RESEARCH

INFLUENCE OF CONSERVATION TILLAGE AND SOIL WATER CONTENT ON CROP YIELD IN DRYLAND COMPACTED ALFISOL OF CENTRAL CHILE

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Chilean dryland areas of the Mediterranean climate region are characterized by highly degraded and compacted soils, which require the use of conservation tillage systems to mitigate water erosion as well as to improve soil water storage. An oat (*Avena sativa* L. cv. Supernova-INIA) - wheat (*Triticum aestivum* L. cv. Pandora-INIA) crop rotation was established under the following conservation systems: no tillage (Nt), Nt + contour plowing (Nt+Cp), Nt + barrier hedge (Nt+Bh), and Nt + subsoiling (Nt+Sb), compared to conventional tillage (Ct) to evaluate their influence on soil water content (SWC) in the profile (10 to 110 cm depth), the soil compaction and their interaction with the crop yield. Experimental plots were established in 2007 and lasted 3 yr till 2009 in a compacted Alfisol. At the end of the growing seasons, SWC was reduced by 44 to 51% in conservation tillage systems and 60% in Ct. Soil water content had a significant ($p < 0.05$) interaction with tillage system and depth; Nt+Sb showed lower SWC between 10 to 30 cm, but higher and similar to the rest between 50 to 110 cm except for Ct. Although, SWC was higher in conservation tillage systems, the high values on soil compaction affected yield. No tillage + subsoiling reduced soil compaction and had a significant increment of grain yield (similar to Ct in seasons 2008 and 2009). These findings show us that the choice of conservation tillage in compacted soils of the Mediterranean region needs to improve soil structure to obtain higher yields and increment SWC.

Key words: Neutron probe, penetrometer resistance, oat, subsoiling, water erosion, wheat.

Several studies have shown that water erosion negatively affects many soil-quality indicators such as depth, organic matter content, nutrient status, and aggregate stability (Schjønning *et al*., 2004). Water erosion is controlled by four basic factors: climate, soil type, topography, and vegetative cover (Jin *et al*., 2007). The prevention and control depends on understanding the mechanics of the erosion process and also on the implementation of control practices. In addition, the repeated use of inadequate tillage systems in soils with slopes, and the high concentration and intensity of precipitation are key factors for the occurrence of the erosion process (Ramos and Martínez-Casasnovas, 2006). This is one of the main factors for land degradation and low yields in many areas of the world (Schjønning *et al*., 2004), including Chile's dryland Mediterranean region (Ovalle *et al*., 2006), where water erosion removes topsoil (horizon A) resulting in highly compacted soils with poor fertility, low infiltration, and water holding capacity (Pala *et al*., 2007). These negative impacts results in an increase in the bulk density, decreased aeration and increased penetration resistance, which results in impeded root development (Letey, 1985; Batey, 2009). This detrimental effect on root growth becomes greater as compaction increase (Lipiec and Hatano, 2003; Motavalli *et al*., 2003).

In short-term, conventional tillage reduce runoff and soil compaction, but this effect is lost as soon as the first rainfall occurs producing the crusting effect (Hoogmoed and Stroosnijder, 1984; Rao *et al*., 1998). On the contrary, conservation tillage systems in rainfed Mediterranean environments avoid crusting and increase water infiltration (Riezebos and Loerts, 1998; Lampurlanés *et al*., 2001; Pansak *et al*., 2008; Fuentes *et al*., 2009; Vidhana Arachchi, 2009). Ramos and Martínez-Casasnovas (2006) found in vineyards in NE Spain, that water infiltration was mostly influenced by rainfall intensity; in high rainfall intensities soil moisture increased in the first strata without significant increases in depth, but in low intensity rainfall, the soil water content increased in the whole profile, especially when conservation.

In Chile, the investigations of soil conservation tillage systems in rainfed areas have been mainly focused in

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runoff and soil losses with little information on water content in the soil profile (Peña, 1986; Peña and Fuentes, 1987; Rodríguez *et al*., 2000). This study was conducted in an oat (*Avena sativa* L.)-wheat (*Triticum aestivum* L.) crop rotation in a degraded Alfisol of the Mediterranean region of central Chile. Therefore, our objectives were to evaluate the influence of different tillage systems on soil water content, as well as soil compaction and their interactions on crop yield.

