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Effect of tillage system on soil temperature in a rainfed Mediterranean Vertisol**

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A b s t r a c t. Soil temperature is a factor that influences the rates of physical, chemical, and biological reactions in soils and has a strong influence on plant growth. A field study was conducted during 2006-2007 and 2009-2010 on a typical rainfed Mediterranean Vertisol to determine the effects of the tillage system and the crop on soil temperature. The experimental treatments were the tillage system (no-tillage and conventional tillage) and the crop (wheat and faba bean). Soil temperature was measured at a 20 cm depth at 1 h intervals from December 1st to November 30th of 2006-2007 and 2009-2010. There was a highly significant relationship between air temperature (both maximum and minimum) and soil temperature for the two tillage systems. Soil temperature was similar in the growing season for both crops but was higher in the conventional tillage than in the no-tillage system, with differences between 0.7 and 2.6ºC depending on the month of the year. A higher soil temperature with conventional tillage can be beneficial in the cold sowing period (November-December), improving crop establishment. In contrast, in critical periods with water deficits (spring) during which grain formation occurs, the lower temperature corresponding to the no-tillage system would be more favourable.

K e y w o r d s: no-tillage, conventional tillage, Vertisol, soil temperature, crop

INTRODUCTION

Soil is a key natural resource, and soil temperature is one of the physical factors that determine crop productivity and sustainability (Adak *et al*., 2012). Soil temperature is also an important environmental factor that regulates the exchange of heat energy between the land surface and the atmosphere (Jackson *et al*., 2008). It determines the rates of physical, chemical, and biological reactions in soils and has strong influences on plant growth and, over the long term, on soil formation (Brooks *et al*., 2004; Qi and Song, 2003). Soil temperature controls biological and biochemical processes in the soil that, in turn, affect soil organic matter formation, fertilizer efficiency, seed germination, plant development, plant winter survival, nutrient uptake and decomposition, and disease and insect occurrence (Karhu *et al*., 2010; Verma *et al*., 2011). The functional activities of plant roots, such as absorption and translocation of water, are also related to soil temperature (Adjepong and Gupta-Afriyi, 1977; Monteith, 1977). Soil respiration, which has a substantial effect on atmospheric carbon cycling, is sensitive to changes in soil temperature (Bond-Lamberty and Thomson, 2010). Soil temperature records are useful for understanding regional eco-environmental conditions and climate change.

Crop species differ in their response to soil temperature, and each species has its optimum range of temperature for maximum growth (Van Wambeke, 1992). Soil temperatures are normally impacted by surface characteristics and turbulent and radiative energy balance in which incoming solar radiation, temperature, and other variables are relevant. Seed germination, seedling emergence, and plant growth are more rapid as the soil temperature increases up to the optimum level. However, extremely high soil temperatures, as those observed in tropical climates (Ghuman an Lal, 1982), may result in seedling mortality, low plant stand, greater water demands, and high incidence and severity of plant diseases (Harrison-Murray and Lal, 1979). In contrast, low soil temperature reduces root growth and nutrient and water uptake and ultimately restricts the rates of transpiration and photosynthesis (Ambebe *et al*., 2009; Repo *et al*., 2005).

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Considering the above context, it is important to quantify the soil temperature regime and to identify management practices that can bring the temperature closer to the optimal range. Some of these practices are the tillage system and the choice to leave stubble on the surface. Those practices usually alter soil temperature and affect crop development, especially winter crops (Wang *et al*., 2009). Surface mulch application stimulates favourable soil water and soil temperature, earlier seedling emergence, more flowers, and fewer weeds (Sarkar *et al*., 2007). Tillage can be used to change pore characteristics (Kay and Vanden Bygaart, 2002) and to influence the soil water content and other soil physical characteristics (Hussein *et al*., 1998) to reduce thermal conductivity.

