Journal of Agricultural Science; Vol. 10, No. 10; 2018
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Ability of Citrus Root System to Overcome a Strong Wax Layer

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Received: May 13, 2018 Accepted: July 2, 2018 Online Published: September 15, 2018

doi:10.5539/jas.v10n10p213 URL: https://doi.org/10.5539/jas.v10n10p213

Abstract

The present work aimed to investigate the effects of mechanical impedance of wax layer (wax discs were installed 0.1 m deep) on root system deepening of citrus seedlings growing in columns with sand and nutrient solution. Two planting systems were evaluated: direct seeding (DS) and planting of seedlings (PS) (plants obtained from seed germination in tubes). Two experiments were carried out in a sequence: first to investigate the wax layer resistance levels (0.14 to 2.7 MPa) on root system penetration and two planting systems (DS and PS). The second evaluated the root and plant development of the two planting systems and two resistance of wax layer to root penetration: control (0.14 MPa) and a strong wax layer (1.06 MPa). The experimental design was randomized blocks, the first experiment in a 2 × 4 factorial scheme with 4 replications and the second a 2 × 2 factorial scheme with 6 replications. Resistance level ≥ 1.52 MPa (60% hard wax and 40% soft wax) completely limited root penetration in the artificial strong layer. The presence of strong wax disc reduced the citrus root system in both planting systems. PS was associated with greater root and shoot vigor, indicating that, in soils with good physical structure and porosity or allowing root deepening beyond the cohesive layer, this planting system is fully adequate, despite the possible benefit of not cutting the pivoting root in direct sowing.

Keywords: root structure, root penetration capacity, rootstock

1. Introduction

The low yield of citrus orchards on Coastal Tablelands of Northeast Brazil, the second largest producing region of the country (IBGE, 2015), is mainly attributed to seasonal rainfall and presence of cohesive soils (Rezende et al., 2015). Cohesive horizons in soils of the Coastal Tablelands, with massive structure and hard to extremely hard consistency when dry, affect water dynamics and the distribution of roots, which are highly sensitive to the presence of cohesion (Souza et al., 2008). Consequently, the depth of the plant root system is reduced, by either the resistance to penetration (Silveira et al., 2010) aggravated by soil drying, or poor aeration (Cintra et al., 1999, 2000).

Numerous experimental results elucidate the problem imposed by the cohesive layer and restriction to root system deepening, and the root system superficially concentrated. For instance, root distribution of five citrus rootstocks in a Gray Argisol of Coastal Tableland, [Volkamer lemon ‘Palermo’ and ‘Catânia’ (*Citrus volkameriana* Pasquale), ‘Rangpur’ lime (*Citrus limonia* Osbeck), ‘Rough Florida’ lemon (*Citrus jambhiri* Lush) and ‘Cleopatra’ mandarin (*Citrus reshni* Hort. ex Tan)], were spatially positioned on average 61% in the 0-0.20 m layer and 90% in the 0-0.40 m layer (Cintra et al., 1999). Similar results were obtained by Souza et al. (2004), and Santana et al. (2006), also in cohesive soils.

Soil tillage also directly affects root distribution, allowing greater or lower exploration of the soil by plant roots (Souza et al., 2008). Because of that, there are recommendations of planting in holes with greater depth beyond the cohesion (Souza et al., 2006), deep subsoiling practices (Rezende, 2013) and use of plant cover (Carvalho et al., 1999, 2001), all aiming to favor root deepening and increase yield (Carvalho et al., 2002). Plant cover management reduces risks of erosion, improves water infiltration capacity and storage to plants, and is related to improvement of soil structure (Carvalho et al., 2004), besides allowing the deposition of organic matter on the soil to increase microbial activity and, in the long run, the carbon stock in the soil (Oliveira et al., 2016).

Beneficial effects on the activity of soil organisms, such as earthworms, which can promote the improvement of its physical structure (macro- and microporosity), lead to increment in the network of channels and biopores for roots to explore the soil in subsurface (White & Kirkegaard, 2010; Gao et al., 2016).

Alternatively, the practice of sowing the rootstock in the definitive site (DS) for later grafting in the field has been performed as a technical option for citrus growers, in order to minimize the agricultural limitations of the Coastal Tablelands (Rezende, 2013), aiming at favoring root system deepening, since the taproot grows free and intact, and maintenance of good water status in the plants in the driest periods of the year (Rezende et al., 2015).

However, it is criticized as a risky practice that exposes very young plants to biotic stress as citrus variegated chlorosis (CVC). The infection of bud emitted after grafting compromises the entire plant.

Impacts of soil drying on root architecture, and the development and yield of citrus plants on Coastal Tablelands are described in the literature (Santana et al., 2006; Souza et al., 2008), when the impediment to root penetration is the major cause of reduction in citrus production, due to the presence of cohesive layers. Hence, the present study aimed to investigate, based on cultivation system adapted from Coelho Filho et al. (2013) and mechanical impedance layer simulations by Clark et al. (2000), and Whalley et al. (2013), the effects of the presence of physical impedance on the root architecture of citrus, considering also two planting systems (direct sowing and planting of seedlings).

