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The Effect of Soil Management on Pore Size Distribution and Water Infiltration

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HIGHLIGHTS

- Different tillage systems affect soil physical properties.
- The final water infiltration rate is a good indicator of changes in soil physical properties.
- Conventional tillage increases total and meso, but decreases microporosity.
- Change in pore size distribution enhances substantially water infiltration.

Abstract: Water infiltration into soil varies significantly with soil type and management practices. Management practices alter soil physical properties, such as porosity and pore size distribution, which play an important role in infiltration. This study was conducted to assess the effect of the long-term use of two different soil tillage systems (conventional, CT, and no-tillage, NT) on soil structure and water infiltration to understanding of the relationship between physical conditions induced by tillage and water infiltration. The experiments were carried out on a Humic Cambisol in southern Brazil from 1995 to 2016. Soil density, porosity, aggregate diameter and soil water infiltration were evaluated under conventional tillage right after one plowing and two subsequent discings (CT0), and six months after these tillage operations (CT6). The results show that different management systems affect differently soil physical properties and, thus, water infiltration. By mechanical mobilization CT brings about modifications in soil structure which promote an increase in total porosity and mesopority, and a decrease in soil microporosity. This in turn results in an increase in the proportion of larger pores in the plow layer and a decrease in soil density, but also in a decrease in aggregate stability. The CT0 measurements showed the highest infiltration rates which were up to 15 times greater than in the NT treatment. The higher infiltration rate in CT0 wears off with time, but in the CT6 measurements six months after tillage it was still 2 times higher than under NT. Tillage, at least initially, increases total porosity and mesoporosity, while at the same time decreasing microporosity. This results in a larger saturated hydraulic conductivity (K). An increase in total porosity alone does not necessarily increase K, if there is an increase in small pores at the cost of decreasing the number of larger pores.

Keywords: conventional tillage; no-tillage; soil conservation.

INTRODUCTION

Changes in soil physical properties can manifest themselves in several ways. In uncultivated land the presence of preferential pathways results in fast preferential water flow [1]. In contrast, in soils under continuous tillage water infiltration is reduced in relation to soil under natural vegetation [2]. However, water infiltration into soils varies significantly with soil type and management practices [3].

Management practices alter soil physical properties such as porosity and pore size distribution [4]. The final water infiltration rate into a soil is the most sensitive indicator of such alterations and is much lower in cropped areas than in natural forest [5]. The same authors showed that using a soil for annual crops, initially with conventional tillage and then with no-tillage, modified the physical attributes of the soil compared to the same soil under natural forest.

Soil management, such as chisel-plowing, which maintains a cover on the soil surface or alters the micro-relief such that water is retained on the surface, increases the water infiltration rate [6]. On the other hand, an increase in tillage intensity degrades the physical properties of a soil [7], reduces water infiltration and, thus, increases water erosion [8]. Water infiltration and, consequently, erosion strongly depend on the manner of soil tillage [9].

The pore size distribution which determines the water transmission properties in a soil, and therefore water infiltration, is influenced by soil tillage. However, the effect of soil tillage and management on transmission properties is not spatially uniform. In general, soil under no-tillage has a higher density and, consequently, also a lower porosity than a plowed soil [10]. In spite of signs of soil compaction under no-tillage, this management system maintains the soil physical properties responsible for a “healthy” soil and good crop development. The increase in soil bulk density under no-tillage is apparently quite often not restrictive to root growth [7]. Even with comparatively high bulk density and low porosity, soil under no-tillage may continue to be functional through improvements in its structure under long-term no-tillage [11]. However, long-term no-tillage can also lead to detrimental effects in some soil physical properties such as bulk density and total porosity [11].

In a long-term no-tillage study [12] found that the soil still had good physical conditions in the furrow for the development of plant roots. Their results suggest that the 10 - 20 cm layer may have more importance than the surface layer for the physical quality of a soil, e.g. its resistance to compaction. The majority of the root mass of a most crops does not go beyond this layer. In the no-tillage study of [12] sowing and root growth caused variability in the physical properties of the soil. However, throughout the investigation wetting and drying cycles caused much more significant changes in the soil physical environment than soil disturbances due to sowing and root growth.

In a study by [13] the surface soil under no-tillage and with crop succession showed a reduced bulk density and increased total porosity and, thus, an increased water infiltration compared to a soil under conventional tillage. This was due to a better structure of the surface soil under no-tillage, partly because the organic carbon content was higher when compared to conventional tillage. Silva and coauthors [14] came to a similar conclusion. Long-term (three decades) no-tillage improved the soil structure of an Oxisol by increasing soil aggregate stability (mainly in the surface layer) compared to conventionally tilled soil.

