DEEP SUBSOILING OF A SUBSURFACE-COMPACTED TYPICAL HAPLUDULT UNDER CITRUS ORCHARD(1)

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SUMMARY

Soil management practices which increase the root depth penetration of citrus are important to the longevity and yield maintenance of this plant, especially in regions where long periods of drought are common, even in soil conventionally subsoiled to a depth of 30-40 cm, when the orchard was first established. The objective of this study was to evaluate the efficiency of subsoiling on the physical and hydric properties of a Typical Hapludult and fruit yield in a 14-year-old citrus orchard located in Piracicaba, SP. The treatments consisted of: no-subsoiling (with no tilling of the soil after the orchard was planted); subsoiling on one side of the plant lines (*Sub. 1*); and subsoiling on both sides of the plant lines (*Sub. 2*). The subsoiling treatments were carried out 1.5 m from the plant lines and to a depth of 0.8 m. Soil samples were taken 120 days after this operation, at four depths, in order to determine physical and hydric properties. Fruit yield was evaluated 150 days after subsoiling. Subsoiling between the plant lines of an old established citrus orchard alters the physical and hydric properties of the soil, which is reflected in increased soil macroporosity and unsaturated hydraulic conductivity, and reduced soil bulk density, critical degree-of-compactness and penetration resistance. The improvements in the physical and hydric properties of the soil were related to an increase in fruit number and orchard yield.

Index terms: soil compaction, soil management, soil physics, subsoiler.

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RESUMO: *SUBSOLAGEM PROFUNDA EM UM ARGISSOLO VERMELHO AMARELO COMPACTADO EM SUBSUPERFÍCIE CULTIVADO COM CITRUS*

As práticas de manejo do solo que aumentam a profundidade do sistema radicular das plantas de citros são importantes para a longevidade e manutenção da produtividade da cultura, principalmente em regiões que apresentam períodos de estiagem, mesmo em áreas onde foi realizada a subsolagem convencional a 30-40 cm de profundidade para implantação do pomar. O objetivo deste trabalho foi avaliar a eficiência da subsolagem sobre as propriedades físico-hídricas de um Argissolo Vermelho-Amarelo distrófico e o rendimento de frutos de um pomar de citros aos 14 anos de idade, em Piracicaba, SP. Os tratamentos consistiram em: sem subsolagem (sem mobilização do solo, após a implantação do pomar); subsolagem em um lado das plantas (Sub. 1); e subsolagem em ambos os lados das plantas (Sub. 2). A subsolagem foi realizada a 1,5 m da linha de plantio (em um ou nos dois lados da linha), a 0,8 m de profundidade. Amostras de solo deformadas e indeformadas foram coletadas 120 dias após a aplicação dos tratamentos, em quatro profundidades, para determinação dos atributos físicos e hídricos do solo. O rendimento dos frutos foi avaliado 150 dias após a subsolagem. A subsolagem realizada nas entrelinhas das plantas do pomar de citros modificou as propriedades físicas e hídricas do solo, refletindo em aumento da macroporosidade e condutividade hidráulica não saturada e redução da densidade do solo, do grau de compactação e da resistência à penetração. As melhorias nas propriedades físicas e hídricas do solo ocasionaram aumento no número e rendimento de frutos do pomar de citros.

Termos de indexação: compactação do solo, manejo do solo, física do solo, subsolador.

INTRODUCTION

Soil compaction is a process of soil structural degradation, and is associated with a reduction in crop yield, which challenges the sustainability of agricultural ecosystems (Soane & van Ouwerkerk, 1994). Compaction is a very common problem of soil physical quality in citrus orchards, due to the heavy traffic of agricultural machinery and implements, which occurs about 15 times a year, for fertilization, management of cover crop, pests, diseases, and harvesting operations (Tersi & Rosa, 1995). Although the soil can be subsoiled during the establishment of the orchard, some subsurface compaction layers limit root depth (Mazza et al., 1994; Minatel et al., 2006). Many studies have shown the damaging effects of soil compaction on citrus plant root growth, limiting the absorption of water and nutrients (Nuñez Moreno & Valdez Gascon, 1994; Souza et al., 2008). However, there has been little work evaluating the effect of deep soil mobilization between the plant lines in the citrus orchard (Abercrombie & du Plessis, 1995). Agricultural practices can induce soil compaction, especially where there is heavy machine and implement traffic, causing negative impacts on the soil physical properties in citrus orchards (Sanches et al., 1999; Fidalski et al., 2007), especially in the zone in-between rows (Homma et al., 2012), and may decrease fruit yields.

