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Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile

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Abstract

No-tillage systems affect soil properties depending on the soil, climate, and the time since its implementation. In heavy no-tilled soils a surface compacted layer is commonly found. Such layer can affect root growth and soil water infiltration. In several cases, surface organic carbon can buffer these problems. The aim of this study was to evaluate the effect of 4- and 7-year-old conventional (CT) and no-tillage (NT) treatments on soil physical properties, root growth, and wheat (*Triticum turgidum* L. var. *durum*) yield in an Entic Haploxeroll of Central Chile. In both tillage treatments we study soil water retention, bulk density (ρ_b), soil particle density (ρ_s), soil water infiltration, mean-weight diameter of soil aggregates (MWD), penetration resistance, grain yield, and root length density (L_v) up to a depth of 15 cm. The MWD and the penetration resistance were higher under NT as compared to CT. For the top 5 cm of soil, L_v was greater under NT as compared to CT. Differences of L_v between NT and CT were 2.09, 7.60, and 4.31 cm root cm^{-3} soil during the two leaves, flowering and grain filling phenological stages, respectively. Generally, the effect of NT on these properties was more evident near the soil surface. In contrast, fast drainage macropores, ρ_s, and soil water infiltration rates were higher under CT than under NT. Tillage treatments did not significantly affect ρ_b and yield. A longer time under no-tillage enhanced aggregate stability, however, other soil physical properties were negatively affected.

Keywords: No-till; Wheat root density; Soil physical properties; Chile

1. Introduction

The use of a particular tillage system affects soil properties depending on the site (i.e., soil, climate) and the number of years since the tillage system has been implemented (Rhoton, 2000). Conventional tillage (CT) disturbs soil structure and may increase the risk of runoff and soil erosion. Conventional tillage also affects soil temperature (Dwyer et al., 1996), soil mechanical impedance (Cox et al., 1990), the continuity of macropores (Roseberg and McCoy, 1992; Shipitalo et al., 2000), soil water availability (Cox et al., 1990; Fuentes et al., 2003), and the depth and distribution of roots (Dwyer et al., 1996).

No-tillage (NT) systems may have, under certain soil, climate and management conditions, potential advantages over CT systems. These advantages include reduced number of machine passes over the field, less fuel consumption, shortened field time during tillage operations (Veseth, 1988; Juergens et al., 2004), reduced

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soil loss due to better aggregate stability (Rhoton et al., 1993; Ghuman and Sur, 2001) and the protective effect of crop residues left over the soil (Veseth, 1987; Dabney et al., 2004). Other soil physical properties benefited by NT systems are increased soil water availability (Unger, 1994; Drury et al., 1999), and increased number of biopores (Francis and Knight, 1993), that may facilitate root growth (Martino and Shaykewich, 1994). Some soils, however, when managed under NT may experience detrimental effects, such as increased bulk density (Ball-Coelho et al., 1998; Lampurlanés and Cantero-Martínez, 2003), lower soil temperatures (Drury et al., 1999), and decreased oxygen diffusion rates (Russell, 1988). Under NT the upper soil tends to be more compacted as compared to conventional tillage (Braim et al., 1992). The increased topsoil compaction under NT systems may decrease water infiltration and the soil may become waterlogged under intense rainfall. No-tillage is, therefore, less appropriate during wet years or in areas with high rainfall (Lampurlanés et al., 2001). In some soils, NT reduces the growth rate of wheat (Braim et al., 1992; Kirkegaard et al., 1995). Reductions in root growth can be associated with a low nitrogen uptake resulting in up to 20% decrease in shoot mass (Braim et al., 1992). Wilhelm and Wortmann (1996) found that root length density of winter wheat increased only in the upper soil layers of a NT system when compared to a CT system. Soil physical changes that occur under NT, can negatively affect the growth of the main root axes, particularly, at the initial stages of plant development (Lampurlanés et al., 2001). Such effect may limit nutrient and water uptake (Qin et al., 2006). Increased resistance lead to an exponential decrease in root length density (Martino and Shaykewich, 1994).

There are contrasting results regarding the effect of tillage system on wheat grain yield. Fuentes et al. (2003) did not find consistent grain yield differences compared to CT when winter wheat was grown in an Ultic Haploxeroll under NT. Similar results were found by Merrill et al. (1996) for spring wheat grown under CT, minimum tillage and NT during three seasons in a Pachic Haploboroll soil, and by Acharya and Sharma (1994) in a Typic Hapludalf soil of India. In contrast, Lawrence et al. (1994) found increased winter wheat grain yield under NT as compared to CT in a Typic Natrustalf soil.

The aim of this study was to evaluate the effect of conventional and no- tillage practices on soil physical properties, root length density and wheat yield in an Entic Haploxeroll. The study is of particular interest due to the Mediterranean climate of the site. No-tillage practices under this type of climate and soil are uncommon.