2. Method

The study was carried out in greenhouse, using two contrasting citrus genotypes (rootstocks) with respect to drought tolerance (Sampaio et al., 2016; Santana-Vieira et al., 2016): 'Rangpur Santa Cruz' lime (*Citrus limonia* Osbeck) (tolerant to drought) and 'Sunki Maravilha' mandarin [*Citrus sunki* (Hayata) hort. ex Tanaka] (sensitive to drought). The study was divided into two experiments with the purpose to simulate only the abiotic stress caused by physical impedance to root penetration. Temperatures were 24.5 and 21.5 °C along the first and second experiments, respectively. Mean relative air humidity was equal to 70% in the first experiment and to 80% in the second one.

2.1 1st Experiment

Effects of cohesive layers with different levels of resistance to root system penetration were artificially simulated to find the limit for the penetration of 'Sunki Maravilha' mandarin roots. The layer with impedance to root development was artificially prepared using wax discs, as described below. This experiment also considered two cultivation systems: direct seeding (DS) and planting of nucellar seedlings (plants obtained from seed germination) grown in tubes (PS).

Possible differences related to the age of plants grown in these two planting systems were avoided by the simultaneous seeding in the definitive PVC tube and nursery tubes, respectively representing DS and PS. To guarantee nucellar seedlings (DS), four seeds were planted in each PVC tube, eliminating the hybrids and maintaining only the most vigorous plant. At 60 days after sowing, the seedlings (PS) were transplanted to the PVC tubes.

Plants were grown in PVC tube (0.15-m external diameter and 0.50-m length) filled by coarse sand washed and sterilized by autoclaving. In the filling process, a paraffin disc was installed at 0.1 m deep, to represent the artificial impedance layer to root system penetration, according to Clark et al. (2000). Only one plant was maintained in each PVC tube. The tubes were placed in aluminum box (0.40 m × 0.70 m × 0.55 m) containing nutrient solution with the following composition, allowing a electrical conductivity close to 2 dS m^{-1}: 5.0 mM of KNO_3, 3.0 mM of $Ca(NO_3)_2{\cdot}5H_2O$, 1.3 mM of $NH_4H_2PO_4$, 1.6 mM of $MgSO_4{\cdot}7H_2O$, 58 µM of $FeSO_4{\cdot}7H_2O$, 29 µM of H_3BO_3, 10 µM of $MnSO_4{\cdot}H_2O$, 1.0 µM of $ZnSO_4{\cdot}7H_2O$, 0.9 µM of $CuSO_4$ and 0.2 µM of $(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$ (Furlani, 1999). Along the experiment, the nutrient solution level was maintained at height of 30 cm, guaranteeing good water supply to the plant in the entire sand profile. The pH was evaluated weekly and adjusted to 6.0 by using sodium hydroxide (NaOH) or hydrochloric acid (HCl). A small 1-mm opening between the pipe wall and the paraffin allowed, through capillary action, the nutrient solution to nourish the plants. The entire system was aerated 24 hours a day, thus avoiding any type of abiotic stress, except the simulated impedance (Figure 1A).

The paraffin discs simulating the presence of an artificial cohesive layer were made by mixing paraffin in the form of lentil (56-58 °C fusion point) and creamy-textured industrial hot wax (60 °C fusion point). The paraffin-wax proportion defined the adopted resistance level, ranging from 0.14 to 2.7 MPa according to Figure 1, with the following concentrations: 10%, 60%, 70% and 80% (Figure 1B). The experiment was carried out in randomized blocks with four replications, totaling 32 pipes. The mixture was poured into a circular aluminum foil mold in such a way to form a disc with 3-mm thickness and 14.7-cm diameter, according to Clark et al. (2000).