In soil, daily temperature fluctuations can penetrate up to 20 to 30 cm of depth, monthly fluctuations penetrate up to 2 m, and annual fluctuations penetrate up to 10 m of depth (Allen *et al*., 2000). Clay soil does not have many pores, and therefore, penetration of air through clay is impeded. As a result, there would be more heat loss near the soil surface than in the deeper subsoil (Nwankwo and Ogagarue, 2012).

The aim of the present study was to determine the influence of the tillage system and the crop on soil temperature within the framework of a long-term field experiment in a Mediterranean rainfed Vertisol.

MATERIALS AND METHODS

Field experiments were conducted in Cordoba, southern Spain (37º 46' N and 4º 31' W, 280 m a.s.l.), on a Vertisol (Typic Haploxererts) typical of the Mediterranean region, where rainfed cropping is the standard practice (Table 1). The study took place during 2006-2007 and 2009-2010 within the framework of a long-term experiment called 'Malagon', which began in 1986 and was designed as a randomised complete block with a split-split plot arrangement and three replications. The main plots tested the effects of the tillage system: no-tillage (NT) and conventional tillage (CT), the subplots were crops (wheat in rotation with faba bean and faba bean in rotation with wheat), and the sub-subplots were the day of the year. Each rotation was duplicated in a reverse crop sequence to obtain data for all the crops on a yearly basis. The area of each sub-subplot was 50 m^2 (10 by 5 m).

The no-tillage plots were seeded with a no-till seed drill. Weeds were controlled with glyphosate [N-(phosphonomethyl) glycine] + MCPA [(4-chloro-2-methylphenoxy) acetic acid] at a rate of 0.5 + 0.5 l a. i. ha^{-1} prior to sowing. The conventional tillage treatment included mouldboard ploughing and disc harrowing and/or vibrating tine cultivation to prepare a proper seedbed. During the faba bean growing season, weeds were controlled using cyanazine [2-(4-chloro-6-ethylamino-1,3,5-triazin-2-yl-amino)-2-methyl propionitrile] at 2 l a. i. ha^{-1}. Glyphosate was applied on faba bean plots at a rate of 0.065 l a. i. ha^{-1} as a post-emergence spray when broomrape (*Orobanche crenata* Forsk) was approximately 0.5–1 cm high (García-Torres *et al*., 1987).

Faba bean (*cv*. Alameda) was planted in 50-cm-wide rows at 170 kg ha^{-1}, and hard red spring wheat (*cv*. Gazul) was planted in 18-cm-wide rows at 150 kg ha^{-1}. Both these crops were planted in late November to early December. Each year, the wheat plots were supplied with an N fertilizer at a rate of 100 kg N ha^{-1} and with a P fertilizer at a rate of 65 kg P ha^{-1}; the fertilizer was incorporated following the standard practice in the conventional tillage soil and banded with drilling in the no-tillage plots.

Soil temperatures were measured with pencil probe thermistors located at a 20 cm soil depth. The soil temperatures were recorded at 1 h intervals from December 1st to November 30th of 2006-2007 and 2009-2010 using calibrated Tinytag temperature loggers.

T a b l e 1. The properties of the Vertisol used in the field experiments Córdoba, Spain

Parameter	Soil depth (cm)		
	0-30	30-60	60-90
Fine sand [< 250-50 μm] (g kg^{-1})	127	143	187
Silt [< 50-2μm] (g kg^{-1})	179	152	26
Clay [< 2μm] (g kg^{-1})	694	705	787
pH_{H_2O}	7.7	7.6	7.6
Organic matter (g kg^{-1})	10.2	7.4	5.3
Calcium carbonate equivalent (g kg^{-1})	75	93	71
CEC (cmol kg^{-1})	46.5	36.6	30