2. Materials and methods

2.1. Sites and cropping systems description

The experimental site is located in the Antumapu Experimental Station of the University of Chile (33°40′S, 70°38′W; 608 m above sea level) in a sandy clay alluvial soil (coarse loamy over sandy, skeletal, mixed, thermic Entic Haploxeroll). Selected soil properties are shown in Table 1. The climate of the

Table 1
Selected soil properties (0–15 cm depth) at the sites previous to no-tillage implementation (years of measurement: 1999 for site A, 1996 for site B. Values in parenthesis correspond to the standard deviation of the mean)

Soil property	Time under crop management	
	Site A: 4 years	Site B: 7 years
Available[a] N (mg kg^{-1})	27.4 (8,1)	7.9 (2.4)
Available[b] P (mg kg^{-1})	9.6 (0.9)	11.1 (0.5)
Available[c] K (mg kg^{-1})	177.8 (21.5)	162.5 (14.8)
pH H_2O (2:1)	8.0 (<0.1)	7.7 (1.1)
Organic carbon[d](% by weight)	1.2 (0.1)	1.06 (0.1)
Particle size distribution[e](% by weight)		
Sand (50–2000 μm)	46.8	43.0
Silt (2–50 μm)	2.8	3.9
Clay (<2 μm)	50.4	53.1

[a] Brenner and Keeney method.
[b] Olsen method: Extraction with $NaHCO_3$ 0.5 mol L^{-1} at pH 8.5.
[c] Ammonium acetate 1N pH 7.
[d] Wet combustion and colorimetry.
[e] Densitometry.

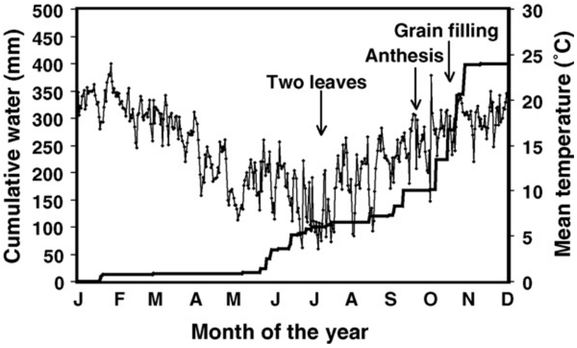

Fig. 1. Mean daily temperatures and cumulative water (precipitation plus irrigation events) during the year 2003.

area is Mediterranean with a long-term mean annual rainfall of 330 mm, mostly concentrated in the winter season (80%). Maximum and minimum annual temperatures are 28.7 and 3.4 °C respectively (Santibáñez and Uribe, 1990). Daily rainfall and daily temperature data (Fig. 1) were obtained from a weather station located 500 m away from the experimental site. Two trials comparing conventional tillage (CT) and no-tillage (NT) had been established at contiguous sites (distance between sites: 100 m). The sites varied in the time at which the trials had been implemented, one site had been under CT and NT for 4 years. The second site had been under the same tillage treatments for 7 years. Each CT and NT treatment considered three field replications (plots of 10 m × 40 m). The sites with their corresponding tillage treatments were cropped with a durum spring wheat (*Triticum turgidum* L. var. *durum*)–maize (*Zea mays* L.) rotation. The studies reported here were carried out in the wheat phase of the rotation. The maize residues on top of the soil prior to wheat planting amounted to approximately 18 Mg ha^{-1}. In the CT treatment, the residues were mechanically shredded and buried with a moldboard plow to a depth of 20 cm. Later, the soil was disked twice using a disk harrow before wheat planting. Under NT, the maize residue was shredded and left on top of the soil. Wheat was planted on July 2, 2003 at a seeding rate of 150 kg ha^{-1} with a NT drill (Semeato SHM 11/13, Brazil) in both tillage treatments (CT and NT). The soil was fertilized with urea and triple super phosphate. Sixty kg N ha^{-1} and 80 kg P_2O_5 ha^{-1} were applied at planting and 90 kg N ha^{-1} of urea were broadcasted at the end of tillering. The weeds were controlled with Glyphosate (3 L ha^{-1}) applied before planting, plus a mixture of 1 L 2,4-D and 8 g Metsulfuron-methyl per ha at tillering for broad leaf weed control. Aphids were controlled at the beginning of stem extension with Chlorpyrifos (0.4 L ha^{-1}). The trials were sprinkler irrigated. A total of five irrigation events were made between October and November 2003 (195 mm of water applied at 20 mm water h^{-1} from 20 days previous to anthesis until 32 days after anthesis). In each event the amount of water applied was the same for NT and CT treatments. The irrigation schedule (frequency and amount) was determined according to the average soil water content of the sites.

2.2. Soil sampling and measurement of soil physical properties

2.2.1. Soil water retention, bulk density, particle density and soil porosity

Soil water retention curves were determined in undisturbed soil cores (5.0 cm diameter and 2.0 cm length) sampled at 0–2, 2–5, and 5–15 cm depth. One core per field replication and depth was extracted between rows at harvest (January 2004). Each core was slowly saturated with degassed tap water from the bottom and then successively equilibrated at −10, −33, −100, −300, and −1500 kPa matric potential in pressure plate extractors (Soil Moisture Equipment Corp., Santa Barbara, CA) equipped with −1, −3−5 and −15-bar ceramic plates. The cores were equilibrated for 96 h at each pressure, weighed, and returned to the pressure plates for the next pressure step. The soil water characteristic curves were constructed by fitting the pressure–soil moisture data to the van Genuchten equation (van Genuchten, 1980):

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha h)^n]^{(-m)} \qquad (1)$$

where θ is the volumetric water content and h the hydraulic head. The parameter α is the inverse of the air entry potential; n and m are empirical constants affecting the shape of the retention curve; θ_s is the saturated water content, and θ_r the residual water content. Eq. (1) was fitted to the experimental data using the RETC program (van Genuchten et al., 1991) and assuming $m = 1 - 1/n$. The saturated hydraulic conductivity (K_s) was estimated with the RETC program and using the Mualem's hydraulic conductivity model.

Soil pores were classified according to the soil water retention data in: pores of non-available water (PUW, matric potential < -1500 kPa); pores of available water (PAW, matric potential between −1500 and −33 kPa); slow drainage pores (SDP, matric potential between −33 and −10 kPa); and fast drainage pores (FDP, matric potential > -10 kPa).