MATERIALS AND METHODS

Site description

The experiment was carried out in the Instituto de Investigaciones Agropecuarias INIA, Cauquenes Experimental Station (35°97' S, 72°24' W), during the 2007, 2008, and 2009 seasons. This is a subhumid Mediterranean climate region with a mean annual precipitation of 695 mm concentrated in autumn and winter. Annual and monthly precipitation in the 3 yr of the study and monthly mean of 44-yr from INIA Cauquenes station is shown in Figure 1. Annual mean temperature is 14.7 °C with a minimum of 4.7 °C in July and a maximum of 27 °C in January (Del Pozo and del Canto, 1999). The soil is classified as Ultic Palexeralfs (CIREN, 1994; Stolpe, 2006) and is made up of materials of granite origin with a slightly acidic pH (5.9) and low organic matter content (1.50%). Detailed soil physical characteristics are shown in Table 1. The area is hilly and land use is mainly for pastures and cereal crops. The study site has a 15% slope which is representative of the study area.

Field experiment description

Five experimental plots of 1000 m^2 (20 × 50 m) were established during seasons 2007 to 2009. Each large plot was located on a hillside with 12.5% slope. Were evaluated four conservation tillage systems: no tillage (Nt), Nt with subsoiling (Nt+Sb) at 40 cm depth conducted in April 2007 before sowing; Nt with *Phalaris aquatica* barrier hedge (Nt+Bh) at 12.5 m distance; and Nt with contour ploughing (Nt+Cp) every 12.5 m with a 1% slope to remove water from the plot, compared to conventional tillage with animal plowing (Ct). The tillage treatments were cropped with an oat (cv. Supernova-INIA) - wheat (cv. Pandora-INIA) - oat (cv. Supernova-INIA) crop rotation. The sowing and harvesting date were middle of May and middle December every year, respectively. Seed rate for oat was 140 kg ha^{-1} and wheat 200 kg ha^{-1}. Fertilization was adjusted every year according to soil analysis realized in March. The soil was fertilized with urea, triple super phosphate, and potassium muriate. Fertilizer sources consisted of 110, 80, and 80 kg ha^{-1} of N, P_2O_5, and K_2O, respectively for oat, and 140, 80, and 80 kg ha^{-1} of N, P_2O_5, and K_2O, respectively for wheat. On the soil surface in conservation tillage systems, the residue was shredded and left on top of the soil after oat and wheat crop (2.5 Mg ha^{-1}).

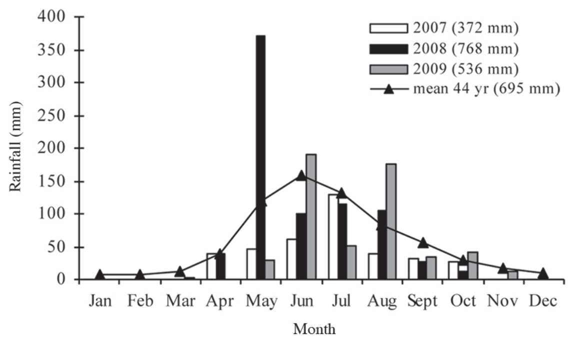


Figure 1. Mean monthly rainfall distribution for Cauquenes from 2007 to 2009 compared to a 44-yr mean precipitation.

Soil and crop measurements

Soil water content was measured with a neutron probe (model 4300 Troxler, Troxler Electronic Lab, Research Triangle Park, North Carolina, USA). Aluminum access tubes with a diameter of 50 mm and a length of 120 cm were installed vertically at a depth of 110 cm at the beginning of the experiment, with three replicates for each treatment, except in Nt+Sb where three tubes were installed per replicate. The first measurement was taken at 0.2 m then at 0.2 increments thereafter to 1 m depth. Monitoring of soil moisture was started after the rainy season from August or September to December. Six access tubes located close to the field experiments were used for calibration; samples were taken at a distance of 0.3 m from each tube and at the same depth as the readings. Regression analysis between gravimetric water content and the neutron probe reading was R^2 = 0.84. Gravimetric water content at each depth was converted into soil volumetric water content by strata of 0.2 m. Then, the SWC was obtained in the 10-30, 30-50, 50-70, 70-90, and 90-110 cm strata depths.