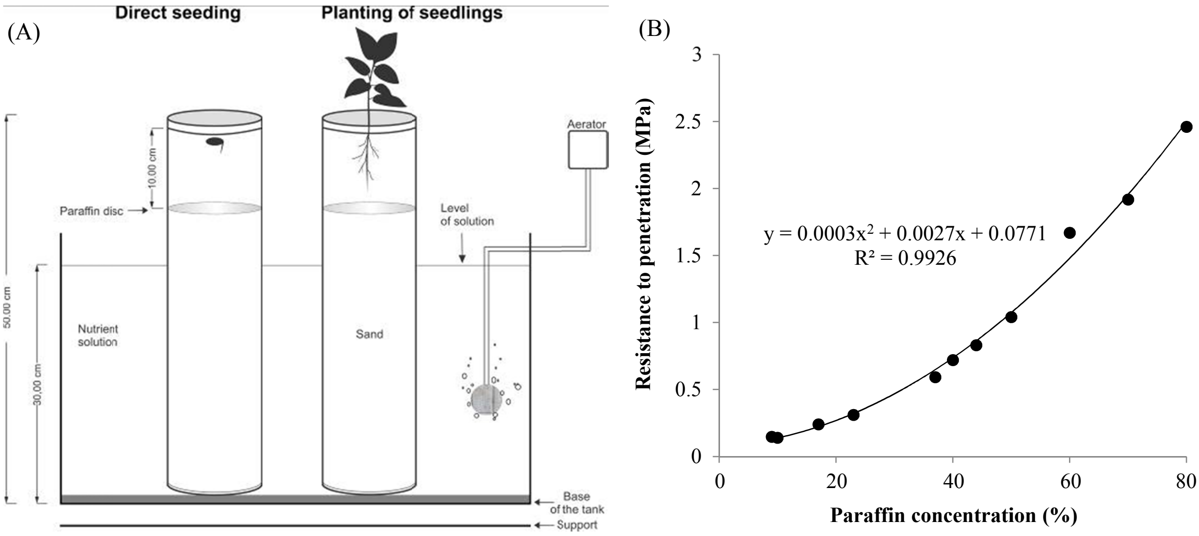


Figure 1. Growing system used in the Experiments 1 and 2, showing the PVC tubes, nutrient solution and the wax disc arrangement in the sand profile in two planting systems, direct seeding and planting of 60-day old seedlings (A). Relationship between hard wax concentration (%) and resistance to root penetration (MPa) determined using a benchtop penetrometer (model MA933). Each point corresponds to the average of three measurements (B)

2.2 2nd Experiment

This experiment tested the effect of two levels of mechanical impedance of wax disc on 'Rangpur Santa Cruz' lime growing in the same system of Experiment 1: 0.14 and 1.06 MPa, respectively corresponding to 10% and 50% hard wax concentrations combined with the soft wax. These levels were defined based on the first experiment: no limiting to root penetration (0.14 MPa, control) and a higher level (1.06 MPa), whose effects do not limit root penetration completely (occurred at 60%, 1.52 MPa). The methodological procedures of this experiment were the same applied in the first experiment.

Before starting the experiment, a quick assay using four genotypes, including 'Sunki Maravilha' and 'Rangpour Santa Cruz' lime, was performed to confirm no limitation to root system to overcome the wax layer with this mechanical impedance (data not show).

2.3 Morphophysiological Evaluations

Both experiments ended four months after planting, when the following growth and physiological variables were determined: number of leaves (NL), plant height (PH), leaf area (LA), root length (RL), root diameter (RD), root dry matter (RDM) and shoot dry matter (SDM).

The LA (cm^2) was estimated based on length and width of leaf multiplied by an adjustment factor equal to 0.72 (Coelho Filho et al., 2012), and the total LA was the sum of all expanded leaves assessed in each plant. Plant height (cm) was assessed as the distance from the base of the plant to the insertion of the last leaf formed. Roots collected in each tub (above and below the wax disc) were washed, stored at 10°C in 30% alcohol until the analysis. A scanner was used to image digitization that were processed using the software WinRhizo, version 2013d, with 400-dpi resolution. The following variables were evaluated: average root diameter (mm) and total root length (cm). For the Experiment 2, root diameter was divided into four classes: 0-2.0; 2.0-3.0; 3.0-4.0 and > 4.0 (mm).

A precision weighing balance was used to determine the shoot dry matter (SDM) and root dry matter (RDM). The samples were maintained in forced air circulation oven at 65 ºC for 72 hours before weighing.

2.4 Statistical Analysis

The design used in both experiments was randomized blocks. The first one, in a 4 × 2 factorial scheme with four replications per treatment, evaluated two factors: physical impedance promoted by the artificial impedance layer (four levels) and two planting systems. In the second experiment, also in factorial scheme (2 × 2), the factors were: two levels of physical impedance promoted by the cohesive layer and two planting systems. Each treatment had six replications, totaling 24 experimental units. In both experiments, data were evaluated as for normality with Shapiro Wilk test ($p \leq 0.05$), as for homogeneity of variances with F test ($p \leq 0.05$) before analysis of variance and the means were compared by Tukey test at 0.05 probability level or by polynomial or linear regressions using the Sisvar 4.6 statistical software (Ferreira, 2011), for the variables in response to the tested levels of physical impedance, when significant effects were observed for factors or interactions.

3. Results

3.1 1st Experiment—Evaluation of Citrus Root Penetration in Substrate With Artificial Wax Layer

Resistance to root penetration increased with the paraffin percentage added to the discs, reaching 2.7 MPa at 80% of hard paraffin (Figure 1B). Paraffin concentration of 10%, used in the control treatment, led to resistance to penetration of 0.14 MPa (Figure 1B). The resistance imposed by the 60% hard paraffin concentration completely limited root system penetration, corresponding to 1.52 MPa.