Although there are plenty of studies which demonstrate that no-tillage leads to better water infiltration than conventional tillage, there are also some studies which show the opposite. Cunha and coauthors [15] assessed the water infiltration rate under different tillage systems. They observed the highest basic water infiltration rate with conventional tillage, followed by no-tillage. Bertol and coauthors [16] found that in a Humic cambisol the initial and final water infiltration rate was about twice as high with conventional tillage than no-tillage. This behavior can explained by the greater number of large pores and lower soil density within the plow layer under conventional tillage. This difference between conventional tillage and no-tillage may also have positive implications for the water storage capacity of a soil [10]. Regardless of the tillage system, water infiltration into soils varies significantly with soil type, as well as time, intensity and duration of a rainfall [3].

Although studies evaluating the effect of different soil tillage systems on soil physical proprieties and water infiltration are common, most of these studies do not compare the situation before and after tillage.

This makes it impossible to obtain more conclusive results. Soil structure and water infiltration are influenced by long-term soil management, but they differ even more before and after plowing.

Understanding the relationship between physical conditions induced by tillage and water infiltration is of crucial importance to decide which soil management should be adopted. In this study we assessed the effect of the long-term use of two soil tillage systems (conventional and no-tillage) on a Humic Cambisol structure, particularly pore size distribution and water infiltration.

MATERIAL AND METHODS

The experimental site was established in 1995 at the Centro de Ciências Agroveterinárias in Lages, Santa Catarina State, Brazil (latitude 27°47'12.9"S, longitude 50°18'25.1"W, 925 m above sea level). The climate type according to the classification of Koeppen [17] is Cfb (subtropical, humid, without a dry season, with fresh summers and frequent frosts in winter). The mean annual temperature is 15.7°C, the mean annual precipitation 1.533 mm [18]. The soil is a “Cambissolo Húmico Alumínico léptico”, and a Humic Cambisol according to the [19] classification. The texture in the top 20 cm is composed as follows: 250 g kg^{-1} sand, 420 g kg^{-1} silt, 330 g kg^{-1} clay. The organic matter content is 33 g kg^{-1}. At the time of the inception of the experiment in May 1995 the pH was 5.5, and the exchangeable Al-content 0.216 meq per 100 g of soil. There were 12 meq Ca+Mg per 100 g of soil, and 78 mg dm^{-3} K and 8.4 mg dm^{-3} P. The soil was limed and fertilized shortly after this date (see below) so that these values are altered now.

The experimental area was covered with native grassland and pasture until the beginning of the experiments in 1995. During the initial cultivation dolomite (3.9 Mg ha^{-1}), phosphorus (125 kg ha^{-1} Triple superphosphate) and potassium (100 kg ha^{-1} potassium chloride) according to the recommendation of [20] were applied and incorporated into the soil. All later fertilizer applications followed the official recommendations of CQFS-RS/SC (2004 and 2016) according to the requirements of the crop planted at the time.

The soil management treatments were conventional tillage (CT, here a plow pass plus two disc passages) in two evaluation periods, (CT0), right after management and (CT6) six months after management, and no-tillage (NT). The treatments were installed with eight replications each in a completely randomized design. The treatment plots measured 6.5 m in width and 14.5 m in length, which results in an area of 94.25 m^2. In the NT and CT treatment the summer crops were mechanically sown, the winter crops were sown by hand. During the 21 years of the experiment, grains and legumes were used and rotated as winter and summer crops. The predominant crops were corn, soybeans, beans and crotalaria in summer, and oats, forage turnips and vetch in winter.

In the CT (CT0 and CT6) treatment the soil was sampled in December 2016, six months after the last management (CT6), as soon as the winter crop (oats) was harvested, and then again a few days later, right after the next tillage operations (CT0) to prepare the summer crop. Sampling in the NT treatment was carried out on the same day as in the CT6 plots. In all cases undisturbed soil cores were collected at 0 - 2.5, 2.5 - 5, 5 - 10 and 10 - 20 cm depth. Samples for the porosity analyses in the CT and NT treatments were taken in rings 2.5 cm in height and 6 cm in diameter (70.69 m^3 soil volume) in the layers 0 - 2.5 and 2.5 - 5 cm, and in rings 5 cm in height and 6 cm in diameter (141.38 cm^3 soil volume) in the layers 5 - 10 and 10 - 20 cm.