Soil compaction as a cone index was measured in the second and third seasons (2008 and 2009) in April prior to sowing the crop by pushing a hand-held cone-tipped (12.8 mm diameter) penetrometer (Field Scout SC900 Soil Compaction Meter; Spectrum Technologies, Plainfield,

Table 1. Study site soil physical characteristics.

Horizons	Depth	Sand	Silt	Clay	Soil texture	Bulk density	Porosity
	cm		%			Mg m^{-3}	%
Ap	0-18	72.6	12.6	14.8	Sandy loam	1.79	28.4
Bt_1	18-36	42.4	13.0	44.5	Clay	1.69	32.4
Bt_2	36-61	34.2	17.6	48.2	Clay	1.75	30.0
Bt_3	61-100	32.2	19.6	48.2	Clay	1.77	29.2

Illinois, USA). Soil compaction readings were recorded in 2.5 cm increments to 20 cm deep with 20 replicates at each plot.

Above-ground biomass and grain yield were recorded at crop maturity in 1 m^2 with four replicates. Root biomass was measured in 10 plants taken at random. Samples of biomass were oven-dried for 48 h at 55 °C (Martínez *et al*., 2009).

Statistical analysis

Soil water content (SWC) was carried out using split-split-plot design (Undurraga *et al*., 2009) of the SAS software program (version 9.1.3 Service Pack, SAS Institute, 2002-2003). The ANOVA was performed with the GLM procedure (linear model) and Tukey test to compare means of significant values ($p \leq 0.05$) assuming the effects of tillage system, sampling date and depth as fixed effects according to the following model:

$$y_{ijkl}=\mu+\alpha_i+\beta_j+\delta_k+\pi_l+p_l+\lambda_{ijl}+(\alpha\beta)_{ij}+(\alpha\delta)_{ik}+(\beta\delta)_{jk}+(\alpha\beta\delta)_{ijk}+\varepsilon_{ijkl}$$

$$i=1,2,3,4,5;\quad j=1,2,3,4,5,6,7,8,9;\quad k=1,2,3,4,5;\quad l=1,2,3.$$

where Y is moisture content, μ general mean, α_i mean effect of ith level of tillage systems (large plot), π_l effect of the lth block, p_{il} random error of large plot, β_j effect of jth level of sampling date (subplot), $\alpha\beta$ corresponds to interaction between tillage system treatments and sampling date, λ_{ijl} subplot random error, δk mean effect of kth depth (sub-subplot), $\alpha\delta$ corresponds to interaction of tillage system treatments and depth, $\beta\delta$ interaction of sampling date and depth treatments, $\alpha\beta\delta$ interaction of the three factors, and ε corresponds to sub-subplot random error.

In addition, an ANOVA of mixed effect models was carried out to determine the effect of annual precipitation on SWC in different tillage systems and depths during the most important phenological crop stages, such as tillering (Zadoks stage 23), stem elongation (Zadoks stage 31), spike emergence (Zadoks stage 59), and grain ripening (Zadoks stage 92) (Stapper, 2007). Thus, tillage system (A) was considered as a fixed factor, soil depth (B) was a random factor and the interaction of both (A*B):