There was no interaction between planting system and physical impedance for the variables PH and SDM, but there was effect for LA ($p > 0.05$) (Table 1). The planting system and the mechanical impedance alone did not affect the leaf area. Plant height was sensitive only to the wax layer ($P > 0.05$). There was no effect of treatments applied for SDM (Table 1). Plant height was not sensitive to this factor. The layer with physical impedance had significant effect on PH ($p < 0.01$), but not on total LA. The applied treatments had no effect on SDM (Table 1). The physical impedance caused by the artificial wax layer led to a quadratic reduction, resulting in reduction of growth, in PH, on the order of 12% for impedance of 2.7 MPa, compared with the control (Figure 2A). The highest level of mechanical impedance in the planting system seedlings promoted a reduction of 23% in the leaf area, when compared to the control (Figure 2B).

Table 1. Means of plant height (PH), leaf area (LA), shoot dry matter (SDM), root length above (RL-AB) and below (RL-BL) the impedance, root dry matter (RDM), total root length (TRL) in the artificial cohesive layer and average root diameter (RD), root diameter above (RD-AB) and below (RD-BL), the impedance for direct seeding (DS) and planting of seedlings (PS), in 4-month-old nucellar seedlings (plants originated from seed germination) of 'Sunki Maravilha' mandarin [*Citrus sunki* (Hayata) hort. ex Tanaka], Experiment 1

Source of variation	PH	LA	SDM	RL-AB	RL-BL	RDM	TRL	RD	RD-AB	RD-BL
Planting systems (Syst)	1.14^{ns}	227^{ns}	0.009^{ns}	24.577^{**}	6.908^{ns}	0.0957^{**}	5.423^{ns}	0.009^{*}	0.007^{ns}	0.010^{*}
Impedance levels (IL)	2.62*	729^{ns}	0.008^{ns}	16.579^{**}	41.306^{**}	0.1456^{**}	13.353^{*}	0.022^{**}	0.028^{**}	0.018^{**}
Interaction Syst × IL	1.00^{ns}	1.657^{*}	0.015^{ns}	$1.094.5^{ns}$	11.380^{**}	0.0622^{**}	18.852^{**}	0.007^{ns}	0.313^{ns}	0.831^{ns}
Means	PH (cm)	LA (cm^2)	SDM (g)	RL-AB (cm)	RL-BL (cm)	RDM (g)	TRL (cm)	RD (mm)	RD-AB (mm)	RD-BL (mm)
Direct seeding (DS)	11.14a	36.99a	0.424a	132.86b	98.08b	0.338a	261.9a	0.633b	0.720a	0.546b
Planting of seedlings (PS)	10.77a	42.05a	0.391a	188.3a	128.98a	0.228b	287.9a	0.670a	0.750a	0.582a
LSD	0.67	15.17	0.135	27.67	25.00	0.064	39.98	0.030	0.038	0.035

Note. Means followed by the same letters do not differ statistically by Tukey test at 0.05 probability level and least significant difference for the studied variables.

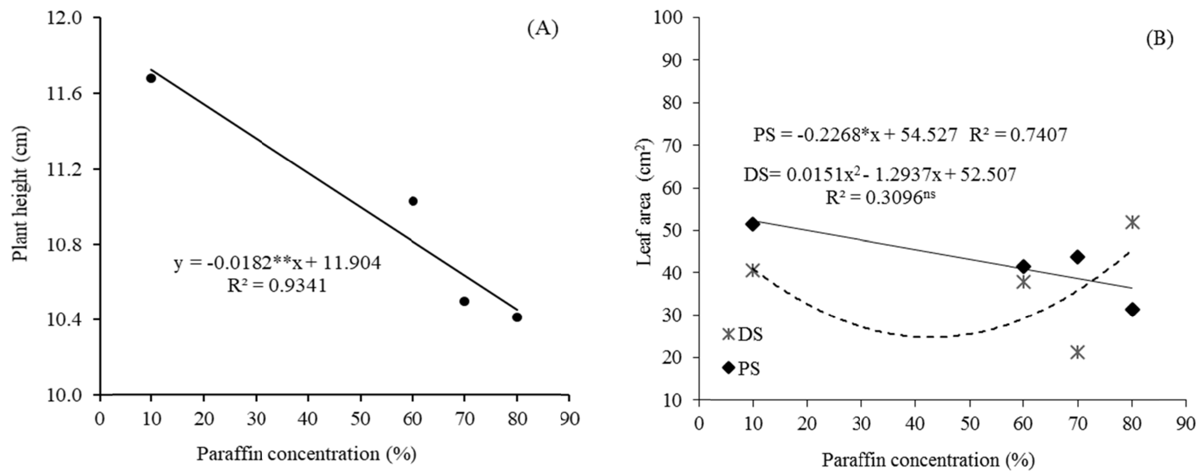
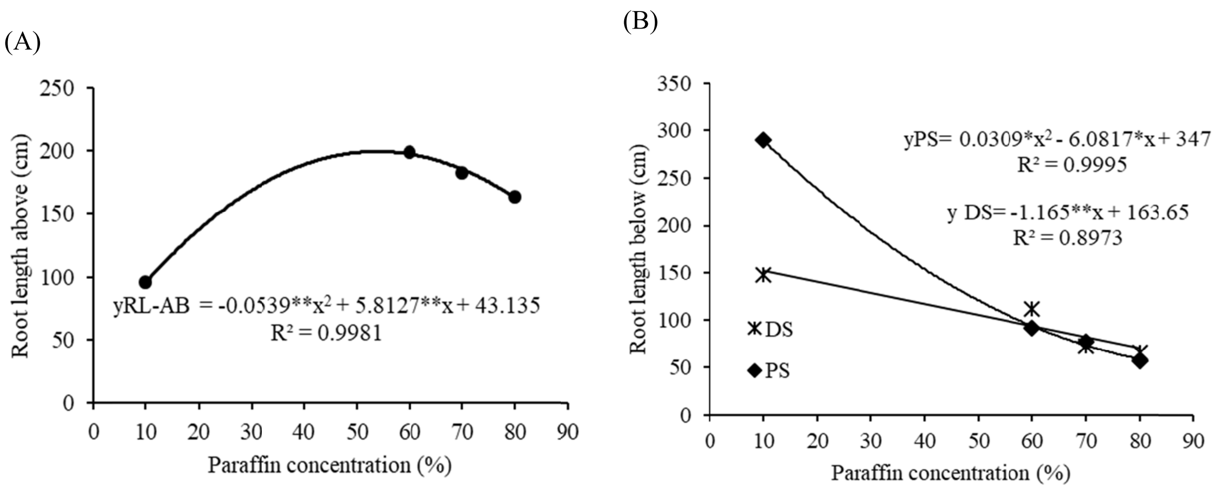


