Structural characterization of a compacted alfisol under different tillage systems

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Abstract

Conservation tillage is a management system used to mitigate and rehabilitate the dryland areas of southern-central Chile in severely compacted soils. The objective of this study was to evaluate the soil physical properties in the root zone under an oat-wheat crop rotation after three years of the establishment of three tillage systems: conventional tillage (CT), zero tillage (ZT) and zero tillage with subsoiling (ZTS). Soil bulk density, porosity, water retention curve, stability of macro- and microaggregates, airflow at field capacity, rest coefficient, and number of roots were evaluated. The results showed that the soil had low water holding capacity in the profile due to the low water retention at the permanent wilting point (matric water potential lower than -1.500 kPa), associated with a high bulk density and clay content. The conservation tillage systems (ZT and ZTS), were similar in the parameters of fast drainage pores (FDP), aggregate stability index, airflow, and rest coefficient compared with CT. However, the volume of pores with diameters between 10-50 μm was higher in ZTS in a 24% and 13%, compared with ZT and CT, respectively. In addition, the root development increased significantly in ZTS. In conclusion, the physical condition of the compacted soil was improved by the zero tillage system with subsoiling, which promoted a better root system in the first horizons in highly compacted soils.

Keywords: Subsoiling, rooting, porosity

1. Introduction

The interior dryland of the central Chilean coastal range is a geographic area associated with a Mediterranean climate where granitic and metamorphic soils, especially Alfisols, are highly susceptible to soil erosion. This agroclimatic zone has historically been cropped to cereals and intensive conventional tillage practices, which have led to a progressive reduction of soil productivity. Conservation tillage systems have the potential to mitigate soil erosion in these degraded soils (Martínez *et al.*, 2012). It has been observed in the first 15 cm of soil that improving water retention capacity and soil structure, results in higher root development of wheat under zero tillage management (Lampurlanés and Cantero-Martínez, 2003; Martínez *et al.*, 2008). It has also been observed that no-tillage compacts clay textured soils negatively affects deep root growth and water absorption from deeper horizons; this is an unfavorable situation for crops in dryland zones (Alvarez and Steinbach, 2009). Subsoiling technique -as a complement to zero tillage-, helps to reduce soil compaction in deep, facilitates root growth and let to greater utilization of water stored in the 50-110 cm soil (Martínez *et al.*, 2011). A complementary effect is that additional water is stored in the root growth zone of the soil and improves plant water availability, which is essential for plants to resist drought periods (Hong-Ling *et al.*, 2008). We test the hypothesis that conservation tillage systems improve the physical conditions of the soil profile of highly degraded soil as compared to conventional tillage. Conventional tillage has been used for many years and has increased the problem in the study area. The objective of this study was to evaluate the soil physical properties in the root zone of a wheat crop after 3 years of conventional tillage and compare it with two conservation tillage systems.

2. Materials and Methods

2.1. Site description

The experiment was carried out from 2007 through 2010 at the INIA Cauquenes Experimental Center (35° 97'S, 72° 24'W). The site is characterized by a sub-humid Mediterranean climate with an average annual rainfall of 690 mm and annual mean temperature of 14.7 °C. The temperature fluctuates between a maximum mean of 27 °C in January and a minimum mean of 4.7 °C in July. The soil is an Alfisol belonging to the Cauquenes Association and classified as Ultic Palexeralf, developed *in situ* from granitic rock and dominated by fine textural classes, clay loam on surface over dense clay in depth. Prior site management consisted of natural grassland for direct sheep grazing. The site is located in the upper part of a hillside with eastern exposure and it has a 12.5% slope. It had homogeneous initial water corroborated by soil morphological descriptions for the three plots established in the study. Table 1 shows values of physical properties of the 0-100 cm depth at the start of the trial (2007).