$$y_{ijk}=\mu_{..}+\alpha_i+\beta_j+(\alpha\beta)_{ij}+\varepsilon_{ijk},$$

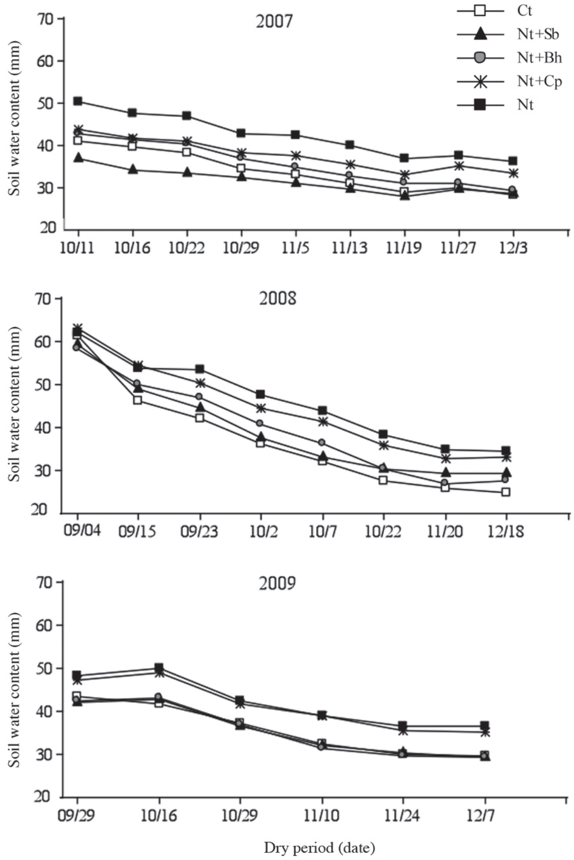
where μ is general mean, α_i mean effect of ith level of factor A (tillage system) subjected to jth level of factor B (depth).

RESULTS AND DISCUSSION

Influence of tillage systems on soil water content

During the experimental period (3 yr) there was an important variation on annual precipitation (Figure 1) and therefore it was necessary to evaluate both the effect of soil tillage and annual precipitation on SWC.

Temporal evolution of total SWC (0-110 cm) decreased gradually during crop development in all tillage systems (Figure 2). This is explained by the fact that evaluations were carried out between September and December, period in which rainfall decreases and water extraction by the crop increases. This drying process is dominated by a vertical flow (De Lannoy *et al*., 2006) in which the development of the plant cover and roots, and water extraction by the crop intervenes, contributing additional variability to the tillage system.



Nt: No tillage; Nt+Sb: Nt + Subsoiling; Nt+Bh: Nt + Barrier hedge; Nt+Cp: Nt + Contour ploughing; Ct: Conventional tillage.

Figure 2. Soil water content (SWC) between 10 to 110 cm layers in the dry period (2007, 2008 and 2009).

In driest years (2007 and 2009), SWC was reduced by 23 to 31%, in which Ct showed the highest decreases in both seasons. However, in a wet year (2008) SWC was reduced by 44 to 51% in conservation systems, while in Ct the reduction was 60% (Figure 2). These results showed that no tillage systems conserve more soil moisture in the profile than traditional tillage; in part it can be explained because in these systems the crop residue is maintained on the surface, producing less evaporation and greater infiltration (Unger *et al*., 1991; Lampurlanés *et al*., 2001; McHugh *et al*., 2007; Jin *et al*., 2008; Pansak, 2008; Govaerts *et al*., 2009). At the end of the evaluations (December), SWC stabilized in all depths and was closely related to the tillage system used.

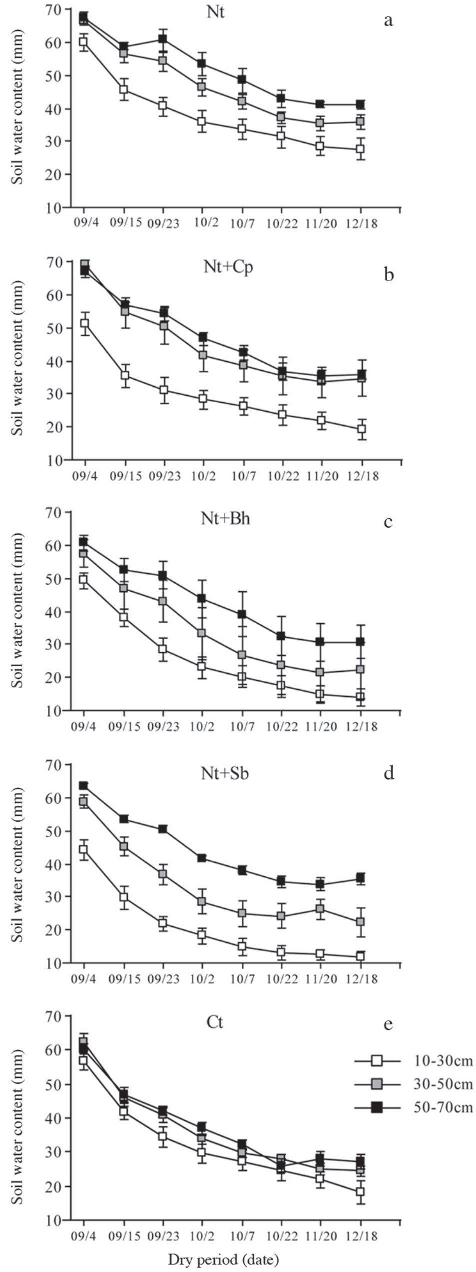
A significant effect ($p < 0.05$) was observed between tillage systems and depth in the 3 yr of the study (Table 2). By comparing SWC per strata (10-30, 30-50, 50-70 cm; Figure 3) in the profile during season 2008, differences were observed between tillage systems providing two different patterns. In the case of Ct, no real differences were observed between the evaluated depths during sampling time (Figure 3e). This can be explained because the Ct with animal ploughing inverts and mixes the soil (20-30 cm) producing the sealing and crusting of the topsoil with the first rainfall, which reduce infiltration and increase runoff (Lampurlanés *et al*., 2001; Ramos and Martínez-Casasnovas, 2006; Munodawafa and Zhou, 2008). In fact, in this site during year 2008 an intense rainfall event of more than 300 mm, produced a runoff between 20-30% for conservation tillage systems while in Ct was 70% (Martínez *et al*., 2009).