Figure 2. Leaf area in the systems of direct seeding (DS) and planting of seedlings (PS) (A) and plant height as a function of the applied impedance levels (B) in 4-month-old nucellar seedlings (plants originated from seed germination) of 'Sunki Maravilha' mandarin [*Citrus sunki* (Hayata) hort. ex Tanaka]

There was interaction ($p < 0.01$) between planting system and physical impedance regarding root system variables: RDM, TRL and RL-BL the physical impediment applied (Table 1). However, there was no interaction regarding RD and RL-AB the wax disc. The increment of levels of mechanical impedance reduced all analyzed roots variables, except the mean root diameter increased (Figures 3A-3E). The impedance of 2.7 MPa in the root length below the physical impediment applied was 57% and 83% in the system of direct sowing and planting of seedlings, when compared to the control, respectively (Figure D). The planting system did not affect the TRL and RD-AB the wax disc.

For both DS and PS, the control treatment (10% of hard wax) led to a vertical direction in the main root growth, whereas at the other concentrations lateral roots showed vertical/horizontal growth. At paraffin concentrations ≥ 60%, root system was curling and flattened above the wax layer. There was interaction between planting system and impedance ($p \leq 0.05$) for root length (RL-AB and RL-BL). Presence of physical impedance and its resistance levels led to linear reduction of root length for the system with planting of seedlings. Direct seeding, however, caused a slight growth of the root system until reaching the limit of root penetration (60% hard paraffin and 40% wax). For total root length, the direct seeding system showed 26.5% more roots ($p \leq 0.05$) compared with the PS (Figure 3).