2.2. Description of the field experiment

Three tillage systems were studied: conventional tillage (CT) and two conservation tillage systems, zero tillage (ZT) and zero tillage with subsoiling (ZTS). Conventional tillage was the control and corresponded to the CT system used by farmers in the zone. This technique used a moldboard plow passed at 20 cm depth with animal traction. Winter oat/wheat were sown manually. Zero tillage in ZT and ZTS systems was done with a no-till seeder, the planter (Vence Tudo, Chile) was drawn by oxes and had 7 rows 17 cm apart, and subsoiling in ZTS was carried out in the first year of the study (2007) only. A subsoiler chisel plow was passed in April at 40 cm depth and 40 cm

spacing in the direction perpendicular to the slope. Stubble cover equivalent to 2.5 Mg ha⁻¹ shredded harvest cereal residue (oats or wheat in according to crop rotation) was maintained in the two soil conservation systems. The plot size was 1000 m².

The sowing date was close to 15 May each year. Plot management consisted in a crop rotation of oats (*Avena sativa* cv. Supernova-INIA in 2007 and 2009) and wheat (*Triticum aestivum* cv. Pandora-INIA in 2008). Sowing rates were 140 kg seed ha⁻¹ for oats and 200 kg seed ha⁻¹ for wheat; fertilization rates were 110, 70, and 80 units of N, P₂O₅, and K₂O for oats and 140, 90, and 80 units of N, P₂O₅, and K₂O for wheat.

2.3. Soil evaluations

Six randomly selected pits per treatment were sampled in Spring 2010, when the wheat crop was at the flowering stage (after 4 years of conventional and zero tillage). Soil samples were collected layer-by-layer following natural soil horizons (100 cm x 40 cm cross-sectional area) down to 100 cm depth. The layers were 0-10, 10-30, 30-45, and 45-60 cm. At each sampling depth, undisturbed and disturbed soil samples were taken for physical analysis (144 samples, 2 undisturbed/disturbed, 4 depths x 6 pits x 3 treatments).

Table 1. Baseline soil profile characteristics

Horizons	Depth cm	Sand -----	Silt %	Clay -----	Textural class (USDA)	Bulk density Mg m ⁻³	Total porosity* %	Porosity number (e)* (cm cm ⁻³)
Sandy								
Ap	0-15	72.6	12.6	14.8	loam	1.79	33	0.90
Bt ₁	15-30	42.4	13.0	44.5	Clay	1.69	36	0.71
Bt ₂	30-60	34.2	17.6	48.2	Clay	1.75	34	0.66
Bt ₃	60-100	32.2	19.6	48.2	Clay	1.77	33	0.63

Source: DESIRE Project. * Data calculated in this study.

2.4. Bulk density (Db)

Bulk density was determined by the core method (Dane and Topp, 2002) in which the dry soil mass at 105 °C is related to the soil volume of the sample. Particle density (Dr) was determined by the picnometer method (Dane and Topp, 2002); the total porosity (N), which is the ratio of the pore volume to the soil volume, as well as the porosity number (e), or ratio of the pore volume to the solid volume were calculated using the following relations:

$$N = [1 - (Db/Dr)] * 100 ; e = [(Dr/Db) - 1] \quad (1)$$

where N is the total porosity (%), e is the pore number (cm³ cm⁻³), Db is the bulk density of the core (Mg m⁻³), and Dr is the particle density (Mg m⁻³). The bulk density was also measured using the clod method (Dbcl) according to Dane and Topp (2002). The inter-aggregate porosity (Piag), which relates to the volume of pores present between the aggregates compared with the soil volume was calculated using a relationship between Db calculated by the core method and the clod as indicated in Equation 2 (Seguel and Horn, 2006):

$$P_{iag} = 1 - (Db/Dbcl) \quad (2)$$

where P_{iag} is the inter-aggregate porosity ($\text{cm}^3 \text{ cm}^{-3}$), D_b is the bulk density measured by the core method and D_{bcl} is the bulk density measured by the clod method.