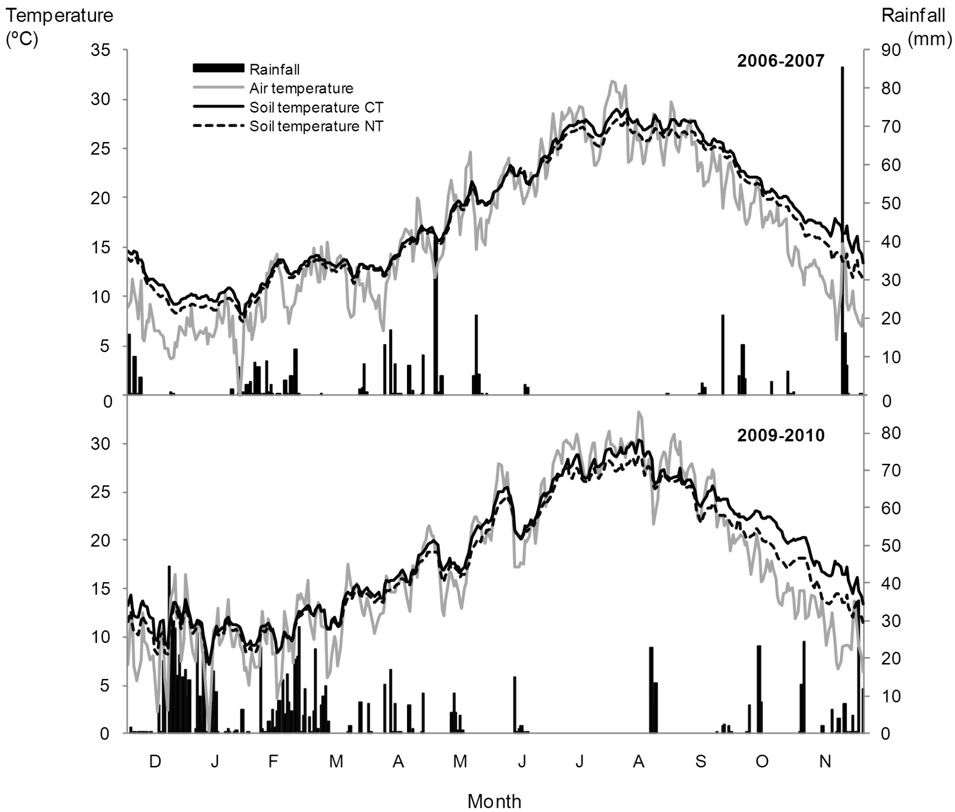

Fig. 1. Daily soil temperature according to the tillage system: conventional tillage (CT), no-tillage (NT), daily air temperature and precipitation.

The data for each variable were subjected to analysis of variance (ANOVA), using a randomised block design combined over years and an error term according to McIntosh (1983). Year was considered a random effect, while crop, tillage system, and day were considered fixed effects. Means were compared using Fishers protected least significant difference (LSD) test at $p<0.05$. The LSDs for comparisons of the different main effects and interaction terms were calculated using appropriate standard error terms. The Statistics v. 8.1 (Analytical Software, 2005) package was used for this purpose.

RESULTS

The average monthly air temperature varied between 6.5 and 27.7°C in 2006-2007 and between 8.8 and 29°C in 2009-2010 (Fig. 1). The lowest average monthly air temperature was observed in January (7.5 and 8.9ºC in 2006-2007 and 2009-2010, respectively) and the highest in July in 2006-2007 (26.9°C) and August in 2009-2010 (28.5°C). The total rainfall for the year 2009-2010 was more than double (959 mm) that for the year 2006-2007 (435 mm) (Fig. 1). Differences in the average annual precipitation occurred among the experimental years compared to the 30-year historical value (584 mm). The year 2006-2007 was a dry year, and 2009-2010 was a wet year. There were also differences in the seasonal rainfall distribution: the greatest rainfall occurred in winter (58% of the annual rainfall) in 2009-2010, while in 2006-2007, the greatest rainfall was in autumn (39% of the annual rainfall).

There was a highly significant relationship between the air temperature (both maximum and minimum) and soil temperature for the two tillage systems (Fig. 2). For both systems, the relationship between soil and minimum air temperature showed a steeper slope than that of the soil and maximum air temperature (Fig. 2). Each degree of the increase in the minimum ambient temperature led to an increase of 0.86°C in the soil temperature, and each degree of the increase in the maximum ambient temperature led to an increase of 0.66ºC in the average soil temperature for both tillage systems (Fig. 2).