Analysis of variance of mixed factors allowed determining the influence of the variability of annual precipitation on the main factors evaluated (tillage system and depth) on SWC during the most important phenological stages (Zadoks stage 23, 31, 59, and 92). Results indicated that the percentage of variance associated with soil depth for 2007 and 2009 ranging between 70% to 82% and 61% to 85%, respectively, whereas in 2008 it ranging between 38 to 64%. These results showed that SWC distribution in the profile was significantly ($p < 0.05$) affected by tillage systems in the driest years (2007 and 2009; Figure 1). The above suggest that the tillage system play an important role in the availability of SWC in this rainfed area. The results showed that Nt+Sb increased water infiltration towards the deeper strata (50-110, Figure 3 and Table 2) leading to higher grain yield as revealed below. In addition, this infiltration pattern will also depend on soil type, crop rotation (Vidhana Arachchi and Liyanage, 2003; Fuentes *et al*., 2009; Alvarez and Steinbach, 2009) and the variation and intensity of the rainfall events (De Lannoy *et al*., 2006; Pala *et al*., 2007; Song *et al*., 2009).

Table 2. Comparison of means soil water content (mm) among tillage systems, for each depth (cm).

Tillage system	Soil depth (cm)				
2007 yr	10-30	30-50	50-70	70-90	90-110
Ct	15.72b	31.46ba	38.38b	39.36b	44.50a
Nt+Sb	11.69b	24.13b	36.42b	41.83b	43.42a
Nt+Bh	16.02b	29.08ba	39.14b	45.68a	48.28a
Nt+Cp	19.18ba	39.21ba	41.69b	42.35b	46.13a
Nt	26.92a	42.28a	48.05a	46.99a	47.08a
2008 yr					
Ct	31.80b	36.24ba	37.46c	38.50b	41.20b
Nt+Sb	20.82c	33.37b	43.87bc	47.21a	49.78ba
Nt+Bh	25.60b	34.22b	42.58bc	46.68a	48.95ba
Nt+Cp	29.54b	44.70ba	46.90ba	47.79a	53.22a
Nt	37.90a	46.74a	51.67a	46.74a	47.10ba
2009 yr					
Ct	25.32bc	31.43bc	37.54c	38.77a	45.45a
Nt+Sb	14.97d	26.65c	39.61bc	45.10a	51.37a
Nt+Bh	20.32dc	27.08c	36.55c	42.14a	51.04a
Nt+Cp	27.49ba	39.44ba	42.61ba	43.79a	53.05a
Nt	32.07a	40.87a	46.57a	43.20a	47.81a

Nt: No tillage; Nt+Sb: Nt + Subsoiling; Nt+Bh: Nt + Barrier hedge; Nt+Cp: Nt + Contour ploughing; Ct: Conventional tillage.
Values with the same letter in the columns do not show significant differences ($p < 0.05$).