The roots of citrus plants are concentrated between 0.40 and 0.75 m from the soil surface (Cintra et al., 1999; Neves et al., 2004). Citrus are true evergreen species, i.e., they transpire throughout the whole year. Therefore, when these plants develop a deep root structure, they increase their capacity for water and nutrient uptake, minimizing the negative effects of drought periods (Calheiros et al., 1992).

By way of deep subsoiling between the plant lines, it is possible to correct the soil physical properties and improve root development and activity (Abercrombie & Hoffman, 1996), increasing the longevity and yield of fruit trees in existing citrus orchards, especially in areas where deep soil preparation was not carried out at planting, or when subsequent traffic caused strong physical impedance in the interrows of orange plantations.

The aim of this work was to evaluate the efficiency of deep subsoiling on the physical and hydric properties of the soil and fruit yield in an old established citrus orchard.

MATERIAL AND METHODS

The experiment was carried out in Piracicaba, São Paulo State (Brazil), in an area with gently undulating relief, at an altitude of 542 m asl. The climate type is tropical Cwa, according to the Köppen classification system. The average annual rainfall is 1,400 mm, with a climate regime characterized by two distinct seasons: a dry winter (April to September) and a rainy summer (October to March).

The soil was classified as a Typical Hapludult (Soil Survey Staff, 2010), corresponding to an Argissolo

Vermelho-Amarelo distrófico, by the Brazilian classification (Embrapa, 2006). The soil texture is sandy/loam clay with 175 g kg^{-1} clay and 813 g kg^{-1} sand in the 0-0.20 m surface layer (Table 1). With increasing soil depth, the clay content increased to 250 g kg^{-1} and sand decreased to 718 g kg^{-1} (0.4 to 0.6 m), which is typical for this soil type. Generally, in all soil layers, sand size was mostly less than 250 µm. The organic carbon (OC) in the soil varied around 14 g dm^{-3} in the surface layer, decreasing to 3 g dm^{-3} in the deeper layers (Table 1). The high OC levels in the surface layer were related to the lack of soil plowing, leading to the accumulation of crop residues and cover plants on the surface.

The experimental area consisted of an established citrus orchard, of Pera sweet orange (*Citrus sinensis* L. Osbeck) grafted on Rangpur lime (*Citrus limonia* L. Osbeck), with plant spacing of 8 x 4 m. The soil was conventionally tilled when the orchard was established in 1995, using a disk plow, at a depth of 20-25 cm. After that, the soil was not tilled anymore and during the period from 1995 to 2009, it was exposed to compaction caused by the mechanized cultural practices used in the orchards, such as fertilization, pest and disease control, harvesting and management of cover crops. This area is predominantly covered by Bahia grass (*Paspalum notatum* Flüggé), as well as other species. The cover crops were mechanically mowed and left on the soil surface.

The experiment was performed in February 2009, with three treatments. The treatments consisted of: *no-subsoiling* (without soil tilling); subsoiling on one side of the plant lines (*Sub. 1*); and subsoiling on both sides of the plant lines (*Sub. 2*) (Figure 1). The subsoiling was carried out with a winged subsoiler produced by the Mafes Agromecânica Company, with one shank (height 0.9 m), with a parabolic booted point, at a 5° angle. Its minimum working power is 85 HP. Subsoiling was performed four days after a 37 mm rainfall, when the soil moisture was near field capacity.

The soil was randomly sampled in May 2009, 120 days after applying the treatments, along a transect at a distance of 1.5 m from the plant lines. For the subsoiling treatments, samples were collected only in Sub. 2, to evaluate the effect of subsoiling on the plowed soil, which was similar when applied on one or both sides of the plant rows. For this reason, the discussion of the results related to soil properties was simplified to subsoiling and no-subsoiling. However, the plants responded differently to these treatments, so the fruit yield was evaluated in all soil treatments.

