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Effects of plough pan development on surface hydrology and on soil physical properties in Southeastern Brazilian plateau

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SUMMARY

Conventional tillage may impose changes in soil physical properties that lead to a decrease in soil physical quality. Although plough pan formation is considered to be an important consequence of conventional tillage practices in Southeastern Brazil, few studies have focused on its hydrological consequences. Detailed investigations in two experimental plots located in the hilly landscape of Serra do Mar close to Rio de Janeiro city were carried out to characterize the changes in soil physical properties and in soil hydrology due to plough pan formation. Conventional (CT) and minimum tillage (MT) practices were implemented in two plots for 3 years and soil matric potential (SMP) was monitored in each plot via nests of tensiometers and Watermark® sensors installed at different depths. Undisturbed soil blocks were collected for micromorphological analyses to quantify the total pore space in soils under CT and MT systems, and in soils under natural tropical forest. Results suggest that soils under the CT system developed a plough pan layer at about 20 cm depth that had 44% less total porosity as compared to surface conditions. It is shown that soils under the CT system tended to stay saturated for longer periods of time after each rainfall event. Besides, during intense rainy periods soils under the CT system may develop hydrologic conditions that favor lateral flows while soils under the MT system were still draining. Such hydrological responses may explain why average soil erosion rates measured for individual rainfall events under the CT system were about 2.5 times greater than the ones observed at MT. The results attested that conventional tillage in this area generated modifications in soil fabric, especially in pore-size distribution and connectivity, which induced important changes in soil hydrology and soil erosion. The agricultural practices used in this area, associated with the local steep hillslopes and intense rainfall events, are definitely not adequate and require the introduction of soil and water conservation practices in order to become sustainable.

1. Introduction

In many situations, agriculture management practices may impose changes in soil properties that lead to a general decrease in soil physical quality and cause a variety of modifications on soil water balance, both at the profile and basin scales (e.g. Vomocil and Flocker, 1966; Warkentin, 1971; Aina, 1979; Wu et al., 1992; Soane and van Ouwerkerk, 1995; Lipiec and Hatano, 2003; Blanco-Canqui et al., 2004; Lipiec et al., 2006; Scanlon et al., 2007; Gerten et al., 2008; Strudley et al., 2008). While the breakdown of soil aggregates takes place at the surface (e.g. Kwaad and Mücher, 1994), soil compaction causes important physical modifications at the subsurface, especially from 10 to 30 cm depths (e.g. Warkentin, 1971; Horn et al., 2000; Boizard et al., 2002).

Compaction rearranges soil particles changing pore-size distribution and connectivity (e.g. Horn, 2003) leading to a decrease in infiltration rates (e.g. Wilkinson and Aina, 1976; Ankeny et al., 1990, 1995; Freese et al., 1993; Potter et al., 1995; Mohanty et al., 1996; Vervoort et al., 2001; Martínez et al., 2008), in saturated hydraulic conductivity (e.g. Logsdon et al., 1992; Liebig et al., 1993; Arvidsson, 2001), and in porosity (e.g. Alakukku, 1996a,b; Richard et al., 1999; Radford et al., 2000; Schäffer et al., 2007), as well as causes an increase in bulk density (e.g. Gameda et al., 1987; Mahboubi et al., 1993; Pierce et al., 1994; Horn et al., 1995;

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Xu and Mermoud, 2001), among other soil physical properties. Depending on soil texture and on the degree of soil compaction, preferential flow can also be favored (Mooney and Nipattasuk, 2003). Besides, soil compaction can also affect the uptake and losses of nutrients in agricultural systems (e.g. Lipiec and Stepniewski, 1995). In general, this new soil condition scenario contributes to an increase in surface runoff (e.g. Adekalu et al., 2006) and soil erosion (e.g. Boiffin et al., 1988; Schilling et al., 2008), leading to an overall decrease in productivity (e.g. Gerard et al., 1982; Veen and Boone, 1990; Bicki and Siemens, 1991; Boone and Veen, 1994; Soane and van Ouwerkerk, 1995; Gregory et al., 2007). More details can be obtained in a vast review literature concerning tillage effects on soil properties (e.g. Soane et al., 1980a,b; Unger and Cassel, 1991; Hadas, 1994; Hakansson, 1994; van Ouwerkerk and Soane, 1995; Horn et al., 2000; Ahuja, 2003; Lipiec et al., 2003; Strudley et al., 2008).

Soil compaction may result from a variety of mechanisms induced by external and/or internal causes (e.g. Hamza and Anderson, 2005). Although the majority of the studies carried out dealt with soil compaction derived from agriculture vehicles (e.g. Warkentin, 1971; Soane et al., 1980a,b; Botta et al., 2008), some studies investigated soil compaction due to plough activities (e.g. Manichon, 1987). The amount of soil compaction depends not only on the applied load but also on parameters like soil characteristics, water content, landscape position, among others (e.g., Lindstrom and Voorhees, 1995; Lancaster et al., 1996).