Soil bulk density, ρ_b, was determined in 7.2 cm diameter soil cores extracted with a manual hammer-driven core sampler previous to tillage and seeding operations (May 2003). The cores were taken at depths of 0–2, 2–5, and 5–15 cm at two sites per plot. Soil particle density, ρ_s, was determined using the pycnometer method (Flint and Flint, 2002) in one sample per plot and soil depth. This method is based on the displacement of water by solid particles (Archimedes method). The displacement of water was determined at 20 °C, by using 50 mL standard pycnometer flasks, which were partially filled with de-aired distilled water and then completed with 10 g (oven-dry basis) of soil. The particle density was calculated as the ratio between the mass of the soil and the displaced volume of water. The total soil porosity (f) was calculated as

$$f = 1 - \frac{\rho_b}{\rho_s} \tag{2}$$

2.2.2. Soil water infiltration

The quasi-steady infiltration rate (q_s) was determined at anthesis in October 2003 and at planting, anthesis, and at harvest in 2004, using the cylinder-infiltrometer method (Reynolds et al., 2002). A two-ring infiltrometer (inner diameter 25 cm, length 30 cm) was inserted into the soil to a depth of 15 cm. The quasi-steady water flux was determined when the infiltration rate became constant with time (4 h).

2.2.3. Aggregate stability

Aggregate stability was determined for each experimental plot using an adaptation of the wet sieving method (Yoder, 1936). Soil samples were taken previous to tillage and planting operations (May 2003) and air dried. Each soil sample was passed trough a 6.68-mm opening sieve (mesh size No. 0.265 in., U.S. Standard). Afterwards, 100 g (equivalent dry soil) of the sieved soil sample was placed over a set of four sieves of 4.75, 2.00, 1.00, and 0.495-mm openings (mesh sizes No. 4, 10, 18, and 35, U.S. Standard). The set of sieves containing the soil sample was slowly immersed in a 20 L high density polyethylene container which was previously filled with 10 L of tap water. To avoid soil slaking during the process of immersion, tap water was sprayed over the soil sample. After immersion, tap water was added to the polyethylene container until the mesh of the upper sieve was in contact with the water. The set of sieves were mechanically agitated (32 mm of vertical displacement) at 30 times min^{-1} for a period of 10 min. The soil aggregates retained in each sieve were oven-dried at 105 °C, weighed and then dispersed with a 1N sodium hexametaphosphate solution. Each dispersed soil sample was relocated in its corresponding sieve. Non-aggregated or individual particles remaining in the sieves were oven-dried at 105 °C, weighed and discounted from the weight determined prior to the dispersion procedure. The mean-weight diameter was used as an index of aggregate stability (vanBavel, 1949). The MWD was calculated as:

$$MWD = \sum_{i=1}^{n} \bar{X}_i W_i \tag{3}$$

where MWD is the mean-weight diameter (mm), n corresponds to the number of aggregate size fractions considered in the analysis, $\bar{X}_i$ is the mean diameter of aggregates that potentially can stay in the i th and $i+1$ sieves (in this case: $\bar{X}_1 = 5.72$ mm, $\bar{X}_2 = 3.38$ mm, $\bar{X}_3 = 1.50$ mm, $\bar{X}_4 = 0.75$ mm, and $\bar{X}_5 = 0.25$ mm), and W_i is the proportion in weight (weight of aggregates in the i th size fraction (g)/total soil weight (g)) of the aggregates (oven-dry basis).

2.2.4. Soil compaction

Vertical and horizontal penetration resistance (VPR and HPR, respectively) were determined previous to soil tilling and planting (May 2003) with a pocket penetrometer (foot diameter = 6.35 mm; model CI-700, SOILTEST Inc. Chicago, IL). Five subplots of 0.025 m^2 were randomly selected in each field replication. A small pit of 30 cm × 30 cm × 30 cm was made at each subplot. Penetrometer readings were taken at depth intervals of 0–2, 2–5, and 5–15 cm depth. The VPR was determined at the top of each depth interval and considering five readings per depth interval. The horizontal penetration resistance was taken perpendicular to the vertical profile of the pit and considered five readings spanning the entire range of the depth interval. The coefficient of stress at rest (KO) was defined as the ratio of the horizontal to the vertical strength (Hartge, 2001; Lang and Huder, 1982; Kezdi, 1969). We further measured penetration resistance by cone index in January 2007, using a hand penetrometer (base area of cones 1, 2 and 5 cm^2, angle = 60°; probing rods of 8 mm and 15 mm diameter, and 50 cm length; model 06.01SA, Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). A total of 15 readings per plot replication were collected at 8 depth intervals (0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, and 30–45 cm). All data were collected after 24 h from irrigation.

2.3. Plant sampling and measurement

2.3.1. Root sampling, root length density and crop yield

The maximum value of root length density in wheat occurs at flowering (e.g., Acharya and Sharma, 1994; Dwyer et al., 1996; Hoad et al., 2001). Soil samples were taken at the two leaves growth stage, flowering (heading), and grain filling at each site (Fig. 1). Two sub samples per plot were collected between rows at 0–2, 2–5, and 5–15 cm depths intervals using a 3.25 cm diameter manual soil core sampler. Root length density (L_v) was determined using the line intersection method (Newman, 1966). Each soil subsample was immersed in a sodium hexametaphosphate (1N) solution. After 30 min, the subsamples were wet-sieved (sieves of 0.495 and 0.125-mm opening) for root collection. Collected roots were randomly placed over a filter paper. Then, the total root length (R) was determined with a transparent polycarbonate grid (1 cm × 1 cm) by counting the number of intersections between roots and the grid.