Table 1. Particle size distribution and organic carbon (OC) content of the soil in a citrus orchard

Layer	Sand			Silt	Clay	OC
	>250 µm	<250 µm	Total			
m	g kg^{-1}					g dm^{-3}
0.0-0.2	183	630	813	12	175	14 a
0.2-0.4	162	578	740	35	225	7 b
0.4-0.6	157	561	718	32	250	3 b
0.6-0.8	150	576	726	23	251	3 b

Disturbed and undisturbed soil samples were taken from the following soil layers: 0.0-0.20; 0.20-0.40; 0.40-0.60 and 0.60-0.80 m. The disturbed samples were evaluated for soil bulk density reference (ρ_{ref}), soil particle density (PD) and moisture at permanent wilting point (θ_{PWP}). The undisturbed samples were collected with a metal cylindrical sampler (height 0.05 m, diameter 0.05 m) to evaluate soil bulk density (BD), macroporosity (Ma), microporosity (Mi), total porosity (TP), penetration resistance (PR), field capacity moisture (θ_{FC}), and water availability to plants (WA), considering the difference between soil moisture at θ_{FC} and the permanent wilting point (θ_{PWP}).

The ρ_{ref} was obtained in the laboratory by applying a uniaxial pressure of 800 kPa with a hydraulic press (Reichert et al., 2009). The particle density was

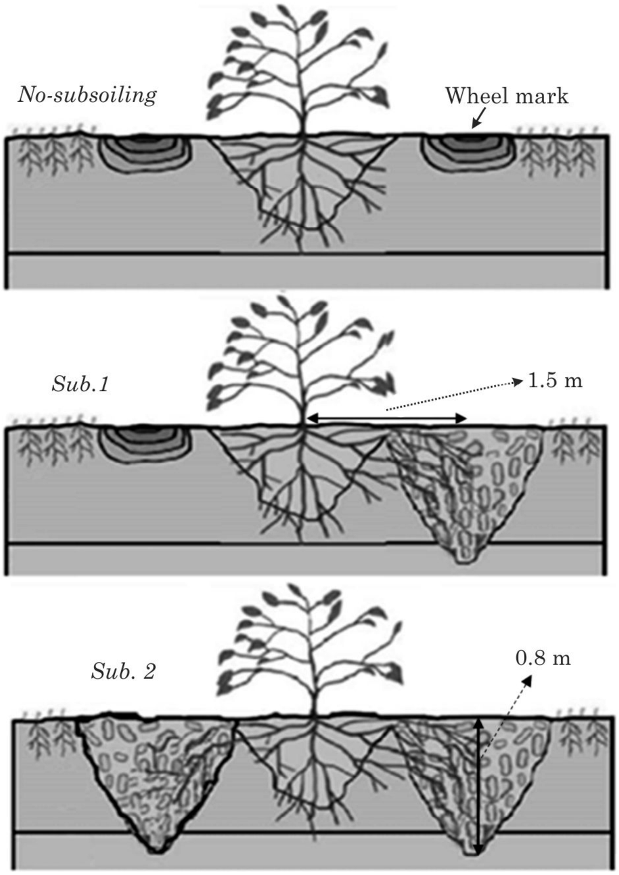

Figure 1. Diagram representing the treatments: No-subsoiling: without soil tillage; *Sub. 1*: subsoiling on one side of the citrus plant lines, and *Sub. 2*: subsoiling on both sides of the citrus plant lines. Extracted from Mafes Agromecânica Company.

evaluated using a helium pycnometer (ACCUPYC 130, Micromeritics Instrument Corporation^{TM}, USA). To determine the θ_{PWP}, a psicrometer was used, namely the WP4-T - Dewpoint Potential Meter (Decagon, 2003). The BD was obtained by the core method (Blake & Hartge, 1986). Soil macroporosity was determined using a sand tension table adjusted to 6 kPa of matric suction (Topp & Zebchuk, 1979). The TP was calculated by the relationship between soil bulk density and particle density, by the equation proposed by Vomocil (1965), where TP(%)=(1-BD/PD)x100. Soil microporosity was determined by the difference between total porosity and macroporosity (Embrapa, 1997).