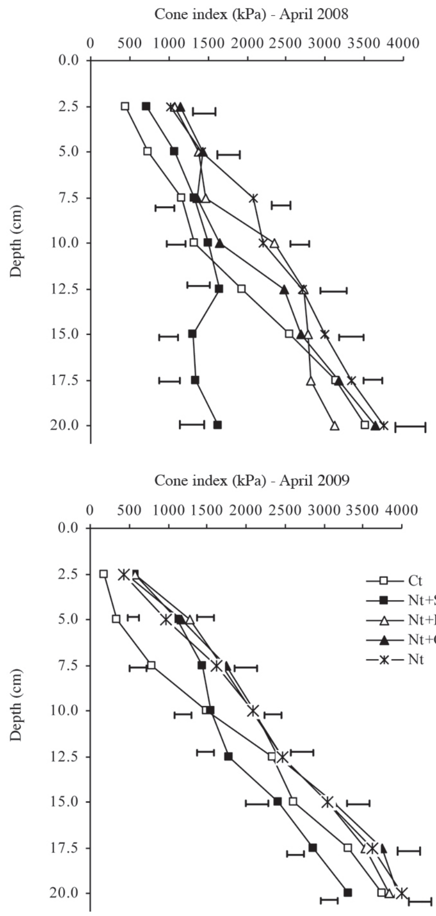


Nt: No tillage (a); Nt+Cp: Nt + Contour ploughing (b); Nt+Bh: Nt + Barrier hedge (c); Nt+Sb: Nt + Subsoiling (d); Ct: Conventional tillage (e).

Figure 3. Soil water content (SWC) at 10-30, 30-50, and 50-70 cm layer, during 2008.

Influence of tillage systems on soil compaction

Soil compaction evaluations were carried out in the second (2008) and third year (2009) of the study period. The results are presented for the eight soil depths in Figure 4. In the second year, soil penetration resistance increased from 500 to 1500 kPa in all tillage system at a depth of 2.5-10



Nt = No tillage; Nt+Sb = Nt + Subsoiling; Nt+Bh = Nt + Barrier hedge; Nt+Cp = Nt + Contour ploughing; Ct = Conventional tillage.

Figure 4. Mechanical resistance profile to measured penetration depth cone index (kPa).

cm of depth. Down to 10-20 cm soil penetration resistance changed substantially in Nt, Nt+Cp, Nt+Bh, and Ct tillage systems which exceeded 2000 kPa, compared with the subsoiled treatment (Nt+Sb) which was significantly lower, maintaining an average of 1500 kPa to a depth of 20 cm. In the third year, soil penetration resistance in Nt+Sb markedly increased over the 2000 kPa below 15 cm of depth, while the rest of the conservation treatments exceeded this threshold at 10 cm.

The high values of soil compaction in depth are explained by the high percentage of clay in B horizon (18 to 100 cm) and an uniform high bulk density profile (≥ 1.7 Mg m^{-3}; Table 1), which limit root growth due to a) soil water being held more tightly and b) high soil resistance to root growth (Letey, 1985; Batey, 2009; Jung *et al.*, 2010). In fact, root biomass per plant at the end of the season (Table 3) in the three years under study showed significantly lower values in those treatments where soil depth was highly compacted (Nt, Nt+Cp, and Nt+Bh). In addition, several authors have mentioned that an increase in soil compaction, over than 1500 kPa, may reduce grain yield (Lipiec and Hatano, 2003; Jung *et al.*, 2010).

Table 3. Root biomass per plant at the grain ripening stage (Zadoks stage 92) between 2007 to 2008.

Tillage system	Dry root yield per plant (g)		
	Oat - 2007	Wheat - 2008	Oat - 2009
Ct	0.24ba	1.09ba	1.09a
Nt+Sb	0.30a	1.36a	1.07a
Nt+Bh	0.19b	1.03b	0.91ba
Nt+Cp	0.18b	0.99b	0.85bc
Nt	0.20b	0.81b	0.66c

Nt: No tillage; Nt+Sb: Nt + Subsoiling; Nt+Bh: Nt + Barrier hedge; Nt+Cp: Nt + Contour ploughing; Ct: Conventional tillage.