The total root length was calculated as:

$$R = \frac{\pi AN}{2H} \quad (4)$$

where A is the area occupied by roots over the filter paper, N is the number of intersections, and H is the total length of the grid.

The L_v (cm root cm^{-3} soil) was calculated by dividing the root length by the volume (cm^{-3}) of the sampling core.

Wheat grain yield was determined in January of 2004 by harvesting three subsamples (0.7 m^2 each) in each plot at each tillage experiment.

2.4. Experimental design and statistical data analysis

We consider two experiments (4 and 7 years of NT) each having a field experiment design of a randomized complete block with two treatments (NT and CT) and three replications. The plot size was 20 m long and 10 m wide. For ANOVA purposes the results were combined over years of NT (experiments having 4 and 7 years of NT) and soil depth. The response to soil management system was tested through changes in L_v, particle density, bulk density, MWD, soil water retention, clay, silt, and sand content, VPR, HPR, and KO. The ANOVA design for q_s and crop yield considered the combined data from the two experiments (years) in a complete block design with tillage system as the main factor. Prior to analysis the data were tested for homogeneity of variance and residuals distribution. Differences in the mean of crop and soil properties were determined using the least significance difference (LSD). The ANOVA and LSD procedures were run with MSTAT-C (Freed and Eisensmith, 1989). The association between management systems, soil, and crop properties was made using principal component analysis (PCA) with InfoStat (V. 2005 P.1, Argentina).

2.5. Abbreviations and symbols

CT: conventional tillage
f: total soil porosity
FDP: fast drainage pores
HPR: horizontal penetration resistance
KO: coefficient of stress at rest
K_s: saturated hydraulic conductivity
L_v: root length density
MWD: mean-weight diameter of soil aggregates
NT: no-tillage
PAW: pores of available water
PCA: principal component analysis
PUW: pores of non-available water
q_s: quasi-steady infiltration rate
SDP: slow drainage pores
SOC: soil organic carbon
VPR: vertical penetration resistance
α: inverse of the air entry potential
ρ_b: soil bulk density
ρ_s: soil particle density
θ_r: residual soil water content
θ_s: saturated soil water content

3. Results and discussion

3.1. Soil physical properties

3.1.1. Soil bulk density and particle density

Bulk density was not significantly affected ($p \leq 0.05$) by tillage treatment (Table 2). Other studies have found similar (e.g., Dao, 1996) as well as opposite (e.g., Ball-Coelho et al., 1998; Schønning and Rasmussen, 2000) results. Contrasting effects of soil management experiments in ρ_b are common. They are mostly related to management factors such as planting machinery (machine weight, tire width, inflation pressure), number of machine passes, as well as the soil water content at which the soil is tilled (Czyz, 2004; Botta et al., 2005).

Soil particle density was affected by both, soil depth and tillage treatment (significant interaction ($p \leq 0.05$)

Table 2

Soil physical properties under conventional tillage (CT) and no-till (NT) treatments (letters (a–e) in the same column indicate significant differences ($p \leq 0.05$))

Years of management	Soil depth (cm)	ρ_b[b] (g cm^{-3})	ρ_s[c] (g cm^{-3})	f[d]	Particle size distribution[a](% by weight)			MWD[e] (mm)	VPR[f] (kg cm^{-2})	HPR[g] (kg cm^{-2})	KO[h]
					Sand (50–2000 μm)	Silt (2–50 μm)	Clay (< 2 μm)				
CT											
4	0–2	1.49	2.88	0.48	46.4	2.6	51.0	0.54e	1.35c	0.79	0.56
	2–5	1.47	2.87	0.49	46.6	1.5	52.0	0.56de	2.0.3bc	1.61	0.78
	5–15	1.41	2.90	0.51	48.3	3.0	48.8	0.81d	3.37a	2.98	0.90
7	0–2	1.39	2.86	0.51	44.6	2.4	53.0	0.34e	2.45c	1.62	0.64
	2–5	1.44	2.87	0.50	46.2	2.5	51.3	0.35e	2.57bc	2.33	0.90
	5–15	1.43	2.94	0.51	41.8	4.1	54.1	0.41e	3.60a	3.16	0.87
NT											
4	0–2	1.46	2.57	0.43	41.1	4.3	54.6	2.19b	2.51b	1.92	0.76
	2–5	1.52	2.80	0.46	41.1	3.2	55.7	1.29c	2.69ab	2.19	0.83
	5–15	1.43	2.74	0.48	39.6	6.5	54.0	1.36c	2.19b	2.20	1.00
7	0–2	1.44	2.50	0.43	43.5	2.7	53.8	2.79a	2.38c	2.07	0.99
	2–5	1.49	2.61	0.43	42.4	3.3	54.3	2.32b	3.30ab	2.60	0.79
	5–15	1.48	2.64	0.44	43.4	3.8	52.8	1.54c	3.57a	3.22	0.90

[a] Measured by the densitometry method.

[b] Soil bulk density.

[c] Soil particle density.

[d] Soil porosity.

[e] Mean-weight diameter.

[f] Vertical penetration resistance.

[g] Horizontal penetration resistance.

[h] Coefficient of stress at rest.

between soil depth and tillage treatment). When considering an average value between 0 and 15 cm depth, ρ_s was lower under NT (2.69 g cm^{-3}) as compared to CT (2.87 g cm^{-3}). Particle density under CT and NT did not significantly varied in depth. As a general trend, however, ρ_s at the oldest NT treatment, seems to decrease in the topsoil (Table 2). Such decrease could be related to variations in soil organic carbon (SOC) (Rühlmann et al., 2006). In a previous study made in the same experimental sites (Reyes et al., 2002), SOC was higher under NT (3.64% for the 0–2 cm depth, 2.55% for the 2–5 cm depth and 2.12% for the 5–15 cm depth) compared to CT (2.22% for the 0–15 cm depth).