The soil temperature was not significantly related to the year and crop. However, there was a significant relationship between soil temperature and the tillage system and day of the year. The average monthly soil temperature ranged from 9.4 to 27.1ºC for 2006-2007 and from 10.3 and 27.6ºC for 2009-2010. In the CT system, the soil temperature was never lower than in the NT system in either year (Fig. 1). The evolution of soil temperature over the years in NT and CT was very similar. The soil temperature was higher in CT than in NT from July to January in the year 2006-2007 and from April to December in 2009-2010 (Fig. 1, Table 2). The differences between the tillage systems were greater

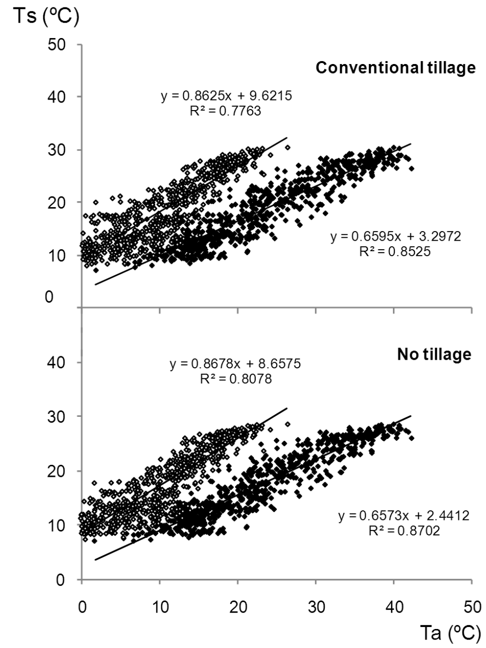

Fig. 2. Relationship between air temperature (Ta) (T_{max} – closed symbols, T_{min} – open symbols) and soil temperature (Ts) according to the tillage system.

T a b l e 2. Soil temperature (ºC) as affected by year and tillage system: no tillage (NT), conventional tillage (CT)

Month	2006-2007		2009-2010	
	CT	NT	CT	NT
December	11.5a*	10.7b	12.2a	11.0b
January	9.9a	9.0b	10.5a	10.1a
February	12.3a	11.9a	10.7a	10.4a
March	13.3a	12.9a	13.3a	12.9a
April	14.8a	14.5a	16.5a	15.8b
May	18.9a	18.5a	19.4a	18.5b
June	22.7a	22.6a	23.4a	22.7b
July	27.2a	26.4b	27.9a	27.0b
August	27.7a	26.6b	28.1a	27.0b
September	25.9a	25.1b	24.5a	23.2b
October	20.7a	19.9b	21.5a	19.2b
November	16.6a	14.5b	16.8a	14.2b

*Within year and month, means followed by the same letter are not significantly different at $p<0.05$ according to LSD.

in November (2.1ºC) in 2006-2007 and in October (2.3ºC) and November (2.6ºC) for 2009-2010 (Table 2). The soil temperature variability was lower in spring and autumn than in summer and winter.

The evolution of soil temperature during the day differed depending on the month of the year (Fig. 3). The soil temperature was higher for NT in October of 2009-2010 and in November of the two studied years, at all hours of the day.

The evolution of the maximum and minimum temperatures during the day was very similar in both studied years. Maximum temperatures were seen at 23:00-00:00 h in almost every month except for summer (July, August, and September) when the maxima occurred between 8:00 and 9:00 h. The minimum soil temperatures occurred between 12:00 and 13:00 h in almost all the months, except the summer, when the minima occurred between 21:00 and 22:00 h.

The greatest differences in soil temperature within the same day occurred in June and under NT (4.3°C versus 2.5ºC in CT in 2006-2007 and 2.2°C versus 1.3°C in CT in 2009-2010).