The critical degree-of-compactness (DC) was determined from the disturbed soil samples, which were air-dried and passed through a 2 mm sieve. The DC of the soil was expressed as a percentage and calculated according to equation 1:

$$DC = 100 * \left(\frac{BD}{\rho_{ref}} \right) \tag{1}$$

where BD is the field soil bulk density and ρ_{ref} is the soil bulk density reference point.

The PR was evaluated in undisturbed soil samples under controlled moisture tension (10 kPa), using a static penetrometer. The penetration rod with a cone-shaped tip (0.04 m basal diameter, 60° angle) was inserted into the soil at a speed of 0.01 m min^{-1}, measuring the three central centimeters of each sample. The WA was calculated as the difference between θ_{FC} and θ_{PWP}. The θ_{FC} of the undisturbed samples was determined at 10 kPa in a Richards chamber.

The unsaturated hydraulic conductivity (K) was measured in the field by a multidisc infiltrometer (TRIMS) and the calculation protocol developed by Ankeny et al. (1991).

Yield and number of fruit per plant were determined at harvest, 150 days after subsoiling, by counting and weighing all fruits from three plants of each of the three treatments.

The experiment was arranged in a randomized block design with three replications. The results were subjected to W test for normality (Shapiro & Wilk, 1965) and variance analysis by the *F* test. The soil property means were compared by the Tukey test ($p<0.05$) using the Statistical Analysis Program (SAS, 2002).

RESULTS AND DISCUSSION

The field operations by agricultural machinery and implement traffic for 14 years had compacted the soil, as shown by BD values (Figure 2a). The use of the subsoiler loosened the structure of the compacted soil surface layer, reducing the BD from 1.60 Mg m^{-3} in the no-subsoiling treatment to 1.42 Mg m^{-3} in the subsoiled lines (subsoiling treatment). This is in agreement with results demonstrated by Voorhess et al. (1975). The efficiency of subsoiling to decompact the soil was significant to a depth of 0.8 m (Figure 2a). Reichert et al. (2009) proposed BD values of 1.40 to 1.50 Mg m^{-3} as being critical for normal plant development in this soil texture, therefore, the conventional management values are above the critical limit, which can restrict the plant production capacity.

The greater bulk density (BD) observed in the no-subsoiling treatment, (conventional system for citrus cultivation) was also observed by other authors (Fidalski et al., 2007; Becerra et al., 2010). This higher BD was due to heavy or repeated traffic of agricultural machine and implement operations. In the case of fruit tree plantations, these operations are always carried out between the plant lines, which can aggravate soil compaction under the wheel tracks, about 0.5 beyond the drip-line of the orange tree canopy. Sanches et al. (1999) also noticed an increase in soil bulk density in a sandy loam soil in Matão, SP, when comparing citrus cultivation to native forest, due to periodic machine and equipment traffic.

The critical degree-of-compactness (DC) decreased from 84 % in the no-subsoiling treatment to 77 % in the subsoiling (Figure 2b). The greater DC value observed where there was no compaction could be due to soil with a damaged structure (Klein, 2006; Reichert et al., 2009). Suzuki et al. (2007) confirm that an increased DC leads to a reduction in macroporosity and unsaturated hydraulic conductivity, and an increase in soil penetration resistance. Thus the reduction in DC observed as a result of subsoiling would be directly related to a reduction in soil bulk density and an increase in macroporosity (Figure 2).

The DC had a positive correlation (Table 2) with PR ($r^2=0.57$, $p<0.05$) and a negative one with Ma ($r^2=-0.66$, $p<0.05$), Mi ($r^2=-0.76$; $p<0.01$), TP ($r^2=-0.98$, $p<0.01$), and with WA ($r^2=-0.76$, $p<0.01$). This demonstrates that high DC values, above the critical limit for adequate plant development (80 % for this soil type) (Reichert et al., 2009), can indicate a poor physical quality, restricting root growth.