3.1.2. Soil compaction

In general, VPR increased with soil depth and years under management in both CT and NT treatments. The only exception was the 4-year-old NT treatment with a slight decrease in VPR in depth (Table 2). The increased VPR with soil depth and time of treatment is most probably related to the weight of the planter (i.e., 2300 kg) (Czyz, 2004; Botta et al., 2005) and to the relatively high soil water content at the time of planting.

After 4 years of tillage treatments, NT had a significantly higher VPR than CT but only for the top 2-cm of soil. This is consistent with the results of Lampurlanés and Cantero-Martínez (2003), who reported higher values of soil penetrometer resistance under NT as compared with other tillage treatments. For the 5–15 cm soil depth, VPR was significantly higher under CT as compared to NT. This pattern disappeared for the 7-year tillage treatments with no significant differences in VPR between NT and CT. The increased SOC under NT might buffered the soil compaction effect of the NT planter, thereby diminishing the differences between tillage treatments in time.

The HPR was higher in the top 2-cm of soil under NT than under CT and increased (though not significantly) with time of treatment (Table 2). The coefficient of stress at rest was generally higher than 0.7 in all treatments, indicating thereby soil compaction problems (Hartge, 2001). The soil resistance to penetration, evaluated with the cone index, was higher under NT as compared to CT. Significant differences, however, were only found for the top 15 cm depth (Table 3).

3.1.3. Aggregate stability and aggregate size distribution

The MWD of soil aggregates was greater under NT as compared to CT and increased with time under NT (Table 2). This pattern might be attributed to greater SOC under NT. The MWD decreased with soil depth under NT but the opposite trend was found under CT. Additionally, the NT treatment had a higher proportion of aggregates with size >2.0 mm than the CT treatment (Fig. 2), particularly in the upper soil layers where organic matter accumulation could enhance aggregation. These results are consistent with the studies of Ball-Coelho et al. (1998), Ghuman and Sur (2001), and Shukla et al. (2003). It is known that aggregate size distribution has a hierarchical relation among soil particles. Soil particles tend to form microaggregates by binding of recalcitrant-humified organic matter with mineral particles (clay–humus complexes). The easily decomposable (labile) organic matter such as fungal hyphae and some polysaccharides bind microaggregates into macroaggregates (Tisdall and Oades, 1982; Bossuyt et al., 2002). The higher proportion of stable soil microaggregates (<0.5 mm) observed under CT could be related to the continuous perturbation of soil caused by tillage, which in turn, mostly disturb macroaggregate's binding agents.

3.1.4. Soil water infiltration

The quasi-steady infiltration rate, q_s, was affected by tillage treatment. For the 2003 period, CT had a faster q_s than NT (Table 4). This pattern was also found by Reyes et al. (2002) in previous experiments in the same soil. When this parameter was determined in 2004, q_s was not significantly different between NT and CT. In terms of trends, the CT treatment had faster q_s than NT, but

Table 3
Effect of tillage treatment on soil compaction as measured by cone index (kg cm^{-2}) in 2007 (at this time, sites A and B had 8 and 11 years under CT and NT, respectively)

Tillage treatment	Soil depth (cm)								
	0–5	5–10	10–15	15–20	20–25	25–30	30–35	35–40	40–45
CT	4.7	8.8	16.0	20.3	19.5	20.4	23.1	23.1	25.0
NT	20.7	26.7	28.2	33.2	34.9	36.2	43.7	45.6	49.4
LSD[a]	3.9	10.5	9.4	25.8	26.1	31.9	36.7	31.3	45.0

[a] Least significant difference $p \leq 0.05$.

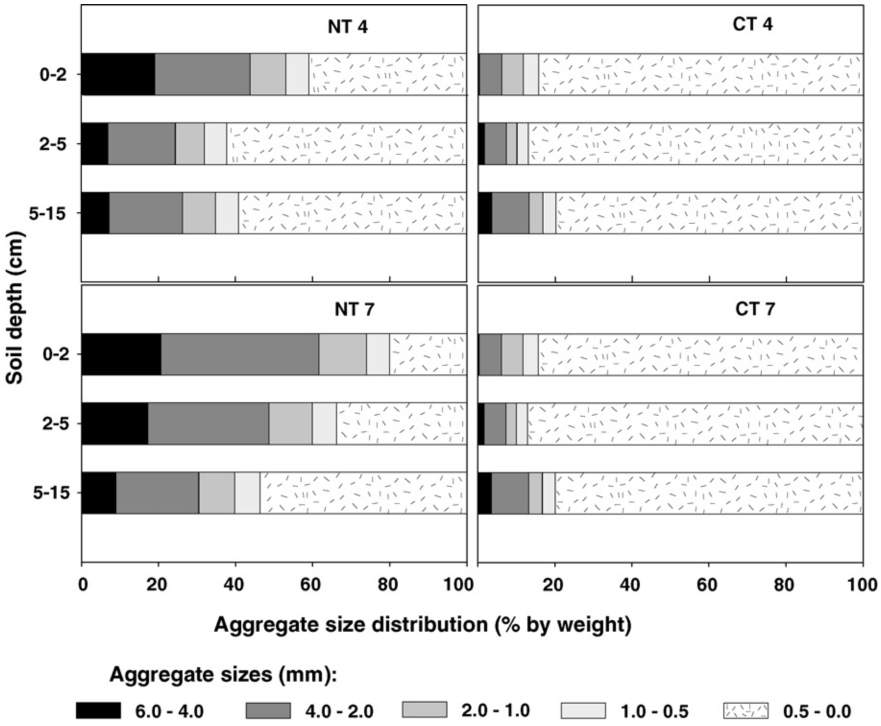

Fig. 2. Aggregate size distribution under the different tillage treatments.