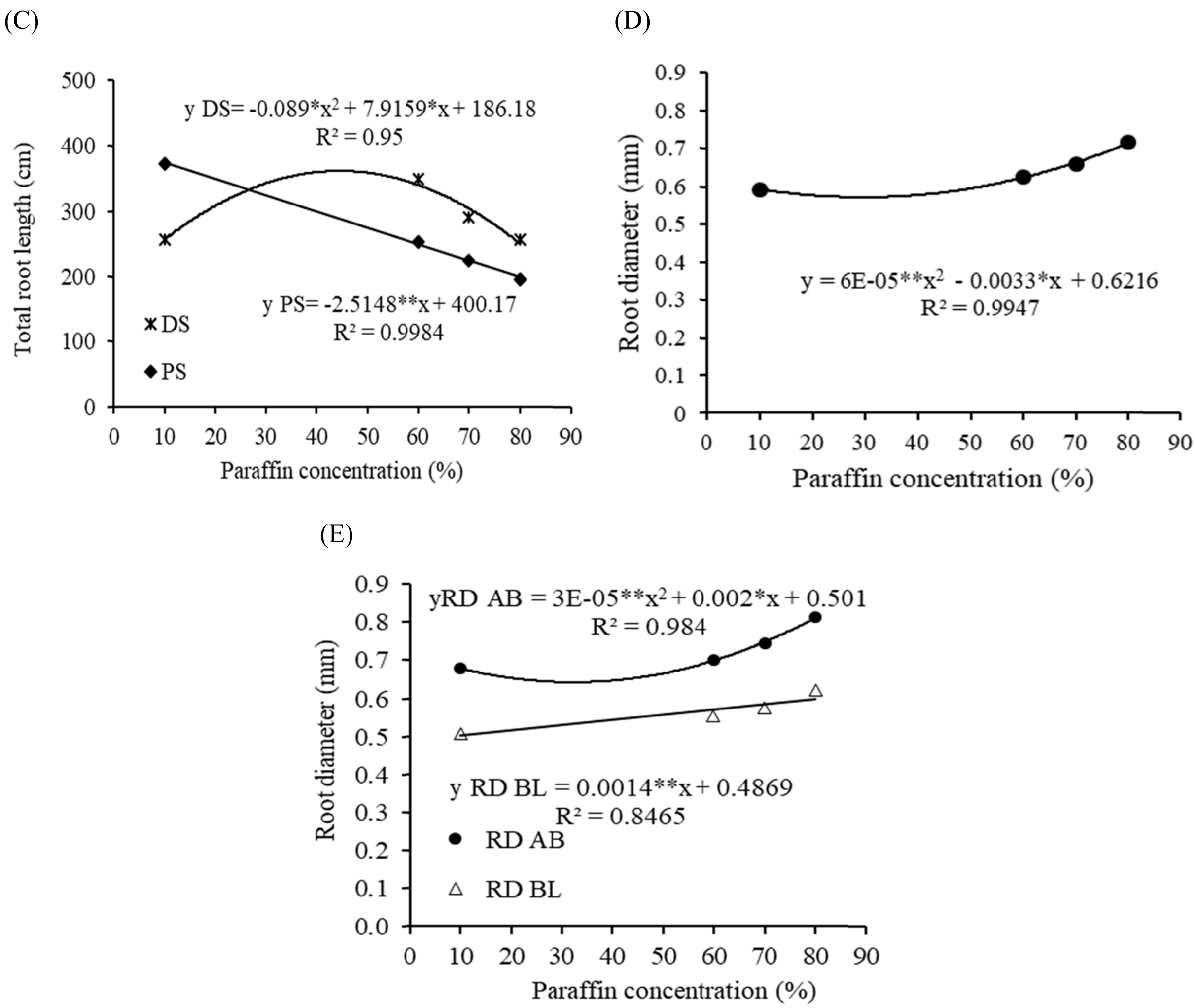


Figure 3. Effect of physical impedance layer on root length above (RL-AB) (A), root length below (B) and total root length (C) for direct seeding (DS) and planting of seedlings (PS), root diameter (D) e root diameter above (RD-AB) and below (RD-BL) for DS and PS (E) in 4-month-old nucellar seedlings (plants originated from seed germination) of 'Sunki Maravilha' mandarin [*Citrus sunki* (Hayata) hort. ex Tanaka], with potential of use as rootstock

Increase in physical resistance to penetration affected root diameter with increment of structural and lateral roots of different order (> 2.0 mm) in relation to thin roots, responsible for the absorption of water and nutrients. The response was positive for the region above the artificial cohesive layer and negative for points below it, which explained the interaction (Figure 4).

3.2 2nd Experiment

Except for SDM, there was no interaction between impedance levels and planting systems (Table 2). The factor planting system affected plant shoot variables, and the planting of seedlings (PS) led to higher vigor, compared with direct seeding, on the order of 48%, 27%, 60% and 49% respectively for PH, SD, LA and SDM (Table 2).

Table 2. Statistical summary and means of growth variables measured in 4-month-old nucellar seedings of 'Rangpur Santa Cruz' lime (*Citrus limonia* Osbeck) subjected to treatments involving physical impedance to root development (IL) and two planting systems: direct seeding (DS) and planting of seedlings (PS). Plant height (PH), stem diameter (SD), leaf area (LA), shoot dry matter (SDM), total root length (TRL), root length above (RL-AB) and below (RL-BL) the impedance, root dry matter (RDM) and average root diameter (RD)

Source of variation	PH	SD	LA	SDM	RL-AB	RL-BL	TRL	RDM	RD
Planting systems (Syst)	401.80**	3.91**	113949.6**	2.30**	138,651.3**	53,261.9**	473,726**	0.856**	0.026 ^{ns}
Impedance levels (IL)	2.04^{ns}	0.007^{ns}	3632.4^{ns}	5.36**	5,760.6^{ns}	199.4ns	29,081.9^{ns}	0.068^{ns}	0.023 ^{ns}
Interaction Syst × IL	13.50^{ns}	0.168^{ns}	6695.4^{ns}	4.73**	6,192.9^{ns}	97.9^{ns}	3,577.89^{ns}	0.0001^{ns}	0.018^{ns}
Mean	PH (cm)	SD (mm)	LA (cm²)	SDM (g)	RL-AB (cm)	RL-BL (cm)	TRL (cm)	RDM (g)	RD (mm)
Direct seeding (DS)	8.74b	2.16b	93.78b	0.645b	204.70b	92.96b	293.57b	0.231b	0.591a
Planting of seedlings (PS)	16.93a	2.97a	231.59a	1.263a	356.72a	187.18a	574.56a	0.609a	0.657a
LSD	2.92	0.371	51.4	0.323	48.85	21.53	73.19	0.163	0.095

Note. Means followed by the same letters do not differ statistically by Tukey test at 0.05 probability level and least significant difference for the studied variables.

