in the field (Busscher, 1990). To further the understanding of soil strength variation, the soil penetration resistance curve (SPR curve) can be utilised. The SPR curve is the reading of SPR variation as a function of bulk density and soil water content. The SPR curve may be a useful parameter for evaluating soil physical quality in areas under annual crops (Gao et al., 2016), native forest or fruit trees (Fidalski et al., 2010), because it is closely related to the effects of soil strength on crop growth (Bengough et al., 2011). However, the SPR curve depends on more parameters than only the soil water content and bulk density (Busscher, 1990; Moraes et al., 2012). Accordingly, the soil organic carbon content and soil textural composition (Gao et al., 2011), or time without soil disturbance are assumed to contribute to change in soil particle arrangement, and particle cementation (Dexter et al., 1988).

The agricultural area managed under no-tillage has increased continuously over the last decade mainly in tropical and subtropical regions, because long-term no-tillage can preserve

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the structural quality of soils over time, and provide suitable soil physical conditions for crop growth (Moraes et al., 2016). However, excessive soil compaction in untilled surface layers is regarded as one of the major reasons for crop yield reductions, especially during dry years (McKenzie et al., 2009), in weakly structured soils (López-Garrido et al., 2014) or in absence of diversified crop rotation systems (Abdollahi et al., 2015).

The increase in soil compaction increases SPR (Moraes et al., 2012) and reduces soil porosity, macroporosity, aeration, water infiltration capacity (Valentine et al., 2012) and hydraulic conductivity (Silva et al., 2009). These soil physical alterations lead to poor root growth (Schmidt et al., 2013), and thus limit the soil depth and volume explored by the roots for the uptake of water and nutrients (Bengough et al., 2011) However, continuous pores or biopores may attenuate deleterious effects of the soil mechanical restrictions on plant growth (Moraes et al., 2016; Calonego and Rosolem, 2010). Thus, soil management is the most important factor in changing soil structural quality, for example through the creation of a continuous and stable network of biopores (Moraes et al., 2016).

Traditionally, SPR values critical to plant growth have been indicated without taking into account either the soil management system or the adoption time. Only a few studies have considered the effects of soil management systems and their adoption time on the determination of SPR critical limits on crop growth and yield (Moraes et al., 2014a). For instance, several studies have assumed that a SPR value greater than 2 MPa at field capacity is limiting to root growth (Lipiec et al., 2012), slowing root elongation to less than half of its rate under unimpeded soil conditions (Gregory, 2006; Bengough et al., 2011). In many agricultural areas, no-tillage has led to SPR values above 2 MPa, however, in these areas no reduction in crop yield (Moraes et al., 2014a), or root growth (Martínez et al., 2008) was observed, revealing a cementation process that strengthened the soil structure in a way that meant the soil functioning was preserved. This strengthening may be ascribed to the formation of a pore network encompassing continuous and vertically oriented biopores that enable root elongation and adequate water and air fluxes in the soil, even under a high SPR (Moraes et al., 2016). Additionally, a well-cemented pore network is more resistant against collapse when the soil is exposed to heavy agricultural machinery traffic (Jin et al., 2013).

The processes that result in soil strength increasing over time without soil disturbance have been reported in the literature, such as age-hardening phenomena (Utomo and Dexter, 1981). These phenomena are the result of two major processes, particle rearrangements, and particle cementation (Dexter et al., 1988). The first process has been called the type A mechanism, and is the true thixotropic effect, involving the rearrangement of soil particles (mainly clay) into new positions of minimum free energy (Dexter et al., 1988; Dexter, 1990). The second, is known as the type B mechanism, and involves the reformation or strengthening of cementing bonds at new points of contact or near-contact between pairs of mineral particles (Dexter, 1990). This higher number of contact points between soil particles, and the strengthening of the bonds among them, leads to greater soil cohesion and internal friction (Fuentes et al., 2013), thus inducing increases in soil penetration resistance without significant alterations to the volume, size and arrangement of pores (Moraes et al., 2014a; Ortigara et al., 2015).

Soil strength and the strength of aggregates formed from disrupted soils increases with time (Utomo and Dexter, 1981). This process has a close association with the Mohr-Coulomb's equation (cohesion and angle of internal friction), which determines the soil shear resistance (Conte et al., 2011). In addition, the soil cohesion is affected by time (Kemper and Rosenau, 1984), water content (Secco et al., 2013), number of pores and cracks (Fuentes et al., 2013), organic matter, temperature, texture (Kemper et al., 1987), mineralogy, and iron and aluminium contents (Sánchez-Girón, 1996). Consequently, increases in soil strength are expected to occur over time after conservation tillage adoption, as a result of age-hardening processes (Horn, 2004).

The definition of critical values of SPR for long-term no-tillage has been widely discussed in the literature, but still remains unclear (Moraes et al., 2014a; De Jong van Lier and Gubiani, 2015), possibly due to the influence of cracks and biopores on root growth (Dexter, 1991). However, there is little information regarding the age hardening phenomena in subtropical clayey soils managed under no-tillage. Thus a better understanding of this process is necessary to establish more accurate critical limits of SPR to allow a better understanding and monitoring of soil compaction and physical quality (Moraes et al., 2014a).

We hypothesised that the absence of soil disturbance (no-tillage system) increases SPR values under the same bulk density and water content over time, as a result of the age hardening process. Thus, distinct SPR critical limits are needed as a function of tillage system, and the use of SPR curves as a soil physical quality indicator is a valuable option. We aimed to study the age hardening phenomena in no-tillage systems, and quantify its influence on the SPR curve of a very clayey soil for describing the evolution of soil physical quality.

2. Material and methods

2.1. Study site

The study was carried out in a long-term experiment established in 1988 at the Experimental Station of Embrapa Soybean, in Londrina (latitude 23°11′S; longitude 51°11′W; and 620 m in altitude) State of Paraná, Southern Brazil. According to the Köppen classification, the climate of the region is humid subtropical (Cfa), with an annual average temperature of 21 °C and with 1651 mm of rainfall (Moreno, 1961). The experiment was established on an Oxisol (Latossolo Vermelho Distroférrico, Brazilian classification; Rhodic Eutrudox, USA classification) with 755 g clay kg^{-1} soil, 178 g silt kg^{-1} soil and 67 g sand kg^{-1} soil. The soil particle density at 0–0.3 m depth is 2.90 Mg m^{-3}, and the mean slope of the experimental area is 0.03 m m^{-1}. Before the establishment of the experiment, the area had been cropped with coffee (*Coffea arabica* L.) for approximately 40 years, with the entire area receiving similar management and inputs.

2.2. Experimental design, treatments, and field management

The experiment was laid out in a 5 × 2factorial (soil tillage × cropping system), distributed in a randomised block design with four replications. The treatments consisted of the following tillage systems: conventional tillage with heavy disking to a depth of 0.15 m, then light disking (0.1 m depth), performed before each winter and summer growing season (CT); minimum tillage with annual chiselling (MTC_1), performed before each winter crop planting, and no-tillage for the summer crop; minimum tillage with chiselling every three years (MTC_3), performed before the winter crop planting, and no-tillage for the other winter/summer crops; continuous no-tillage for 11 years, established in 2001 (NT_{11}); and continuous no-tillage for 24 years (NT_{24}), established in 1988. Between 1988 and 2001, the soil under NT_{11} was tilled with a mouldboard plough (average working depth of 0.32 m), followed by light disking before planting the summer crop, and heavy disking (average working depth of 0.15 m) followed by light disking (0.07 m work depth) before the planting of the winter crop. The MTC_1 and MTC_3 plots were chiselled using a mounted chisel