In the laboratory the rings were saturated with water, then submitted to tensions of 1 and 6 kPa on a column of sand, and later dried in an oven at 105 ºC for 48 hours according to the method described by [21]. Soil density was obtained by dividing the dry soil mass by the volume of the ring. Total porosity (Tp) was determined with the help of soil density (Sd) and the average particle density (Pd) from the relationship:

$$\mathrm{Tp} = 1 - \frac{\mathrm{Sd}}{\mathrm{Pd}} \qquad (1)$$

The volume of mesopores and micropores was evaluated according to the methodology described in [39]. Additional soil samples were collected in the aforementioned soil layers to determine the average diameter of the aggregates (ADA) by wet sieving. Subsamples of 25 g were pre-wetted for 10 min and then placed in vertical oscillation equipment for 10 min over a set of sieves with 4.76, 2.00, 1.00, and 0.25 mm mesh size. The weighted mean ADA was calculated for each sample as described by [22].

Water infiltration into the soil was determined by the double ring infiltrometer method [23] with a 30 cm diameter inner and a 60 cm diameter outer ring. The rings were inserted 10 cm deep into the soil and there were three replicates per treatment. Both ring compartments were filled with water, but measurements were only made on the inner ring. The amount of water entering the soil was measured with a graduated ruler float.

Ruler readings were taken after 1, 2, 3, 4, 5, 10, 15, 20, 30 and then every 10 minutes until 120 minutes. Water was added manually whenever necessary. Prior to the water infiltration measurements, the antecedent water content of the soil was determined gravimetrically. For that purpose, soil samples were collected in each treatment in the area surrounding the water infiltration sites at soil depths of 0 - 2.5, 2.5 - 5, 5 - 10 and 10 - 20 cm using an auger. Samples were weighed, oven dried at 105 °C for 24 h, and then reweighed to calculate the gravimetric water content.

Statistical analysis of the data was performed using Assistat [24]. Data normality was tested with the Shapiro-Wilk test. Significant differences between treatments in each layer were determined by analysis of variance (ANOVA). Subsequently, a Tukey test was performed to assess whether the results of the treatments were different or not ($p \leq 0.05$).

RESULTS

Plowing breaks down the structural aggregates and decreases soil density (Sd) immediately after the mechanical operations. Hence, Sd is lower in the CT0 than in the NT variant, except in the 0 to 2.5 cm layer (Tab. 1). Note that differences are visible in all layers, but they are statistically significant only in the 0 to 2.5 cm and the 5 to 10 cm layer.

Six months after tillage (CT6) Sd has increased in all layers to values which are statistically not significantly different from the NT treatment, except in the top layer. In the 2.5 to 5 cm and the 10 to 20 cm layer the CT0 and CT6 values are not statistically different either, but visually they are.

The Sd results presented here are different from those of [26] in related studies where Sd was 19% higher in NT in relation CT at a depth of 0 - 10 cm. The reason may be that in these studies the effect of conventional tillage was not evaluated right after the operations, but several months later. This hints that the lower Sd due to plowing decreases as time goes by, as observed here between CT0 and CT6. [27] argued that soil under NT has a denser surface, because there is no plowing to remove the cumulative effect of the traffic of agricultural machines on the soil. These authors also emphasize that the high clay content of the Oxisol they studied favored soil compaction in the NT surface layer compared to CT.

The total porosity (TP) was greater in CT0 in the layer 10 – 20 cm, in the another layer CT6 and CT0 where greater the NT treatment. In the layer 2.5 - 5 cm treatments not difference (Table 1). The CT0 mesoporosity values shown in Tab. 1 also reflect the positive changes resulting from the tillage operations. They are higher in all layers evaluated here compared to the NT treatment. However, six months after tillage (CT6) the mesoporosity has decreased significantly, but still remains above the values for NT, except in the top layer.

For microporosity (Tab. 1) the soil management has the opposite effect, the soil in CT0 has a much lower microporosity in all layers than the NT variant. However, six months after tillage (CT6) microporosity has increased significantly to values which are statistically not significantly different from the NT treatment, except in the top layer.

The average diameter of the aggregates (ADA) reveals results one would expect from tillage. Right after tillage (CT0) the ADA is much smaller than in the NT variant, except in the top layer (Tab. 1). Six months after tillage (CT6), an ADA increased sharply and is greater than CT0 in the 5 - 10 and 10 - 20 cm layers. Statistically the CT6 and NT ADA-values are not significantly different.