2.5. Soil water retention curve

The soil water retention curve was obtained in undisturbed soil cores (height: 5.0 cm; diameter: 5.9 cm). The samples were saturated from the bottom and balanced at pressures of 0.2, 6, 33, 100, and 1500 kPa; the first two pressures were obtained in a sand box and the last three in a pressure plate (Dane and Topp, 2002). The pore size distribution was calculated from the soil water characteristic curve. The soil pores drained sequentially from the largest to the smallest size as the water pressure increases according to their effective radius (Hartge and Horn, 2009). Equation 3 expresses the relation of the pore size to the water extraction pressure:

$$r_p = [(2\gamma \cos \alpha) / (h \rho g)] \quad (3)$$

where r_p is the equivalent pore radius (mm), γ is the water surface tension (N m^{-1}), α is soil to water contact angle (degrees), h is the capillary rise (cm) in the pore of radius r_p from the sand-box or the pressure chamber, ρ is the water density (Mg m^{-3}), and g is the acceleration due to gravity (m s^{-2}). Bearing in mind that for the soil wetting angle (α), perfect wetting is considered when $\alpha=0$, ($\cos \alpha=1$), water drained at a determined pressure or height (h) comes from a pore with an equivalent radius equal to or greater than the behavior of the capillary tube radius r_p . The equilibrium pressures determined in the soil water retention curve (matric potential) allow classifying the soil pores in fast drainage pores (FDP) ($>50 \mu\text{m}$), as the difference in water content between matric equilibriums of -0.2 and -6 kPa, slow drainage pores (SDP) (10-50 μm), as the difference in water content between

matric equilibriums of -6 and -33 kPa, and useful water for plants (UW) (0.2-10 μm), as the difference in soil water content between soil matric potentials of -33 and -1500 kPa (Hartge and Horn, 2009).

2.6. Macro-aggregate stability

Macro-aggregate stability was determined by the dry and wet sieving method (Hartge and Horn, 2009).

The disturbed samples were air-dried, 200 g subsample of aggregates (dry soil exposed to air and up to 3 cm diameter) were randomly taken from each sample and placed on a set of sieves with diameters of 19, 9.5, 6.35, 4.75, 3.33, and 2 mm. The subsample was sieved for 2 min at a frequency of 60 Hz and the sample water content was determined. Once the dry sieving was finished, the aggregate mass left in each sieve was determined and the partial fraction of each size (ratio between sieve soil mass and total soil mass) was calculated and corrected for its water content to determine the initial distribution of aggregate sizes. A second sieving was then done under water where the set of sieves was shaken with 5 cm upward and downward movements for 5 min at 60 rpm. The soil remaining in each sieve was dried at 105 °C for 16 h or more to determine the aggregate fraction for each size. The variation of weighted mean diameter (ΔWMD) was determined with the results of the dry and wet sieving (Hartge and Horn, 2009) by the equation:

$$\Delta\text{WMD} (\text{mm}) = \frac{\sum(n_{i1} \times d_i) - (n_{i2} \times d_i)}{n_{i1}} \quad (4)$$

where d is the aggregate mean diameter in range i that corresponds to each range of sieves being used (in the present study: 24.50, 14.25, 7.93, 5.55, 4.04, 2.67, and 1.00 mm), n_{i1} is the dry mass of the fraction in range i for dry sieving, and n_{i2} is dry mass in range i of wet sieving. Therefore, with the results of both sievings (dry and wet), a stability analysis is performed for

each natural aggregate size range from a known distribution of aggregates obtained in dry sieving. The lowest ΔWMD value indicates the highest soil stability (Hartge and Horn, 2009).

2.7. Micro-aggregate stability

Micro-aggregate stability was determined by the dispersion ratio (DR) method described by Seguel *et al.* (2003). Two soil samples of 50 g with aggregates between 1 and 2 mm diameter were obtained by sieving air-dried soil; one of the subsamples was subjected to a slight dispersion in 150 cm³ distilled water, while the other sample was subjected to a drastic dispersion with the same amount of distilled water and 20 cm³ of sodium pyrophosphate. Both samples were left to rest during the night. The drastically dispersed sample was then mechanically shaken for 10 min in a 75 cycle Hamilton Beach blender. Finally, the samples were poured into 1L measuring cylinders filled up to 1000 cm³ with distilled water. The density of the suspension was measured with a hydrometer along with the temperature 40 s after the start of the decanting process. The clay and silt content of both samples was calculated by the Bouyoucos hydrometer method based on Stoke's law (Dane and Topp, 2002) using the equation:

$$\text{DR} = [(S+C)\text{sd}/(S+C)\text{dd}] * 100 \quad (5)$$

where DR is the dispersion ratio, (S + C)sd is the percentage of silt and clay found in the sample with slight dispersion (sd) and (S + C)dd is the percentage of silt and clay found in the sample with drastic dispersion (dd). The lowest DR value indicates the highest soil stability