only at planting and anthesis. Conventional tillage creates macropores that could facilitate infiltration, particularly after plowing. Indeed, fast drainage pores (Fig. 3) were consistently greater under CT than under NT. At harvesting, the FDP created by tillage might lessen as a result of repackaging of soil aggregates. Thus, differences between NT and CT decreased in time. The increased organic C under NT may counteract the slow q_s caused by greater soil compaction. Greater bulk density and penetration resistance under NT as compared to CT are indicators of soil compaction and thereby loss of soil macropores. Other studies (e.g., Lal and Vandoren, 1990; Shukla et al., 2003; Ghuman and Sur, 2001) have found faster q_s under NT as compared to CT. In those cases, q_s was particularly affected by the amount of SOC.

Table 4
Quasi-steady infiltration rates, q_s (cm h^{-1}), under conventional (CT) and no-tillage (NT) treatments (during the 2003 measurement, values were averaged between years of management. During the 2004 measurement, values were obtained for the 4-year treatments)

Tillage treatment	Year 2003	Year 2004		
	Anthesis	Planting	Anthesis	Harvesting
CT	12.95	4.17	3.03	3.74
NT	2.42	2.64	1.06	4.42
LSD[a]	8.41		2.94[b]	

[a] Least significant difference $p \leq 0.05$.

[b] Value corresponds to least significant difference $p \leq 0.05$ for the interaction phenological stage and tillage treatment.

3.1.5. Soil water retention and pore size distribution

The residual water content considers the water that is unavailable to plants, which is held in small pores and in films that surround soil particles. The θ_r was generally higher under NT (Table 5, Fig. 4). Higher θ_r values imply a greater soil water retention as well as greater proportion of micropores. An increased proportion of micropores is indicative of soil compaction.

The air-entry value $1/\alpha$ is defined as the potential at which air enters the largest pores of the soil. This parameter is also related to soil pores that form a continuous network of flow paths within the soil (Assouline et al., 1998). Greater air entry values were found under NT, implying that the soil under NT requires lower water potentials, and thereby more time, to unsaturate, particularly after a precipitation or irrigation event (Table 5). Greenland (1981), indicated that soils with a volume of macropores (i.e., $> 50\ \mu$m) lower than 10% may decrease root respiration. In our study, NT treatments showed a fast draining pore

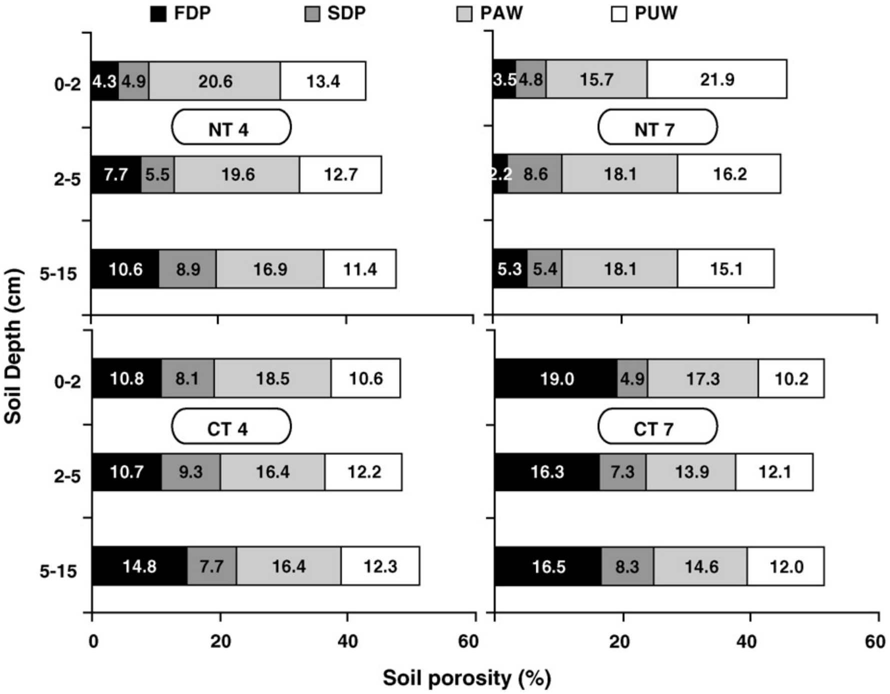

Fig. 3. Pores (% of total soil volume) size distribution under the different tillage treatments. PUW: Pores of unavailable water for the crop; PAW: pores of available water for the crop, SDP: slow drainage pores; FDP: fast drainage pores.

volume (i.e., $>30\,\mu m$) below this point (Fig. 3), thereby root respiration might be diminished under this management system.