In our study soil management has a substantial effect on water infiltration into the soil, as can be seen in Figure 1a and Figure 1b. CT0 displays the highest infiltration rate and accumulated amount of water infiltration during the entire time of water application. The water infiltration rate at 10 minutes is 95 cm h^{-1} which is 19 times greater in relation to NT (Figure 1a). At the end of the two hours of water application the infiltration rate is 15 times greater.

Six months after tillage (CT6) the water infiltration rate has decreased substantially (from 69 to 9.6 cm h^{-1}), but is still about 2 times higher than in NT.

Table 1. Physical soil characteristics (mean of eight replications) at four depths intervals in a Humic Cambisol right after tillage (CT0), six months after tillage (CT6), and with no-tillage (NT); soil density (Sd); total porosity (Tp); mesoporosity (Me); microporosity (Mi); average diameter of the aggregates (ADA).

Trat.	Sd (g cm^3)	Tp (%)	Me (%)	Mi (%)	ADA (mm)
---Layer 0.0 - 2.5 cm---					
CT 6	1.17 a	63.46 ab	14.14 b	39.98 a	5.31 a
CT 0	1.04 b	59.93 b	21.68 a	28.35 c	5.57 a
NT	0.86 c	66.34 a	17.77 ab	35.52 b	5.32 a
Average	1.02	63.24	17.86	34.62	5.40
CV (%)	5.35	5.34	21.65	8.57	6.81
---Layer 2.5 - 5.0 cm---					
CT 6	1.22 a	62.28 a	13.0 b	40.57 a	5.38 ab
CT 0	1.11 a	61.46 a	20.7 a	31.39 b	5.10 b
NT	1.21 a	59.18 a	10.7 b	38.96 a	5.62 a
Average	1.18	60.97	14.83	36.97	5.37
CV (%)	7.04	4.52	25.03	6.63	5.54
---Layer 5.0 - 10.0 cm---					
CT 6	1.35 a	61.39 a	11.30 b	40.92 a	5.69 a
CT 0	1.18 b	62.78 a	20.00 a	33.53 b	4.72 b
NT	1.31 a	54.11 b	6.35 b	40.63 a	5.53 a
Average	1.28	59.43	12.59	38.36	5.31
CV (%)	4.68	7.50	38.88	7.48	7.53
---Layer 10.0 - 20.0 cm---					
CT 6	1.33 a	55.20 b	7.11 b	42.06 a	5.44 a
CT 0	1.28 a	60.80 a	17.52 a	35.15 b	4.87 b
NT	1.33 a	53.30 b	5.14 b	42.37 a	5.31 a
Average	1.31	56.41	9.92	39.86	5.20
CV (%)	6.88	6.44	37.07	7.13	6.08

Note: CV: coefficient of variation. Small letters indicate the statistical significant difference between the values in every layer by Tukey ($p \leq 0.05$).