2.8. Airflow at field capacity

Airflow was measured similar to that described by Peth (2004), using undisturbed soil samples equilibrated on water retention at -33 kPa. The base of the

cylinder was connected to a vacuum chamber resting on a container with water to maintain the vacuum. Suction was applied to cause airflow between the atmosphere and the chamber at time *t*. The vacuum was 0.1 kPa, which was measured by a 1cm difference in height of a water manometer. Air volume (*V*) that flowed into the soil sample was determined by the formula:

$$V = h * \pi * (R_c)^2 \quad (6)$$

where *V* is air volume (cm³) that flew through the soil sample and entered the vacuum chamber at time *t*, *h* is the height at which the vacuum chamber is lifted above the water level (cm), and *R_c* is the radius of the vacuum chamber (cm) on which the soil sample is attached. Airflow was then determined by equation 7 (Peth, 2004):

$$F_{\text{air}} = \rho_1 * g * (V * L / t * \Delta p * A) \quad (7)$$

where *F_{air}* is the airflow (m s⁻¹), ρ_1 is air density during measurement (1.228 kg m⁻³, considering an atmospheric pressure of 1033 mbar and temperature of 20 °C), *g* is the acceleration due to gravity (9.81 m s⁻²), *V* is the volume of air that flows through the sample (m³), *L* is the length of the soil sample (m), *t* is measured time (s) for the volume *V*, Δp is the difference in pressure (hPa) recorded on the water manometer, and *A* is the cross-sectional area of the soil sample (m²).

2.9. Rest coefficient

Soil mechanical impedance was measured vertically and horizontally with a cone penetrometer (EXTECH mod. 475044). Four horizontal and four vertical measurements were taken in each sampling unit (soil pit), which covered a 40 cm wide and 10 cm deep area in the Ap horizon; the rest coefficient (*ko*) was calculated as the ratio between horizontal and vertical impedance, where *ko* > 1 reveals soil compaction (Hartge and Bachmann, 2004).

No further measurements were taken since low soil moisture conditions at greater depths caused resistance values to exceed the equipment's measurement capability (0-200 Nt).

2.10. Roots

To visualize the root growth, four grids (10 x 10 cm²) were traced on a 40 cm wide and down to 80 cm depth (White and Kirkegaard, 2010). The number of roots was counted for each layer with six replicates and was described in accordance with size class: fine to very fine (< 2 mm), medium (2 to 5 mm), and coarse (5 to 10 mm) according to Schoeneberger *et al.* (2002).

2.11. Statistical analysis

The data were collected with six replicates from each treatment. We used the Anderson-Darling test to verify the assumption of normality, and Bartlett's test for homogeneity of variances. After the verifications of assumptions of the error terms, data were subjected to ANOVA with a completely randomized design with a factorial structure, where the effect of the tillage systems in each physical parameter was analyzed with two factors (tillage systems and depth). When corresponded, means were compared by Tukey's test ($p \leq 0.05$) with the SAS statistical program (SAS Institute, 1999).

3. Results

3.1. Soil density and porosity

The results of bulk density (Db) and total porosity (N) after three-year crop rotation system under conventional (CT) and zero tillage systems (ZT and ZTS) are shown in Table 2. In the topsoil (0-10 cm depth), Db was significantly lower in the three tillage systems (1.39 Mg m⁻³); at this depth it was lower in CT although

the differences were not significant. Total porosity (N) were higher in the topsoil (48% cm cm⁻³), with no difference between treatments and a trend of higher values in CT.