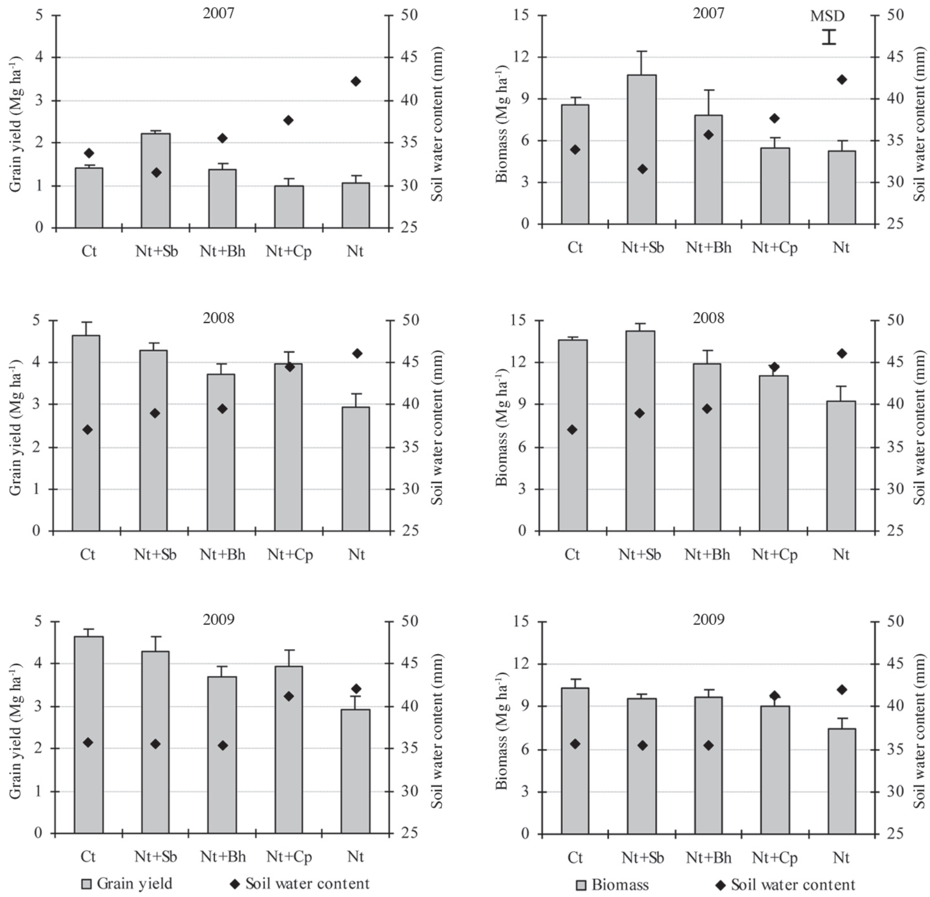
Influence of tillage systems on crop yield

In the first year of the study (2007), with average rainfall of only 372 mm, oat grain yield and biomass production of Nt+Sb was significant ($p < 0.01$) higher than the rest of the treatments, while Nt+Cp and Nt obtained the lowest productivity (Figure 5, 2007 yr). In 2008, with 768 mm of rainfall (more humid year), the highest wheat productivity was observed in the Nt+Sb and Ct treatments, and the lowest in Nt (Figure 5, 2008 yr). Finally, in the third year (with 536 mm, but with spring rainfall) oat crop production was higher in the Nt+Sb, Ct and Nt+Bh treatments compared to Nt (Figure 5, 2009 yr).

Our results indicate a common pattern for the three years, where Nt+Sb and Ct treatments showed the highest yield; Nt+Sb reduced SWC between 10-30 cm depth and favored water extraction by the crop leading to higher productivity particularly in dryer years (e.g. 2007), while Ct showed the lowest SWC in the profile (Table 2, Figure 3). Although, Nt systems are potentially better for dryland conditions, because they maintains greater water content in the soil, the higher soil strength reduces root growth and yield.

As expected, the annual rainfall distribution affected SWC and yield. Years with lowest rainfall, 2007 and 2009 showed a different pattern and yield of oat production. In 2007, the highest rainfall period occurred between June-July; however, 2009 has two rainfall periods, one in May-June and the other in August-September, when the crop was at the stem elongation phenological stage (Zadoks stage 31). In both years the biomass production was similar, but the yield was severely affected in 2007 yr.