As occurred for the variables related to the shoots, the planting systems affected the roots (p > 0.01) and the planting of seedlings also led to increments on the order of 62%, 58%, 49%, 11% and 58% in TRL, RDM, RL-BL and RL-AB the impedance and root diameter, respectively, compared with direct seeding. The physical impedance did not affect the TRL, RDM, RL-BL and RL-AB wax layer and RD. However, the 50% hard wax concentration provided a 70% reduction in SDM in the DS system in relation to PS (Table 2).

Considering the TRL for different diameter classes (0-2.0; 2.0-3.0; 3.0-4.0; > 4.0 mm), no interactions occurred as well, but the factors (impeded layer and planting systems) affected the classes 0-2.0 and 2.0-3.0 mm. It should be pointed out that plants subjected to strong layer and particularly the PS presented the highest values of TRL in these diameter classes (Figure 4).

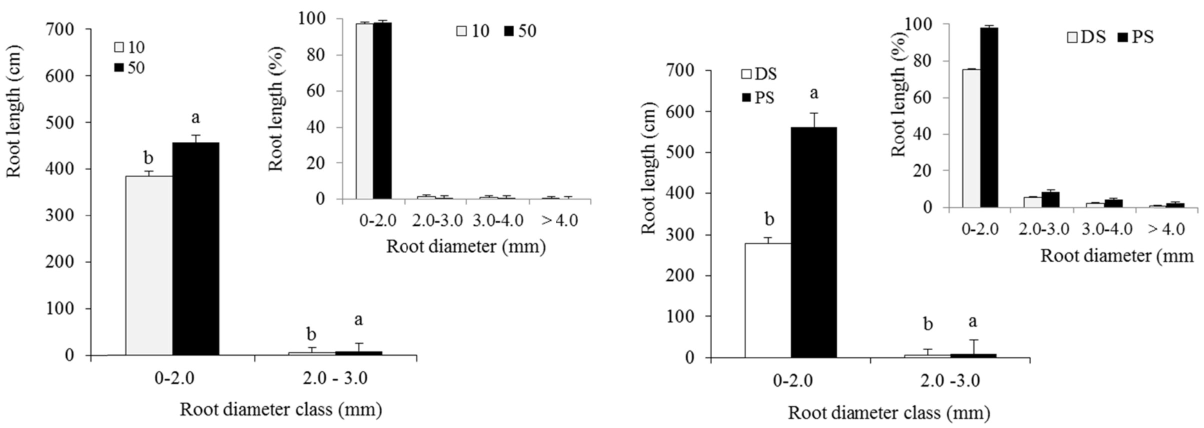


Figure 4. Root length for the diameter classes 0-2.0 and 2.0-3.0 (mm) in 4-month-old nucellar seedlings (plants originated from seed germination) of 'Rangpur Santa Cruz' lime (*Citrus limonia* Osbeck). Bars indicate mean standard error at the impedance levels (n = 6). Different lowercase letters indicate statistical difference (p < 0.05) between the impedance levels

4. Discussion

The presence of wax disc simulating cohesive layer with resistance to penetration ≥ 1.52 MPa limited the root penetration of the nucellar seedlings of 'Sunki Maravilha' mandarin and 'Rangpur Santa Cruz' lime, regardless of the planting system. This value is lower than that established as critical under field conditions, 2.0 MPa (Tormena et al., 1998). When there is a reduction of 50% in plant root system (Gregory et al., 2009). Limiting the advance of roots to deeper layers, by the physical impedance, leads to reduction in plant height (Figure 2B) and increment in root diameter above the physical impedance (Figure 4).

The resistance ≥ 1.52 MPa confined the root distribution above the mechanical impedance (0-10 cm), but at lower resistance levels roots were able to overcome the impedance, and gradually expand to greater depths. These results corroborate studies on root distribution in both field and protected environment, such as Santana et al. (2006), Silveira et al. (2008), Souza et al. (2008). In soils of Coastal Tablelands, with high bulk density and low macroporosity in the cohesive horizon, increase in soil resistance to root penetration and reduction in porous space have marked effect on the distribution of roots of cultivated plants (Santana et al., 2006), confining them to the surface layers of the soil.

Under full limitation to root penetration (Experiment 1), there are no differences in root diameter between the systems, indicating that intrinsically there are no differences regarding the capacity to penetrate cohesive soils. Root diameters observed in the first experiment were higher above the wax layer (Figure 3) a typical response to the higher resistance to penetration only observed on first experiment, an adaptive response of the roots (Gregory et al., 2009) to the hard soil. Higher values of root diameter in the PS, when there was no limitation to root penetration (Table 2), suggest greater capacity of these plants to explore harder soils, which goes against the assumptions of gains with the seeding in definitive site under field conditions. Increment in root diameter, combined with the effects of higher total root length, above and below the wax disc by planting of seedlings (Table 2) suggest plants with greater capacity to explore the soil, to hydraulically transport water, indicating higher hydraulic conductivity in this system (Comas et al., 2013).