The penetration resistance (PR), determined at field capacity moisture (θ_{FC}), varied from 1.29 MPa in subsoiling to 1.90 MPa without subsoiling (Figure 2c), in agreement with the results presented by Voorhees et al. (1975). The PR increased with increasing soil depth in the no-subsoiling treatment (Figure 2c). This greater PR could be related to the process of age-hardening of the aggregates, which re-adhere and remain resistant for a time after the initial soil tillage (Utomo & Dexter, 1981). Furthermore, machine and implement traffic used in cultural operations lead to coarser and more dense soil aggregates (Semmel et al., 1990), increasing PR. On the other hand, practices

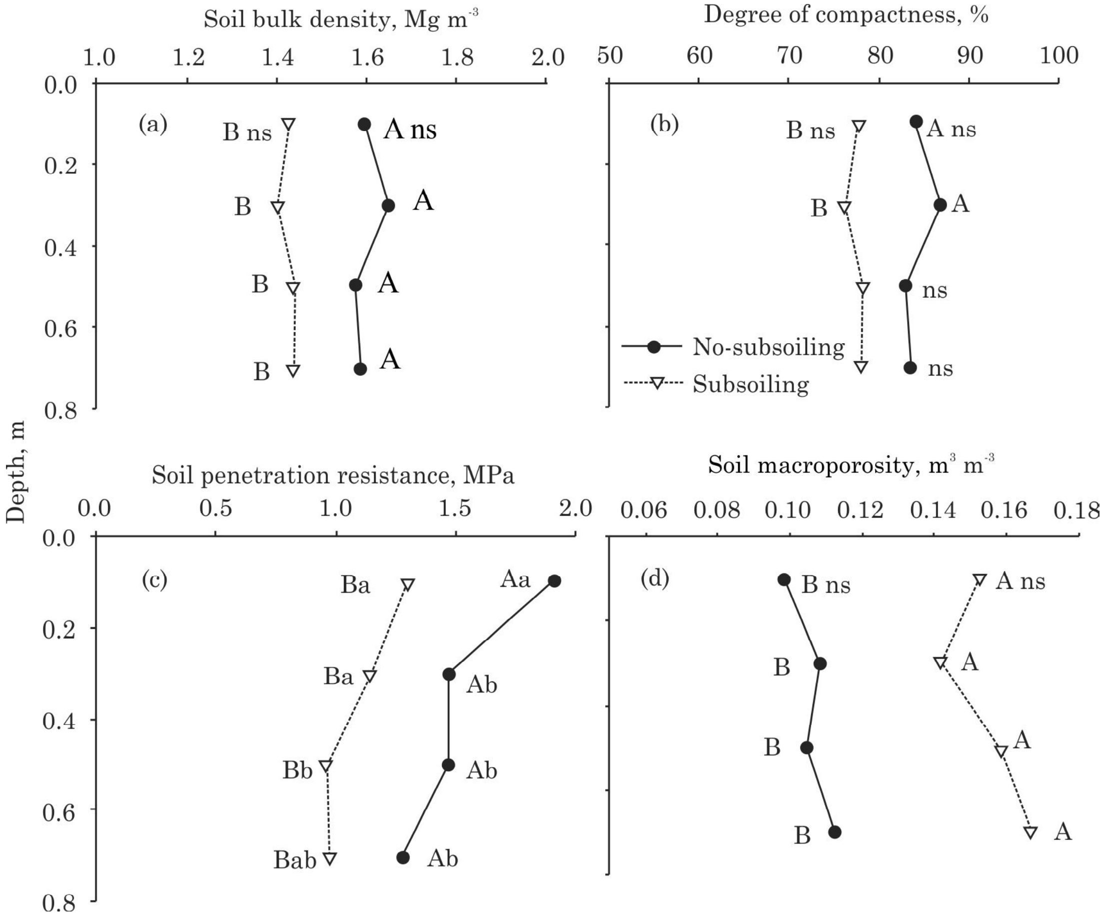

Figure 2. Soil physical properties in the treatments no-subsoiling and subsoiling, applied in a citrus orchard. Capital letters indicate differences between treatments and small letters, differences between depths; ns indicates no significance, based on the Tukey test (p<0.05).

that mobilize the soil, such as subsoiling, result in the breaking of links between soil particles and aggregates, which reduces PR (Dexter, 1988; Medeiros et al., 2011).