DISCUSSION

Trends in soil temperature are considered to be correlated with changes in solar radiation (Jacobs *et al*., 2011). The daily variations in solar radiation can affect the ground temperature to a depth of approximately 1 m. In our case, as in other studies (Chen *et al*., 2011; Liu *et al*., 2013), soil temperature was strongly related to air temperature and was also slightly lower under NT due to crop residues that accumulated on the surface of the NT treatment.

Similar to the results reported by Wang *et al*. (2009), in general, for every day of the year, the soil temperature was higher in the CT treatment than in the NT treatment. Some studies (Tenge *et al*., 1998) show this trend during the day but an opposite trend overnight. Moroizumi and Horino (2002) found higher values of soil temperature under a CT treatment. The tillage depth under CT makes the soil more porous, and as a result, the soil likely has lower thermal conductivity (Sarkar and Singh, 2007). This change leads to greater heat retention under CT. In addition, the higher soil temperature under CT may be due to a surface difference: under NT, the soil surface is partially covered by remnants of straw from the previous crop, causing the soil to absorb less solar radiation during the day (Wang *et al*., 2009). Overnight, the cause of the lower temperature in the NT treatment may be that the soil (especially in the upper profile) is loose and easily loses the energy stored during the day (Wang *et al*., 2009).

The autumn months presented the largest differences in soil temperature in relation to the tillage system. The factor driving this pattern might be the state of the crop in autumn: at that time, there was still no crop on the surface or the crop was in a state of early growth. According to Wang *et al*.