Table 3 shows that inter-aggregate porosity was higher in the upper (0-10 cm) than in the rest of the soil profile. There was no significant interaction between factors and tillage systems. ZT had the lowest values below 30 cm of depth; while the higher values were observed in CT and ZTS, which is not necessarily related to a higher structural porosity, but they could correspond to cracks caused by drying, so that its functionality should be analyzed together with other soil properties.

3.2. Pore size distribution

There were no significant differences in the slopes of the curves for each horizon among tillage systems (data not shown). There was a higher total porosity at the surface (0-10 cm) with a high slope between saturation (pressure = 0) and field capacity (FC, -33 kPa), which indicates an abundance of coarse pores. The soil water retention at low pressures is related to the structural conditions, while at high pressures to the soil texture (Hartge and Horn, 2009). The soil water retention curve indicates that the volume of small pores (<0.2 µm) increased with soil depth and clay content (>44.5% of clay at 15 cm depth; Table 1). It was found that the maximum water storage capacity for the first horizon (0-20 cm) was around 40 mm of water.

Pore size distribution was derived from the water retention curve (Equation 3) and defined in Table 4, as fast drainage (>50 µm), slow drainage (10-50 µm) and useful pores (0.2-1.0 µm). Fast drainage pores were greater at 0-10 cm of depth, but similar between treatments; while at greater depths (below 30 cm depth), significantly decreased the coarse porosity ($p \leq 0.05$), which possibly could affect the soil aeration and root growth potential. In contrast, slow drainage pores were higher under ZTS than CT and ZT; this difference can be important when

plant water availability is determined by water contained in slow drainage pores. Although it is difficult to show a value for pore space which suppress root growth, some authors have observed that macro-porosity should be greater than 10% for adequate elongation and maximum root growth (Richards, 1983). The fast drainage pores (Table 4) had values greater than or equal to 10% up to 45 cm depth, except for ZT in the 30-45 cm depth. Finally, the useful water pores were higher in CT than ZTS.

Table 2. Bulk density, total porosity (N), and pore number (e) in accordance with tillage systems.

Depth (cm)	Tillage systems			Mean
	CT	ZTS	ZT	
<i>Bulk density ($Mg\ m^{-3}$)</i>				
0-10	1.33	1.44	1.40	1.37 a
10-30	1.52	1.57	1.55	1.55 b
30-45	1.58	1.60	1.66	1.61 b
45-60	1.62	1.61	1.66	1.63 b
Mean	1.51	1.59	1.57	
	a	a	a	
<i>Total porosity (N) (%)</i>				
0-10	50	46	47	48 a
10-30	43	41	42	42 b
30-45	41	40	38	40 b
45-60	39	40	38	39 b
Mean	43	42	41	
	a	a	a	
<i>Pore number (e) ($cm\ cm^{-3}$)</i>				
0-10	0.99	0.84	0.90	0.91 a
10-30	0.75	0.69	0.71	0.72 b
30-45	0.68	0.67	0.60	0.65 b
45-60	0.64	0.66	0.61	0.64 b
Mean	0.77	0.72	0.71	
	a	a	a	

CT: Conventional tillage; ZTS: Zero tillage with subsoiling, ZT: Zero tillage. Means for tillage systems (rows) and depth (columns) with the same letter are not significantly different ($p \leq 0.05$).

Table 3. Inter-aggregate porosity (%) in accordance with tillage systems.

Depth (cm)	Tillage systems			Mean
	CT	ZTS	ZT	
0-10	22	21	23	22 a
10-30	14	12	15	14 b
30-45	9	10	6	8 b
45-60	11	11	6	9 b
Mean	14	14	13	
	a	a	a	

CT: Conventional tillage; ZTS: Zero tillage with subsoiling, ZT: Zero tillage. Means for tillage systems (rows) and depth (columns) with the same letter are not significantly different ($p \leq 0.05$).

Table 4. Pore size distribution (%) as related to tillage systems.