Penetration resistance was positively correlated with BD (Figure 3) and DC, but inversely correlated with porosity (Table 2). In the no-subsoiling, PR values were very close to the critical limit for plant growth (2 MPa) (Silva et al., 1994; Tormena et al., 1998). However, it is necessary to consider that PR had an inverse potential relation to soil moisture (Silveira et al., 2010; Figueiredo et al., 2011a), i.e., without subsoiling, in periods when soil moisture was below field capacity (which frequently occurs in non-irrigated orchards) the PR can reach the critical limit for good plant development faster.

Soil decompacting by the subsoiler elevated macroporosity (Ma) from 0.10 to 0.16 $cm^3 cm^{-3}$ in the soil surface layer (Figure 2d), and significant differences ($p< 0.05$) between treatments were observed at all soil depths. The reduction in Ma was related to the increase in BD; the correlation between Ma and BD was negative ($r^2 = -0.75$, $p < 0.01$) (Table 2).

Significant differences in total porosity (TP) were observed in all studied soil layers (Table 3), with mean values of 0.40 $cm^3 cm^{-3}$ in the no-subsoiling and 0.47 $cm^3 cm^{-3}$ in the subsoiling treatment. Soil compaction resulting from tractor traffic increased BD and decreased TP in an almond orchard in Almeria, Spain (Becerra et al., 2010). Soil porosity is drastically reduced by soil compaction (Dias Júnior & Pierce, 1996; Figueiredo et al., 2011b). In general, these soil properties indicate possible restrictions to plant root growth. Practices which improve porosity benefit the crop as they favor soil gas exchange (Silveira Junior et al., 2012), and increase soil water infiltration and drainage (Xu et al., 1992).

The water availability to plants (WA) and θ_{FC} did not differ ($p<0.05$) between the evaluated treatments (Table 3). Possibly, this similarity in soil water retention was due to the soil texture although there was a positive correlation between WA and TP and a negative correlation between WA and BD (Table 2).

The unsaturated hydraulic conductivity (K) in the soil varied between 7 and 22 cm h^{-1} (Figure 4); this

Table 2. Pearson correlation between physical and hydric properties of a soil under no-subsoiling and subsoiling treatments in a citrus orchard (n = 24)

	BD	Ma	Mi	TP	DC	PR
Ma	-0.75**					
Mi	-0.69*	0.05^{ns}				
TP	-0.69**	0.75**	0.68**			
DC	0.98**	-0.66*	-0.76**	-0.98**		
PR	0.64*	-0.70*	-0.20^{ns}	-0.64**	0.57*	
WA	-0.69**	0.03^{ns}	0.98**	0.68*	-0.76**	-0.20^{ns}

BD: soil bulk density; Ma: soil macroporosity; Mi: soil microporosity; TP: soil total porosity; DC: degree-of-compactness; PR: soil penetration resistance; WA: water availability to the plants. *, **: significant at 5 and 1 %, respectively, and ns: no significant difference.

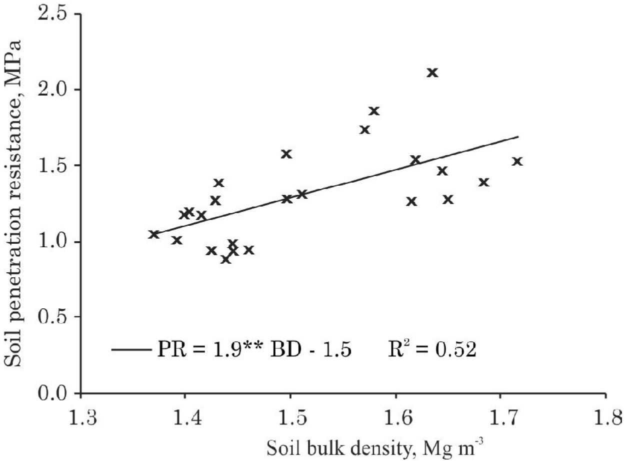

Figure 3. Penetration resistance in function of soil bulk density, in the soil no-subsoiling and subsoiling treatments in a citrus orchard (n = 24). The PR was evaluated in soil samples under controlled moisture tension (10kPa).