The saturated hydraulic conductivity, estimated by Mualem's model (Mualem, 1976), was lower under NT than under CT (Table 5), which is consistent with our results of soil water infiltration (Table 4). K_s was also affected by years of management and soil depth. For the NT treatments, K_s decreased as a function of treatment age with lower K_s under the 7-year-old treatment. The CT treatment showed the opposite trend, which might be attributed to soil perturbation caused by tillage. For

Table 5
Fitted van Genuchten parameters of soil moisture characteristic for conventional tillage (CT) and no-till (NT) treatments

Years of management	Soil depth (cm)	Fitted parameters[a]				
		θ_r	θ_s	α	n	K_s
CT						
	0–2	0.0004	0.4810	0.0206	1.2563	1.86
4	2–5	0.0690	0.4853	0.0177	1.3564	2.50
	5–15	0.0077	0.5121	0.0416	1.2247	2.54
	0–2	0.0006	0.5134	0.0589	1.2314	3.27
7	2–5	0.0344	0.4971	0.0582	1.2391	3.87
	5–15	0.0243	0.5131	0.0501	1.2426	3.54
NT						
	0–2	0.0933	0.4288	0.0052	1.4582	1.14
4	2–5	0.0533	0.4536	0.0101	1.3398	1.19
	5–15	0.0474	0.4783	0.0186	1.3221	2.51
	0–2	0.1670	0.4571	0.0056	1.3950	0.89
7	2–5	0.0912	0.4555	0.0067	1.3321	1.06
	5–15	0.0825	0.4361	0.0072	1.3612	1.25

[a] Units of parameters: θ_r, residual water content (cm^3 cm^{-3}); θ_s, saturated water content (cm^3 cm^{-3}); α, inverse of the air entry potential (cm^{-1}); n, empirical constant affecting the shape of the retention curve (non-dimensional); K_s: saturated hydraulic conductivity (cm h^{-1}).

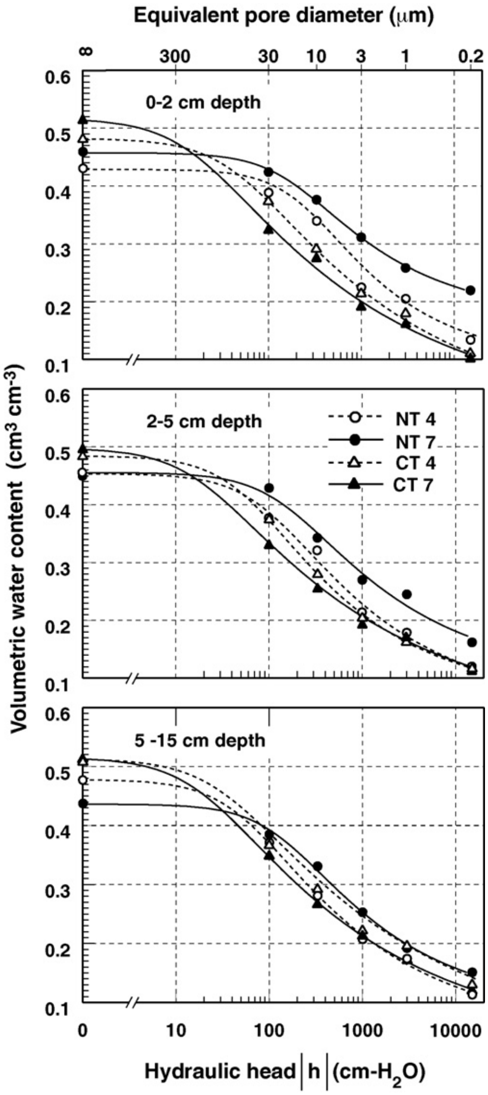

Fig. 4. Measured soil moisture characteristic (symbols) and fitted van Genuchten equations (lines) for the different tillage treatments.

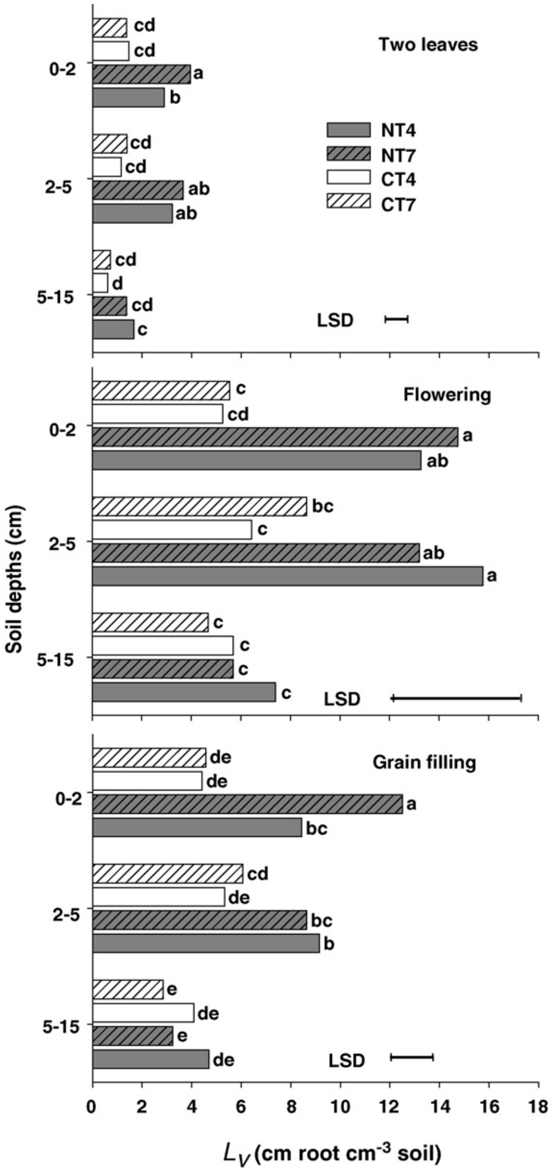

Fig. 5. Root length density (L_v) at the phenological stages of two leaves, flowering, and grain filling (i.e., 40, 117, and 131 days after sowing, respectively) for the different tillage treatments.

both, NT and CT treatments, K_s increased in depth. This pattern was more accentuated under NT.