Depth (cm)	Tillage systems			Mean
	CT	ZTS	ZT	
<i>Fast drainage pores ($>50\ \mu m$)</i>				
0-10	23.6	19.6	22.8	22.0 a
10-30	14.0	16.7	15.1	15.0 b
30-45	11.6	10.3	8.7	10.0 c
45-60	8.7	9.3	9.4	9.0 c
Mean	14.5	14.0	14.0	
	a	a	a	
<i>Slow drainage pores ($10-50\ \mu m$)</i>				
0-10	8.3	8.3	6.3	7.6 a
10-30	6.6	9.0	6.6	7.4 a
30-45	4.8	4.8	4.3	4.6 b
45-60	3.9	5.0	3.6	4.2 b
Mean	5.9	6.8	5.2	
	b	a	b	
<i>Usefull water pores ($0.2-10\ \mu m$)</i>				
0-10	6.6	5.5	6.3	6.1 a
10-30	6.2	4.5	5.0	5.2 a b
30-45	4.7	4.1	3.9	4.3 b c
45-60	4.2	3.0	3.2	3.5 c
Mean	5.4	4.3	4.6	
	a	b	ab	

CT: Conventional tillage; ZTS: Zero tillage with subsoiling, ZT: Zero tillage. Means for tillage systems (rows) and depth (columns) with the same letter are not significantly different ($p \leq 0.05$).

Table 5. Aggregate stability (<3 cm diameter) as related to tillage systems.

Depth cm	Tillage systems			Mean	
	CT	ZTS	ZT		
<i>Macro-aggregate stability</i>					
ΔWMD (mm)					
0-10	3.72	3.22	1.78	2.91	c
10-30	6.54	4.92	5.68	5.71	b
30-45	6.41	7.81	7.19	7.14	a
45-60	8.00	8.47	8.32	8.26	a
Mean	6.17	6.11	5.74		
	a	a	a		
<i>Micro-aggregate stability</i>					
DR (%)					
0-10	41	30	36	36	a
10-30	12	30	21	21	b
30-45	11	9	15	12	c
45-60	16	13	16	15	b c
Mean	20	21	22		
	a	a	a		

CT: Conventional tillage; ZTS: Zero tillage with subsoiling, ZT: Zero tillage, Δ WMD: variation of weighted mean diameter, DR: dispersion ratio. Means for tillage systems (rows) and depth (columns) with the same letter are not significantly different ($p \leq 0.05$).

3.3. Aggregate stability

Aggregate stability was significantly different for soil depth (macro and microaggregate), as shown in Table 5. Macro-aggregate stability (1-30 mm), was evaluated by the variation of weighted mean diameter (Δ WMD), and micro-aggregate stability (1 to 2 mm) was evaluated by the dispersion ratio (DR). The lowest value for each index indicates a higher aggregate stability (equations 4 and 5). The DR index, associated with micro-aggregates, decreased (higher stability) as soil depth increased; however, macro-aggregate stability increased (lower stability) as soil depth increased (Table 5).

According to Seguel *et al.* (2003), DR values lower than 30% correspond to highly stable soils, where the clay content plays an important role in the formation of micro-aggregates. Both index are related to soil structure; while the stability of micro-aggregates was associated to a high clay content, which drastically increased from 20 cm depth downwards (Table 1); macro-aggregate was related to soil organic matter, which was higher at the surface of the profile.

3.4. Pore system functionality

Figure 1 illustrates airflow at increasing soil depths measured from samples equilibrated at field capacity (-33 kPa). Airflow increased significantly ($p \leq 0.05$) as soil depth increased, contrary to the coarse pore distribution in the profile, with means of 6.8 cm h^{-1} in the first horizon (0-10 cm) to 21.4 cm h^{-1} in depth (45-60 cm). The means between tillage systems or the soil depth by airflow interaction were significant. The trend lines of Figure 1 shows an uniform increase in airflow in the conservation tillage systems (ZT and ZTS) as soil depth increased, compared to the conventional tillage. The latter shows uneven flow with abrupt changes between horizons in CT, which could reflect structural discontinuity within the soil profile.

3.5. Rest coefficient

There were no significant differences for this variable among tillage systems (data not shown). CT had a value of 1.33, which exceeded the $k_o > 1$ threshold, that indicates soil compaction (Hartge and Bachmann, 2004). At the sampling date (end of October), the first soil horizon showed a water content close to the permanent wilting point, with mechanical impedance values which exceeded the equipment measuring capability (0-200 Nt) and revealed a high degree of resistance due to soil drying.