Table 3. Physical and hydric properties of a soil under citrus trees

Treatment	Soil layer	TP	θ_{FC}	WA
	m	m^3 m^{-3}		
No-subsoiling	0.0-0.2	0.40 a	0.28^{ns}	0.23^{ns}
	0.2-0.4	0.39 a	0.25	0.15
	0.4-0.6	0.41 a	0.28	0.16
	0.6-0.8	0.41 a	0.27	0.16
Subsoiling	0.0-0.2	0.47 b	0.29	0.24
	0.2-0.4	0.48 b	0.31	0.21
	0.4-0.6	0.47 b	0.28	0.16
	0.6-0.8	0.47 b	0.27	0.16

No-subsoiling: without tilling the soil; subsoiling on both sides of the plant lines; TP: soil total porosity; θ_{FC}: field capacity; WA: water availability to the plants. ns: not significant. Different letters in each soil layer indicate differences between treatments by the Tukey test (p<0.05).

enables it to be classified as porous materials with high permeability (Reynolds & Elrick, 1986), related to the sandy texture of the soil studied. A significant difference of K between treatments was only observed at higher matric potentials, between -0.1 and -0.35 kPa. At a matric potential of -0.1 kPa, K was 18 cm h^{-1} in the no-subsoiling, and 23 cm h^{-1} in the subsoiling tretament (Figure 4), showing that decompaction increased the soil capacity to transmit water. The same behavior was observed in the matric potential of -0.35 kPa, as K increased from 11.5 to 14 cm h^{-1} (Figure 4).

In studies on soil physical alterations in soils cultivated with citrus, Soares et al. (2005) also observed a reduction in soil water infiltration caused by compaction due to crop management practices. This reduction in K was a consequence of intensive machine traffic between the crop rows. Systems with little soil tillage and heavy machine traffic can compact the soil to a depth of 0.4 m (Salire et al., 1994).

On the other hand, when the matric potential was reduced to -1.0 kPa, no differences in K were observed among treatments. In this case, we must consider that water movement in unsaturated soils is affected by the size distribution and connectivity of the pores (Ahuja et al., 1984), and that the stability of sandy soils affected by changes in the hydric behavior, provoked by soil compaction, is greater than of soils with a higher clay content.

Improvements in soil physical conditions reflected positively on the yield of citrus and on the number of fruits per plant. In the treatments no-subsoiling, *Sub. 1*, and *Sub. 2*, the yields were, respectively, 42,

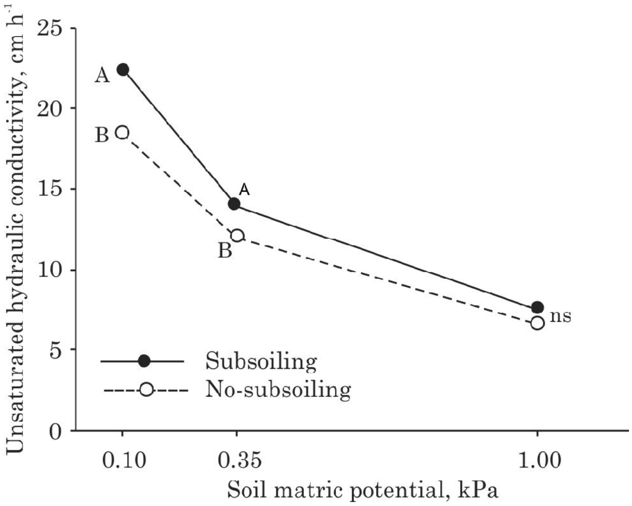

Figure 4. Unsaturated hydraulic conductivity measured in the soil surface layer, in the soil no-subsoiling and subsoiling treatments in a citrus orchard. Where are these different letters indicate significant differences between subsoiling and no-subsoiling, and ns indicates no significance, based on the Tukey test (p< 0.05).

