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Tillage effects on the soil water balance and the use of water by oats and wheat in a Mediterranean climate

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ABSTRACT

In the drylands of the Cordillera de la costa of central Chile, the water balance variables are governed by a typical Mediterranean precipitation pattern. In this environment, agronomic management practices are mainly aimed at improving the availability of water in the soil, creating optimal conditions for the crops to effectively use the available water. The aim of this study was to determine the soil water balance and water use efficiency in an oat-wheat crop rotation grown in a duplex soil with two contrasting textural layers. An experiment was conducted during the years 2007–2009 at the Experimental Center Cauquenes located in the inner dryland of the coastal range of central Chile. Conventional tillage (Ct), no tillage (Nt) and no tillage with subsoiling (Nt + Sb) systems were established. The water balance for each year of study and the total biomass, grain yield, harvest index (HI), ^{13}C discrimination ($\Delta^{13}C$), crop evapotranspiration (ETc) and water use efficiency (WUE) were determined. The crop evapotranspiration (ETc) varied between 273 and 360 mm, with an overall seasonal average of 300 mm. The conservation tillage systems have a positive effect on SWC; however, the results are related to the annual rainfall. In a dry year, Nt + Sb improved the water use efficiency to 8.10 kg ha^{-1} mm^{-1}, higher than that of Ct and Nt by 40% and 55%, respectively. We have demonstrated how understanding the impact of soil tillage systems on compacted soils with an abrupt contrasting soil texture can improve water use efficiency and consequently reduce water loss.

1. Introduction

In regions having a Mediterranean climate, the water availability is a limiting factor for agriculture; therefore, efficient use of the available water is essential to agricultural production (Cantero-Martínez et al., 2007; Zhang et al., 2008). Moreover, in rain-fed areas with a Mediterranean climate, the rainfall occurs mainly during the winter months with a prolonged drought thereafter. These rain events control the variables that determine the soil water balance. A portion of the rain is not stored in the soil profile and is lost from the root zone. The Mediterranean climate of central Chile has an average rainfall of 690 mm, and 80% of this falls in the winter and autumn (Martínez et al., 2011). The water use efficiency (WUE) is closely related to the effective use of rainfall, which is the only source of water (Hatfield et al., 2001). From an agronomic perspective, the WUE is a ratio between the crop yield (kg ha^{-1}) and evapotranspiration (ETc) (mm), while from a physiological perspective, the WUE is the ratio between the carbon dioxide assimilation and transpiration, also termed transpiration efficiency (TE, leaf level). The TE is negatively related to the carbon isotope discrimination ($\Delta^{13}C$) (Farquhar et al., 1982; Condon et al., 1993). Thus, the $\Delta^{13}C$, measured in the leaf or the grain, has been used as a method to estimate the seasonal TE, and low $\Delta^{13}C$ values are negatively correlated with high TE (Blum, 2011). The use of water by crops in rain-fed areas is determined by the rainfall and the water loss variables, i.e., root water uptake, surface runoff and deep drainage (Passioura, 2006). Water use is the main driver of crop yield under water-limiting conditions (Blum, 2011); therefore, to increase the biomass production under drought conditions, it is necessary to maximize the absorption of water from the soil, which is expressed as higher crop transpiration. It follows that crop management aimed at improving the availability of water in the soil is required to maximize the effective use of water, particularly in dry environments where important losses in the soil water balance and constraints to root growth occur (Turner, 2004).

The severe soil degradation in Chile's dryland Mediterranean

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region, where water erosion removes topsoil, resulting in highly densified soils with low infiltration, and the limited water retention of the soils in the area, increase the water loss in terms of the water balance, either by runoff or by evaporation from the soil surface (Uribe et al., 2003). Water runoff can occur at the surface or subsurface of the soil, depending on the texture of the soil profile and the topography of the area (Hardie et al., 2012). Water runoff may be an important factor in the loss of textural changes in the soil profile due to changes in the hydraulic conductivity of the soil horizons, impairing the vertical flux (Jury and Horton, 2004) and favouring water losses via subsurface runoff, which can also restrict rooting depths. A soil containing two distinct horizons of contrasting textures is known as a duplex soil and shows a considerable increase in clay content from the topsoil to the subsoil horizon (Soil Survey Staff, 2014, p. 17). Soil series with abrupt textural change occur in four orders: Alfisols > Mollisols, Utilsols > Aridisols (Bockheim, 2016). Duplex soils are associated with a range of management problems, including waterlogging, poor crop establishment, crusting, poor root penetration, water erosion and poor nutritional status (Hardie et al., 2012). In a duplex soil in Western Australia under a similar agro clime as central Chile, Eastham and Gregory (2000) found that water loss through subsurface drainage was related to the seasonal rainfall in each year, with percentages ranging between 8 and 18% of the total rainfall.

One way to improve the soil water balance is by the use of conservation tillage, which retains approximately 15% more water in the topsoil compared to conventional agricultural systems (Acevedo and Silva, 2003). This effect has been explained by the protective effect of the organic residue cover on the soil surface, which reduces direct water evaporation from soil and reduces surface runoff (Shaver et al., 2003; Pieri et al., 2009). The system also improves the physical soil conditions for the development of roots, mainly on the soil surface, by increasing the water absorption capacity and nutrient availability (Martínez et al., 2008).