Although there is an enormous literature on the morphological evidences of soil compaction (e.g. Horn et al., 1995; Gantzer and Anderson, 2002; Soares et al., 2005) few studies address these evidences on ploughed pans (e.g. Boizard et al., 2002) and the resulting hydrological effects. Plough pan formation is considered to be an important consequence of conventional tillage practices in Brazil (e.g. Stone and Silveira, 1999; Dias Junior, 2000; Silva et al., 2003; Reichert et al., 2003, 2007; Machado, 2003; Alves and Suzuki, 2004). In the hilly topography of the Serra do Mar plateau north of Rio de Janeiro city, the original tropical rainforest has been continuously replaced by urban areas and farming activities. This is the situation in the region of Paty do Alferes where a combination of intensive farming (especially tomato plantations) on steep hillslopes, severe rainstorms and downhill soil ploughing favor surface runoff and soil erosion, leading to a continuous decrease in soil productivity. The main focus of this study is to compare two tillage systems (conventional and minimum) as well as to characterize the changes in soil physical properties and in soil hydrology induced by the plough pan formation in experimental agricultural plots located in the hilly landscape of Serra do Mar in Southeastern Brazil, close to Rio de Janeiro city.

2. Study area

This research was carried out at the Experimental Campus of PESAGRO (Agricultural Research Company of Rio de Janeiro State) in the city of Paty do Alferes, located at the highlands of Serra do Mar, a mountainous area that emerges along the seacoast of Southeastern Brazil (Fig. 1). Although this city has traditionally been a cropland area for more than 200 years, including old coffee plantations, it also has also been used throughout these years to wood exploration and grazing (Desusmo, 1998). Over the last few decades, tomato plantations have been extensively installed in this area, which stands for about 40% of the total production of Rio de Janeiro State.

Annual rainfall in the area is about 1200 mm, with the highest rainfall rate period corresponding to the period from November through January (575 mm), representing about 50% of the annual rainfall (Desusmo, 1998). The driest period, on the other hand, takes place from June to August, with an average rainfall of about 75 mm, corresponding to about 6% of the annual rainfall. The climate of this area is a Cw KÖPPEN type with a potential evapotranspiration varying from 135 mm in January, down to 45 mm in July, with an average annual total of about 1070 mm.

Bedrock geology is constituted by a variety of Meso to Neoproterozoic garnet–biotite gneisses and Cambrian granites (see review in Fernandes et al. (2010)). Landscape dissection in this area produced a hilly topography with typical soil-mantled convex hilltops, with elevations varying from about 600–700 m (hilltop) to about 500 m (valley bottom). In general, such combination of environmental factors favored intensive chemical weathering and originated thick soils (from 2 to 10 m) that are highly weathered (mainly kaolinite clays) and have a low fertility, mostly Dystrophic Red Latosol (Typic Haplorthox) with about 40% of clay in the upper 20 cm of the soil profile (Pinheiro et al., 2004). Conventional tillage practices in the area include the usage of wheel vehicles for downhill ploughing, without incorporation of soil conservation procedures. For more details concerning the studied area see Palmieri et al. (2000) and Bertolino (2004).

3. Methods

3.1. Experimental plots

The experimental study was conducted on erosion plots (22 m × 4 m), installed side by side in 1995, at the mid section (30% slope) of a representative hillslope of the area (Fig. 1). The lower portion of each erosion plot was connected to two water and sediment reservoirs (500 l each): a first tank to collect the runoff and sediment produced in the plot and a second one in case of overflow from the first one (Fig. 2).

In this study, two different soil tillage systems were compared: (a) conventional tillage (CT) – with one downhill disc plowing (about 18 cm depth) followed by one light disc harrowing, in addition to burning residues from previous cultivation; (b) minimum tillage (MT) – the seedlings are planted direct without tillage and without burning the residues from previous cultivation and with preservation of vegetative cover between plantation lines, covering about 80% of the soil surface. The results to be discussed here comprise experiments with cultivation of a cropping sequence including green pepper (*Capsicum annuum*) and common beans (*Phaseolus vulgaris*). The plots were cultivated with a rotation of vegetables: pepper (December/2000–June/2001), beans (August/2001–December/2001), pepper (December/2001–July 17/2002) and beans (July/2002–February/2003).

3.2. Soil physical properties

Undisturbed soil cores (50 cm^3) were collected in order to characterize the soil physical properties in the CT and MT systems. In each system, soil samples were taken at three depths (0–5, 15–20 and 30–35 cm) from the upper, mid and lower portions of the plot (with replication), resulting in a total of 36 soil samples in the two plots. In this study, the following soil physical properties were analyzed: total porosity, macroporosity and microporosity (Danielson and Sutherland, 1986). With the purpose of comparing the studied tillage systems with the original conditions, soil samples were also collected under natural tropical forest (F), for the same depths and topographic settings.

3.3. Image analyses

In order to characterize pore-size distribution and continuity as well as the spatial arrangement of soil constituents, undisturbed soil blocks were collected using Kubiena aluminum boxes (11 cm