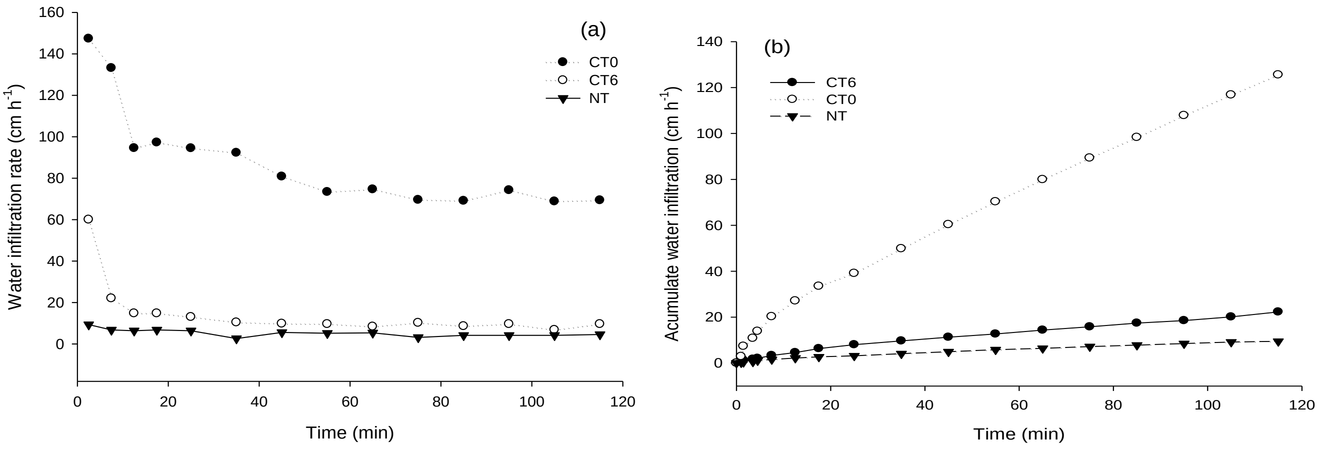

Figure 1. Water infiltration into a Humic Cambisol (mean of three replications) right after tillage (CT0), six months after tillage (CT6), and with no-tillage (NT): a) water infiltration rate, b) accumulated amount of water infiltration.

The same behaviour as shown for the water infiltration rate can be observed in the accumulated infiltration of water into the soil. CT0 shows the highest values throughout the evaluated period (Figure 1b). After 10 minutes of water application the accumulated infiltration reaches 20 cm of water, which is 17 times higher compared to NT. At the end of the two hours of water application the accumulated water infiltration in CT0 is 15 times higher than in NT. In CT6 the accumulated water infiltration was 2 times more than in NT.

DISCUSSION

In the introduction we said that the final water infiltration rate into a soil is the most sensitive indicator of alterations to the pore size distribution. According to the theory of water infiltration [32; 33; 34] the final water infiltration rate approaches a constant value (Figure 1a) which is the saturated hydraulic conductivity of a soil (K). As the water infiltration rate approaches this constant value (K), the cumulative water infiltration, which increases rapidly at first and then ever slower, approaches a constant rate of increase ($\Delta I/\Delta t$, Fig 1b) which again equals K.

The decrease in soil density in superficial CT is due to the higher content of organic matter (OM) when compared to the lower layers. OM improves the soil structure, thus, better structural conditions are observed in NT due to the higher OM content compared to CT, as observed in a previous study in the same area [25].. After two decades of no-tillage [11] found that the surface structural conditions in NT were better when compared to CT, due to the higher OM content in the soil. The lower Sd (and higher Tp) in the CT0 treatment is due to the plowing which provides a "stirring" and thereby a loosening of the soil in the plow layer (here from 0 to 17 cm). The same was observed by [26] who noted a decrease in Sd due to tillage, provided there is no machine traffic after the tillage and seeding operations.

In the top layer the ADA-value is higher in CT0 than in the other two treatments. This is because plowing inverts the soil and thereby shifts larger aggregates from lower in the soil to the top and vice versa. However, according to Andrade and coauthors [13] CT can reduce aggregation in the surface layer in the long term, due to the periodic mechanical disturbance of the soil under tillage, and also due to the lower level of OM in this management system. [29] blamed the decrease in the OM content and in the resistance of the aggregates to rainwater action on the exposure of the soil surface due to tillage operations which lead to an inadequate soil cover.

This leads us to infer that the difference between ADA right after tillage (CT0) and ADA with no-tillage (NT) is of short duration, if tillage is carried out only twice a year as in our case. This may be related to the high clay content of the soil in question. According to [28] a high clay content contributes to an increase in the aggregation of soil particles.

Table 2 shows the final water infiltration rate, i.e. the saturated hydraulic conductivity for CT0, CT6 and NT. The values were derived by putting a linear regression through the last 5 points in the three accumulated water infiltration curves for each treatment, when the rate of increase in the cumulative water infiltration was essentially constant. K could also have been evaluated by estimating the final water infiltration rates but extracting it from the cumulative water infiltration data was given preference, because they fluctuate less (compare Figures 1a and b). As one can see, the value for CT0 is much higher than for CT6, which in turn is a about twice higher than the value for NT.

The concentric ring method has limitations due to the hydraulic load above the ground, which simulates the conditions of a flood and does not represent the conditions of natural rain (40). The use of methods that do not consider the impact of raindrops can cause an overestimation of the values of water infiltration in the soil (41), with a greater overestimation in conditions of low soil cover, as in CT treatments. Zero hydraulic load can be achieved, in practice, with the use of a rain simulator; however, this device has a high acquisition cost and more complex operation (40).

Table 2. Gravimetric soil moisture content (θg in %) in various depths intervals (cm) and mean off Saturated hydraulic conductivity (K in cm h^{-1}) in a Humic Cambisol just prior to water infiltration tests right after tillage (CT0), six months after tillage (CT6), and with no-tillage (NT). The last column gives the mean for 0 - 20 cm in each treatment.