In this study, we explore the hypothesis that in rain-fed areas of duplex soils of the coastal range, conservation tillage systems have a positive effect on the soil water balance when compared with conventional tillage by reducing water loss from runoff and deep percolation and increasing the water availability to oat and wheat crops. Additionally, we expect that conservation systems improve the effective use of water, resulting in an increased WUE and a higher yield compared to conventional tillage. The aim of this study was to determine the soil water balance and water use efficiency in an oat-wheat crop rotation that was cultivated in a Mediterranean rain-fed Alfisol of the interior dryland of central Chile under different tillage systems.

2. Materials and methods

2.1. Site description

The research was conducted during 2007–2009 at the Cauquenes Experimental Center of the National Institute for Agricultural Research (35° 97′S, 72° 24′W, 140 m.a.s.l.). The site is characterized by a semi-arid Mediterranean climate, with an average annual rainfall of 690 mm and an average annual temperature of 14.7 °C, ranging from an average high in January of 27 °C to an average low in July of 4 °C. The soil is an Alfisol and is classified as Ultic Palexeralf developed in situ from granitic rock, with a dominance of fine textural classes (CIREN, 1997). The duplex nature of the soil indicates an abrupt increase in clay content in the lower horizons. Table 1 gives the values of the soil physical properties at the beginning of the experiment. The dry bulk density and total porosity of each horizon layer were measured with soil cores (height: 5.0 cm; diameter 5.9 cm).

2.2. Description of the experiment

Three large experimental plots of 1000 m^2 (20 m x 50 m) were established on a hillside with a 12.5% slope. The treatments were located perpendicular to the slope, with an eastern exposition. Two conservation tillage systems were evaluated: no tillage (Nt) and no tillage with subsoiling (Nt + Sb). The planter (Vence Tudo, Chile) was drawn by oxes and had 7 rows 17 cm apart. In Nt + Sb, the subsoiling was carried out in the first year of study, before sowing (April 2007) at 40 cm depth, with a subsoil plough with three points spaced 40 cm apart and passing perpendicular to the dominant slope. In the conservation tillage systems (Nt and Nt + Sb), 2.5 Mg ha^{-1} of residue was left on top of the soil (oat or wheat straw, according to the crop rotation). The conservation tillage systems were compared to conventional tillage (CT) with animal traction, which corresponded to the tillage system practised by the small farmers in the area, with a mouldboard plough 20–25 cm deep. The soil was then harrowed with a nail harrow and the seed was distributed manually. The previous crop at the site was natural pasture with grazing sheep.

Planting took place around May 15th of each year. The crop was considered to be an oat (*Avena sativa* cv. Supernova-INIA)-wheat (*Triticum aestivum* cv. Pandora-INIA) crop rotation. The seed was disinfected with fungicide for rust control. The seeding rate was 140 kg ha^{-1} for oats (2007 and 2009) and 200 kg ha^{-1} for wheat (2008). The fertilization consisted of 110, 70 and 80 kg ha^{-1} for oats and 140, 90 and 80 kg ha^{-1} for wheat of N, P_2O_5 and K_2O, respectively. Fertilization was similar for each tillage system and was based on the yearly soil chemical analysis (0–20 cm depth). The fertilizer was applied with the seed at the time of planting for each tillage system. The harvest took place around December 15th of each year.

2.3. Water balance

The components of the water balance for each tillage system and year of study were determined to ascertain the various inputs and losses of the soil water balance. The following equation was used:

$$Pp + \theta_{initial} = Es + \theta_{final} + Dp + ETc \quad (1)$$

where Pp is precipitation (mm) (rainfall), $\theta_{initial}$ is the soil water content (SWC) of the soil at planting (mm), Es is surface runoff (mm), θ_{final} is the SWC at harvest (mm), Dp is the loss of water out of the root zone through drainage (deep percolation and/or subsurface runoff) (mm) and ETc is the crop evapotranspiration (mm).

2.3.1. Variables of the water balance

2.3.1.1. Precipitation (Pp). The rainfall records were supplied by the pluviograph (Model PV008, GIS Ibérica, Spain) in the field experiment in addition to the data provided by the meteorological station of the Cauquenes Experimental Station (35° 95′S, 72° 28′W, 140 m.a.s.l.), which was situated approximately 6 km away from the field experiment.

2.3.1.2. Surface runoff (Es). The surface runoff was determined by placing two 1-m^3 tanks at each treatment site. The first tank had 42 runoff orifices, one of which connected to the second tank. The surface runoff of each rainfall event was evaluated for each tillage system.

2.3.1.3. Soil water content (SWC) (θ). The SWC was measured to estimate crop evapotranspiration (ETc) between the first node and maturity; prior to that time the crop evapotranspiration was considered to correspond to the reference potential evapotranspiration (ETo). SWC was measured with a neutron probe (Troxler model 4300, USA) at depths of 10–30, 30–50, 50–70, 70–90 and 90–110 cm, every 7–15 days. The measurements began on October 11, September 04 and September 29 in the years 2007, 2008 and 2009, respectively. The neutron metre access tubes were made of aluminium tubes 5 cm in diameter, reaching a depth of 110 cm in the soil. Three tubes per experimental unit were installed at the conventional tillage and no tillage sites, while 9 tubes were used for the tillage with subsoiling