Interactions between factors (planting systems and mechanical impedance to root penetration) for root system variables occurred due to the difference between the responses of the planting systems to the resistance levels. Results suggest that root deepening does not explain any plant growth response when there are limitations to root development. Hence, only with the presence of strong wax disc, plants directly sown, supposedly with greater root deepening capacity, have higher capacity to explore the soil surface, because they promoted increase in root length density (Figure 3). Plant ability to increase root density above the cohesive layer explains the presence of greater root concentration in cohesive soils of the Coastal Tablelands (Cardoso et al., 2006; Santana et al., 2006; Silveira et al., 2008), and the most superficial soil layers are where the highest water uptake by plants occurs.

When roots are subjected to physical limitation to deepening, the ability to deeply explore soils may not be given by the capacity to penetrate compacted soils, but by the capacity to locate the presence of porosities promoted by either living organisms such as earthworms or cracks that may be created by the decomposition of roots from crops pre-established in successions or areas with soil structures without compaction, which may occur in soils with higher clay contents (Gao et al., 2016). In this case, root penetration to greater depths depends more on how roots are able to find connections between pores than on their capacity to deform hard soils, and the most important factors are the differences between types of soil and management (Gao et al., 2016). Souza et al. (2004) observed much higher presence and deepening of citrus roots in soil chemically poorer, but without cohesion, in comparison to other two soils chemically richer, but with cohesion, which allows to infer that in this case the cohesive aspect overcame soil chemical conditions.

The planting of seedlings, compared with direct sowing, led to greater root development with physical impedance ≤ 1.52 MPa. This can be explained by the fact this planting system already had structures of secondary roots favoring the increase of absorption roots and, additionally 'Rangpur Cravo Santa Cruz' lime has a very vigorous root system, easily breaking the physical impedance (Table 2). Therefore, in our studied model, when there is no nutritional or physical-hydraulic restriction to development below the impedance, plants originated from seedlings, simulating the seeds in bags (PS), can increase root length density, increasing their capacity to absorb water and nutrients, because they increased the length of thin roots comparatively. Nothing can be claimed about root deepening capacity, which may be associated with possible changes in root angle (Manschadi et al., 2008; Whalley et al., 2013), which could not be detected in the studied model, unlike grass crops (Whalley et al., 2013), since the plant perforated only one point of the paraffin disc, regardless of the planting system. Such behavior is associated with more vertical structures, attributed to plants under direct seeding, which were not detected in the studied model, regardless of the physical impedance level.

It is interesting that plants grown without physical limitation (0.14 MPa) and PS showed higher value of total root length. Hence, the interaction (planting system versus physical impedance) observed in the first experiment was caused because the critical limit of root system penetration was determined, which did not occur in the second experiment. Since the tested physical impedance was easily broken. Therefore, roots grew below the impedance to satisfactorily nourish the plants, thus leading to no difference between treatments. In this experiment, none of the planting systems exhibited greater capacity to penetrate the paraffin layer, since there was no interaction between planting systems and resistance to root penetration.

Regardless of the planting system, plants were able to explore the soil below the paraffin disc with only one hole in the paraffin, differently from what occurs in plants with fasciculate roots (Clark et al., 2000; Whalley et al., 2013). This does not corroborate that there will be increase in the deepening capacity due to the presence of intact taproot. Instead, soil structure would better explain the subsurface distribution of plant root system under field conditions, since in the studied system there were no limitations of nutrition and aeration, because there were more roots below the impedance in the conventional planting system. In this context, a factor associated with root distribution structure, related to the lateral distribution angle, may affect the exploration of the subsurface, promoting higher drought tolerance and being the possible key for adaptation to dry environments (Manschadi et al., 2006). Hence, studies on genotypical variability are important in the selection of plants for absorption of water and nutrients (Lynch, 2011; Whalley et al., 2013).

In conclusion, the presence of strong structures reduces root system exploration in young nucellar citrus plant regardless the planting systems at resistance to root penetration ≥ 1.52 MPa. When there was no limitation to root growth, the conventional planting was associated with higher vigor of roots and shoots, indicating that, in soils with good physical structure and porosity or that allow root deepening beyond the cohesive layer, this planting system is totally adequate, despite the possible benefit of not cutting the taproot in the direct seeding.

Acknowledgements

The authors thank the CNPq for the support to MACF (311327/2015-0; 483229/20112-1); CAPES to the PhD scholarship to LBO and FAGJ; CAPES to the MSc scholarship to SSA; and Embrapa/Macroprogram 2 for the support to MACF, ASG and WSSF.

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