	Depth interval (cm)					
	0 - 2.5	2.5 - 5	5 - 10	10 - 20	Mean	K
Treatment	θg (%)					K (cm h^{-1})
CT0	21	24	26	27	26	72.74
CT6	24	26	26	29	27	8.56
NT	27	29	30	35	32	4.18
C.V.	10.2	7.8	6,9	11.2	9,3	110

Results observed by Canqui and coauthors [30], they, too, indicate that NT does not increase water infiltration in the long-term. It has a limited or no positive effect on water infiltration compared to conventional management. In contrast, the results of [31] show higher water infiltration in NT than in CT. The same authors observed a high OM content which results in a greater biological activity of the soil with a consequent increase of macro-aggregates and effective porosity, allowing greater infiltration of water into the soil.

In chapter 3.3.3 of their book [36] present the capillary tube model for hydraulic conductivity (K). According to this model K is given by the following equation:

$$K = \frac{\pi \cdot \rho \cdot g}{8 \cdot \mu} . \sum_{i=1}^{n} (n_i \cdot r_i^4) \quad (2)$$

where π = 3.14, ρ = density of water, g = gravitational acceleration, μ = kinematic viscosity of water, n = number of pores of radius r per unit area, and r = pore radius.

This equation says that K depends on the sum of the pore radii raised to the 4th power. This implies that a large pore contributes much more to K than a small pore. For example, a pore with twice the radius of another contributes $(2 \cdot r)^4 \Rightarrow 16$ times more to K.

Now, the results presented above show that tillage, at least initially, increases total porosity and mesoporosity, while at the same time it decreases microporosity (Table 1). According to Equation 2 this will result in a higher K (Table 2), because there are more large pores. Note that an increase in total porosity alone does not necessarily increase K, if there is an increase in small pores at the cost of decreasing the number of larger pores.

In CT6 and NT the mesoporosity values, averaged over 0 - 20 cm depth, are 43 and 50% lower than in CT0, respectively. CT0 has the highest total porosity and mesoporosity in all zones of the plow layer. This results in the higher rate of water infiltration and greater accumulated infiltration at the end of the two hours of water application. Bertol and coauthors [3] state that the infiltration of water into a soil varies significantly with the adopted soil management system and is influenced by the quantity of residues and the method of sowing.

The initial water infiltration rate depends on the soil water content at the time infiltration begins (initial water content). If the soil is wet, the rate is lower than if it is dry [32; 33; 34]. However, the initial water content does not affect the final water infiltration rate. Under dry conditions it merely takes longer to reach it than under wet conditions.

When averaged over the 0 - 20 cm depth the (gravimetric) soil water content that preceded the water infiltration tests here ranged from 26% in CT0 to 32% in NT. This is a fairly small range. In individual soil layers the moisture content varied somewhat more (Tab. 2). The lowest value with 21% occurred in the 0 - 2.5 cm layer of CT0, and the highest with 35% in the 10 - 20 cm layer of NT. The variation in the initial water content was largest in NT (27 - 35%), and a bit less in CT0 (21 - 27%) and CT6 (24 - 29%).

However, it is necessary to comment here, that mechanical mobilization, soil cultivation, and surface coverage by crop residues affect soil and water losses by water erosion. No-tillage is the most effective treatment to control soil loss, compared with conventional tillage. Consequently, the water losses too are influenced by soil mechanical mobilization [37].

Another relevant aspect, related by different soil managements is the cost of the total losses of nutrients in the form of fertilizer, by water erosion is higher in conventional tillage than in no-tillage, indicating efficacy in no-tillage in reducing value compared to conventional tillage [38].

CONCLUSIONS

The CT management system used here brought about modifications in soil structure due to mechanical action. The end result was an increase in the proportion of larger pores in the plow layer, leading to a decrease in soil density, but also in aggregate stability. However, these changes persisted only for six months.

The rate of infiltration of water into the soil and the accumulated amount of water infiltration were also influenced by the tillage operations. Right after tillage the water infiltration rate and amount were much higher (15 times) than in NT. These differences become smaller with time. However, six months after tillage the water infiltration rate and the accumulated infiltration were still about two times higher than in NT. Tillage, at least initially, increased total porosity and mesoporosity, while at the same time decreasing microporosity. This resulted in a larger saturated hydraulic conductivity (K) as predicted by Eq. (2) and, thus, in more water infiltration.

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