Figure 1. Airflow in soil profile in accordance with tillage systems. Horizontal bars represent standard error of the mean. Same letters indicate non significant differences ($p \leq 0.05$). Conventional tillage: rhombus, Zero tillage: triangles, Zero tillage with subsoiling: squares.

3.6. Roots

An analysis of the roots with soil depth showed the rooting pattern of the crop in the tillage systems. The fine and very fine roots (0 to 2 mm diameter) had significant differences between tillage systems. The soil depth $\times$ root interaction was also significant (Table 6). The roots were concentrated in the surface horizon (0-20 cm). The ZTS had 39 roots per 100 cm², value significantly higher ($p \leq 0.05$) to the other tillage systems, which had means of 30 and 22 roots/100cm² in ZT and CT, respectively. CT had significantly lower (36 roots/100 cm², $p \leq 0.05$) roots than ZTS (75 roots/100 cm²) in the first 0-20 cm depth, while in the total profile (60 cm) CT and ZT were not significantly different.

Table 6. Mean of number of roots per 100 cm² for tillage systems

Depth cm	Tillage systems					
	Ct		ZTS		ZT	
10	22.08	c	38	a	30.13	b
20	14.58	b	33.67	a	17.63	b
30	10.08	b	17.08	a	11.13	b
40	6.42	ab	9.08	a	3.63	b
50	3.17	ab	4.58	a	0.75	b
60	2.75	ab	3.67	a	0.38	b
70	0	a	0.42	a	0	a
80	0	a	0.42	a	0	a

CT: Conventional tillage; ZTS: Zero tillage with subsoiling, ZT: Zero tillage. Means with the same letter are not significantly different ($p \leq 0.05$).

4. Discussion

The bulk density of the soil (Db) was not affected by the tillage systems in spite of an input of organic mulch in the soil conservation systems of 2.5 Mg ha⁻¹ of crop residues. This was probably due to the low amount of organic mulch left on top of the soil, as Mulumba and Lal (2008), did not find changes in Db with organic mulch rates up to 16 Mg ha⁻¹, or because the evaluation period was short, considering that the residue decomposition is slower when they are not incorporated in depth (Radicetti *et al.*, 2016). Nevertheless, the presence of organic mulch most probably prevented the increase of Db in this clay soil (Glab and Kulig, 2008).

The water retention curves reflected a condition that characterizes the soils in the dryland of the Chilean central coast range, having a low water holding capacity (66.4 mm in the soil profile) and high permanent wilting point increasing in the deepest horizons due to higher clay content.

The lower total porosity negatively affects root biomass in compacted soils (Martínez *et al.*, 2011), due to the reduced soil aeration, reflecting a lower continuity and connectivity of macropores (Martínez *et al.*, 2016). However, the contribution of slow drainage pores is important to improve the amount of usable water for the crop growth (Hartge and Horn, 2009). ZTS showed a volume of pores (10–50 μm) higher in a 24% and 13% to ZT and CT, respectively. Mulumba and Lal (2008) indicated that the use of crop residues higher than 8 Mg ha^{-1} in an Alfisol, increased the usable water in ZT systems between 0 and 10 cm of depth. In the present study, the lower input of crop residues (2.5 Mg ha^{-1}) was not enough to increase the total porosity in severely degraded soils. However, the soil cover resulting from residues left on the surface in conservation tillage systems, protect the soil surface by absorbing the energy from the impact of raindrops, especially during intense rainfalls (Martínez *et al.*, 2012). In addition, conservation tillage systems have shown a soil structure more stable than soils under conventional tillage as found by Martínez *et al.* (2008), Fuentes *et al.* (2009) and Álvarez and Steinbach (2009). The aggregate stability indices in the present study, evaluated by four years after the start of the trial, did not reveal any significant differences in the structural stability among tillage systems. This was probably due to the initial condition of the soils in the study area, where soil degradation is a severe problem (Martínez *et al.*, 2012).