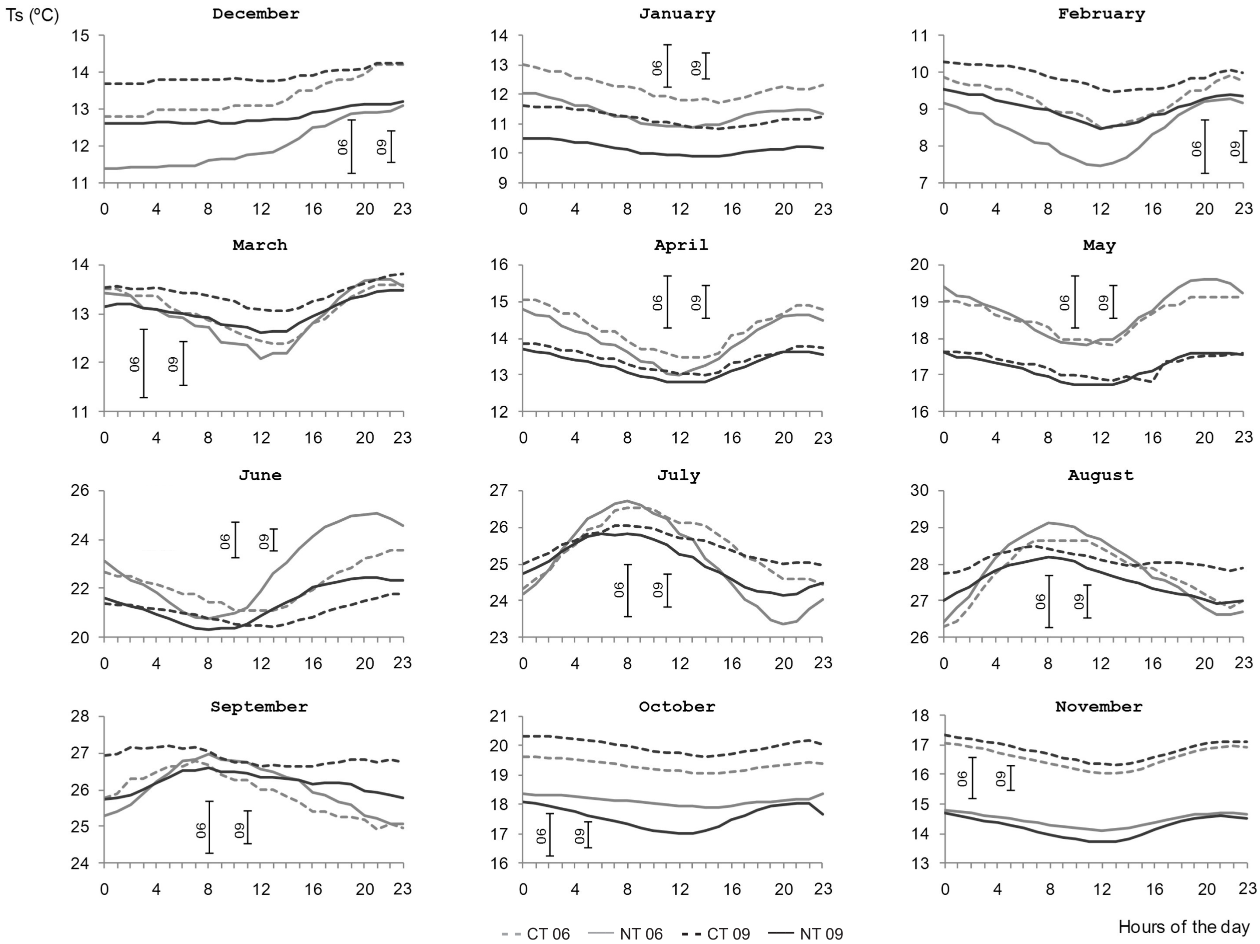

Fig. 3. Hourly soil temperature according to the tillage system: conventional tillage (CT), no-tillage (NT) and month and year of study. Vertical bars represent LSD to compare tillage system within year: 2006-2007 (06), 2009-2010 (09).

(2009), as the crop grows, the canopy covers the ground and prevents it from absorbing solar radiation directly, reducing the differences between the tillage systems.

The amplitude of the soil diurnal temperature wave decreases with increasing distance from the exchange surface because heat is stored in each succeeding layer, so less heat is passed on to the next layer (Campbell and Norman, 1998). In addition, clay soil does not have many pores, and thereby, penetration of air through clay is impeded. As a result, there would be more heat loss near the soil surface than in the deeper subsoil. Except for the summer months, the soil temperature reached its maximum at 23:00-00:00 h of the day and its minimum at 12:00-13:00 h. These results are similar to those obtained by Campbell and Norman (1998) and McIntosh and Sharratt (2001), whereas in our experiment, there was a lag of maximum and minimum temperatures between the air and the ground of approximately 6 h at a soil depth similar to the depth studied here. However, in the summer months, this gap increased to 15 h. A different trend of daily soil temperature in the summer months was also shown by Licht and Al-Kaisi (2005), who ascribed the trend to the dry and clear sky conditions that occur in this season.

In our experiment, higher grain yields were obtained with the NT system (López-Bellido *et al*., 2012). The high clay content of the soil under study leads to high moisture retention; therefore, there were no differences in the content or availability of water at sowing between the tillage systems, but differences did exist at harvest (López-Bellido *et al*., 2007). However, the root systems (density and biomass at depth) of both wheat and faba bean are favoured in the NT system (Muñoz-Romero *et al*., 2010, 2011). This pattern together with other factors, such as increased organic matter that exists in the NT system (López-Bellido *et al*., 2010), will improve crop establishment and grain yield.

The influence of soil temperature on crop growth may vary according to the stage of growth, and even high temperatures can become negative if such temperatures interact with other factors such as the water content of the soil, which is critical under rainfed Mediterranean conditions.

CONCLUSIONS

1. Over the entire experiment in the Mediterranean rainfed Vertisol, the soil temperature during the growing season of wheat and faba bean was not significantly different between the crops. The soil temperature was higher in the system with conventional tillage than with no tillage. The differences ranged between 0.7 and 2.6ºC for different periods of the year.

2. There was a clear significant trend to higher yields of wheat and faba bean under no-tillage compared to conventional tillage.

3. In the cold season (November-December) when the sowing is conducted, the higher soil temperature of conventional tillage could contribute to better crop establishment. However, at the critical stage of flowering and grain formation in spring, the drought stress that is so prevalent in the Mediterranean climate can be buffered by the lower soil temperature of the no-tillage system.

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