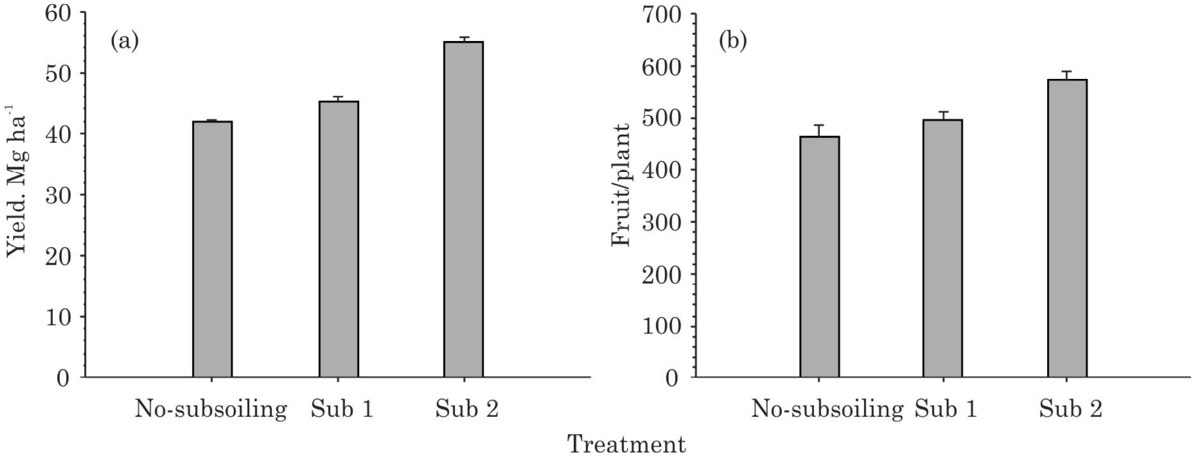

Figure 5. Fruit yield (a) and number of fruits per plant (b) in a citrus orchard subjected to the treatments: no-subsoiling, subsoiled on one side of the plant lines (*Sub. 1*), and subsoiled on both sides of the plant lines (*Sub. 2*). The vertical bars indicate standard errors.

45 and 55 Mg ha^{-1} (Figure 5a). The same trend was observed in fruit number per plant, with 462, 497 and 572, respectively, in the same treatments (Figure 5b).

The yield increase was proportionately greater than the increment in number of fruits, demonstrating that the treatments with soil subsoiling promoted greater fructification, also resulting in greater fruit mass than in the no-subsoiling treatments. Nuñez Moreno & Valdez Gascon (1994) concluded that the fruit production of citrus orchards on soils compacted by management practices decreased.

The yield assessment showed that improvements in soil physical and hydric properties, resulting from subsoiling, considerably increase the citrus plant performance (Figure 5). These improvements influenced crop yield, with a 31 % increase in fruit mass. Thus, interrow subsoiling in established citrus orchards, despite damaging roots in the tilled zone, could have a positive effect on plant growth, due to increased root depth penetration (Shaxson & Barber, 2003). The reduction in soil bulk density and mechanical penetration resistance increased the macroporosity, with consequent increase in hydraulic conductivity along the profile (down to 0.80 m), showing that subsoiling contributed to improve the soil structure, favor the flow of air, water and nutrients along the profile, and consequently, to increase the citrus yield (Figure 5). It is important to consider that subsoiling could only have short-lived effects on physical properties, as reported by Minatel et al. (2006), in a sandy clay loam Typical Haplustox, where no positive influences of subsoiling were observed after one year of this mechanical practice, in a citrus orchard in Santa Adelia, SP. Besides the effect of soil tillage on reducing soil impedance, other amelioration techniques could be helpful to improve soil structure and avoid restrictions for woody plants grown on compacted soils (Day & Bassuk, 1994). On the other hand, subsoiling is an essential technique to increase root depth penetration in soils with strong physical limitations, as of cohesive layers (Melo Filho et al., 2009).

Thus, subsoiling between the plant lines of citrus orchards alters the physical and hydraulic properties of the soil, reflected in increased soil macroporosity and unsaturated hydraulic conductivity and in reduced soil bulk density, critical degree-of-compactness and penetration resistance. The improvements in soil physical and hydric properties increase fruit number and orchard yield.

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