3.1.6. Root length density and grain yield

For the top 5 cm of soil, L_v was greater under NT than under CT (Fig. 5). This trend was found during the two leaves, flowering, and grain filling stages, with average L_v values for NT of 3.43, 14.30, and 9.53 cm cm^{-3}, and 1.34, 6.70, and 5.22 cm cm^{-3} for CT, respectively. The continuous addition of crop residues have increased soil organic carbon, particularly in the topsoil. This increase in SOC have created a new topsoil environment with better and more stable aggregates that may favor, at least indirectly, root development in time. However, soil compaction, particularly of the deeper soil layers may have caused a significant decrease of L_v in depth. From 5–15 cm depth, the effects of management treatment and years under management were not clear. Soil compaction of deeper soil layers under NT may impeded the optimal development of roots, decreasing then differences between management treatments. Other studies have found similar results (e.g., Acharya and Sharma, 1994; Merrill et al., 1996; Ball-Coelho et al., 1998; Lampurlanés and Cantero-Martínez, 2003).

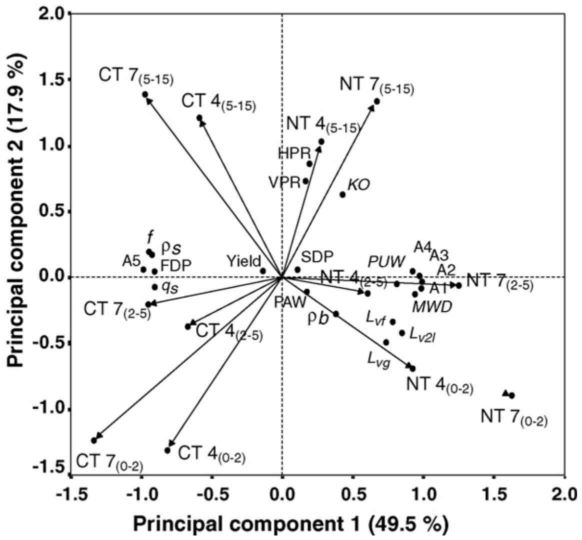

Fig. 6. Principal component analysis for the treatments NT4, NT7, CT4, and CT7 as a function of crop and soil parameters. VPR: Vertical penetration resistance; HPR: horizontal penetration resistance, KO: coefficient of stress at rest; PUW: pores of unavailable water for the crop; PAW: pores of available water for the crop, SDP: slow drainage pores; FDP: fast drainage pores; *f*: soil porosity; ρ_s: soil particle density; ρ_b: bulk density; MWD: mean-weight diameter of soil aggregates; A1–A5: size class of soil aggregates (4.8–6.7, 2.0–4.8, 1.0–2.0, 0.5–1.0, and < 0.5 mm respectively); L_v 2l, L_v f, and L_v g: root density at two leaves, flowering, and grain filling stages respectively.

Grain yield under NT was 2.9 and 2.3 Mg ha^{-1} for the 4 and 7 years treatments, respectively. The CT treatment had a slightly greater yield with 3.2 and 3.9 Mg ha^{-1} for the 4 and 7 years treatments, respectively. Nevertheless, no significant differences in grain yield were found between the NT and CT treatments. Overall wheat grain yield (NT and CT included) was 3.1 Mg ha^{-1}, which is below the range of grain yield for these type of soil and climatic conditions (5–6 Mg ha^{-1}). Late seeding time may cause this reduced yield.

It seems that variations in L_v between management treatments did not cause significant differences in grain yield. As a general trend, wheat roots can develop up to 60 cm-depth in these soils. In our study, L_v was only measured in the upper 15 cm of soil. Thereby the complete effect of L_v on grain yield was not possible to evaluate.

3.1.7. Multivariate analysis

The PCA shows that the first-two principal components explained 67.4% of the experimental variance (Fig. 6). Soil parameters with the highest weight in the abscissa axis were MWD and *f*, which are related to soil structural stability and soil water and air mobility. The ordinate axis (second principal component) was related to soil compaction and soil depth. Under NT, the MWD and the water stable aggregates (≥ 0.5 mm) were positively associated to L_v, particularly in the upper 2-cm of soil. No direct association between aggregate and pore sizes were found. This is a predictable pattern since aggregate size was obtained by wet sieving in order to measure structural stability and not the size of intact soil aggregates. Under CT, the FDP were highly associated to *f*, confirming the effect of tillage in the formation of clods and thereby of macropores.

4. Conclusions

There is an increased need to understand the beneficial and detrimental effects of NT, particularly in soils pedogenetically developed under semi-arid conditions and where residue transformations are mostly limited by soil water. We evaluated the effect of conventional and no-tillage treatments on soil physical properties, root growth, and wheat yield in an Entic Haploxeroll of Central Chile. The results of this study shows that NT management systems affect soil physical properties predominantly at the top 5 cm of soil. Particularly, the NT system enhanced soil aggregate stability and L_v. In contrast, soil water infiltration and coarse porosity decreased under NT as compared to CT. Under rainy conditions or in over-irrigated systems, the lack of infiltration could delay root growth or even cause root diseases. It seems that under NT root length density was favored by a higher soil structural stability. Nevertheless, no clear relationship between root length density and surface soil compaction was found. The implementation of other management practices that help to increase water infiltration and thereby decrease soil compaction, may consider the introduction of new crops in the rotation. Such crops should enhance root development and soil bioturbation. It is well known that soil compaction is affected by the management system as well as by the soil water content at planting time. Thus, a better understanding of optimal soil conditions during field operations are needed in order to improve soil properties and thereby crop yields.

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