The variation of the weighted mean diameter indicated a loss of macro-aggregate stability as soil depth increased, so it is possible that the observed inter-

aggregate porosity in the subsoil was the result of cracks caused by drying. The higher stability on the soil surface would indicate a structure that depends on processes related to adding organic matter as demonstrated by Martínez *et al.* (2008) in a Mollisol managed with ZT, where aggregate stability increased over time (4 to 7 yr). The high percentage of clay under the 20 cm soil depth was related to the dispersion ratio index, which indicated higher stability as the soil depth increased because of the presence of clay clusters (Chenu and Plante, 2006).

The airflow at a pressure of -33 kPa reflects the conductivity of drainage pores ($>10 \mu\text{m}$). On the contrary to the expected, the surface airflow was lower in the three tillage systems, this could be due to a higher tortuosity of the coarse pore system (Dörner *et al.*, 2009). Airflow values between 5 and 7 cm h^{-1} at the first 10 cm of depth were similar to the results obtained by Seguel *et al.* (2015), which measured in a granitic soil cultivated with vines. As the soil depth increased, airflow increased in the deep clay-textured horizons by cracks produced by drying, being more effective than the structural porosity. The abrupt airflow changes between the evaluated horizons for the CT system could reflect a disruption in pore continuity that reduced the flow capacity between the plowed layer and the subsoil (Dexter *et al.*, 2004). Thus, functionality of the soil system seems to be more influenced by the form, size, tortuosity, and degree of connection between pores than by total macro-pore volume (Dörner *et al.*, 2009).

At the 0–20 cm depth, conservation tillage systems had a higher number of roots per unit area with significant differences as compared with conventional tillage. Martínez *et al.*, (2008) observed a similar result for the first 5 cm of soil with ZT management for 4 and 7 yr versus a soil subjected to CT. Although penetration resistance was not significantly different between treatments, the conservation tillage systems in compacted soils had rest coefficient (k_0) values below the critical value ($k_0 < 1$) as

shown by Hartge and Bachmann (2004). Even though it was expected that soil under CT could exhibit better physical conditions for root growth because of the lower strength induced by plowing, it was observed that this tillage system reached values as high as those for ZT throughout the season, especially as a result of soil settlement (Agostini *et al.*, 2012). Subsoiling would therefore be effective to reduce penetration resistance as depth increases (Nunes *et al.*, 2015), but given the low physical mechanical stability of the soils (lower organic matter content as depth increases), the effect is rapidly lost from one season to another (Martínez *et al.*, 2011).

The increased formation of biopores and structural pores produced by conservation tillage is associated with better soil structure and had a positive impact on root development and crop yield (Botta *et al.*, 2010; Zhang *et al.*, 2014). This was observed in the ZTS treatment where results surpassed CT and ZT systems for both the number of roots and root growth as the soil depth increased. Water absorption in this system could increase by a bigger and deeper root system (Kirkegaard and Lilley, 2007).

It was also observed a poor wheat root growth in the ZT treatment below 40 cm of depth, which was lower than the 80-180 cm of depth observed by other authors (Bonfil *et al.*, 1999; Kirkegaard and Lilley, 2007). White and Kirkegaard (2010), also observed that the abundance of roots strongly decreased at a depth of 60 cm in the transition to a denser textured subsoil. This result is associated with the compaction effect that has been reported in clay-textured soils (Jin *et al.*, 2007; Alvarez and Steinbach, 2009), and the high mechanical resistance observed in the deeper horizons of the profile in this study, which revealed a high degree of resistance that would limit root elongation during the driest period of crop development; this being a critical situation for a zone where root exploration is essential to increase crop water availability.

5. Conclusions

At the end of the 4-yr study, the results showed that soil physical parameters related to soil bulk density, porosity and aggregates were found to be similar in the conservation and conventional tillage systems. However, the volume of pores with diameters between 10-50 μm was significantly higher in ZTS. In addition, the higher slow drainage pores and abundance of surface roots observed in ZTS, increased the crop water availability under water stress conditions. The subsoiling was an essential complement to zero tillage, because it promoted a better root system in the first horizons and higher exploration at depth in these severely compacted soils.

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