This investigation suggests that the choice of conservation tillage system without any modification on soil structure will affect crop yield in compacted soils. In addition, in the Mediterranean climate region, the annual rainfall distribution and the water deficit at the end of the growing season is other limiting factor for cereal production, due to the low water infiltration and low root biomass in compacted soils (Sojka *et al.*, 1993; Hong-ling *et al.*, 2008; Alvarez and Steinbach, 2009; Vidhana Arachchi, 2009). Therefore, no tillage combined with subsoiling (Nt+Sb) is particularly relevant in these



Minimun significant difference (MSD) according to Tukey test (p ≤ 0.05).
Nt = No tillage; Nt+Sb = Nt + Subsoiling; Nt+Bh = Nt + Barrier hedge; Nt+Cp = Nt + Contour ploughing; Ct = Conventional tillage.

Figure 5. Relationship between grain yield and biomass production with soil water content during 2007 (oat), 2008 (wheat), and 2009 (oat).

environments where much of crop growth occurs in spring (at the start of the dry season) and is generally subjected to a water deficit during the grain filling-period of cereals (De Vita *et al*., 2007; He *et al*., 2009; Jin *et al*., 2009).

CONCLUSIONS

Crop residues maintained on the surface and conservation tillage system preserved more SWC in the profile than conventional tillage after the rainy season. This practice is relevant in Mediterranean climate regions where much of crop growth occurs in spring, when the rainfall period is ended. Although, SWC was higher in conservation tillage systems, the high values on soil compaction affected yields. The results of the present study showed that the soil conditions are of major importance to SWC and determine the differences observed between tillage systems. Nt+Sb reduced soil compaction and had a significant increment of grain yield. In this scenery, the benefits of improving soil structure are necessary to obtain higher yields. In addition, this conservation tillage system generates environmental benefits in these highly compacted and degraded soils of the country.

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Influencia de la labranza de conservación y el contenido de agua sobre el rendimiento del cultivo en un Alfisol compactado del Secano Central de Chile. En Chile, las zonas de clima mediterráneo se caracterizan por suelos altamente degradados y compactados por erosión, lo que requiere el uso de sistemas de labranza conservacionista para mitigar la erosión hídrica, así como incrementar el contenido de agua en el suelo. Se evaluó una rotación avena (*Avena sativa* L. cv. Supernova-INIA) - trigo (*Triticum aestivum* L. cv. Pandora-INIA) establecida bajo los siguientes sistemas conservacionistas: cero labranza (Nt), Nt + curvas de nivel (Nt+Cp), Nt + franjas vivas (Nt+Bh) y Nt + subsolado (Nt+Sb), las que fueron comparadas al sistema de labranza convencional (Ct), para evaluar su influencia en el contenido de agua en el suelo (SWC) en el perfil (10 a 110 cm profundidad), la compactación del suelo y su interacción con el rendimiento del cultivo. Las parcelas experimentales fueron establecidas 3 años seguidos (2007 al 2009) en un Alfisol compactado. Al final de la temporada, el SWC disminuyó 44 a 51% en los sistemas conservacionistas y 60% en el sistema convencional. El sistema de labranza y la profundidad tuvieron un efecto significativo ($p < 0.05$) en el SWC; Nt+Sb presentó un menor contenido de agua entre los 10 y 30 cm y similar al resto de los sistemas conservacionistas entre los 50 y 110 cm, sin embargo, superior a Ct. Aunque los sistemas conservacionistas mostraron un mayor SWC, la alta compactación afectó los rendimientos. Cero labranza + subsolado redujo la compactación del suelo e incrementó significativamente el rendimiento en grano (similar a Ct en las temporadas 2008 y 2009). Estos resultados nos muestran que la elección de un sistema conservacionista en suelos compactados de la región mediterránea, requiere mejorar la estructura del suelo para obtener mejores rendimientos e incrementar el contenido de agua en el suelo.

Palabras clave: neutrómetro, resistencia a la penetración, avena, subsolado, erosión hídrica, trigo.

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