Effects of soil tillage and mulching on thermal performance of a Luvisol topsoil layer

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Abstract

Andrade, J.A., Alexandre, C.A., Basch, G. 2010. Effects of soil tillage and mulching on thermal performance of a Luvisol topsoil layer. *Folia oecol.*, 37: 1–7.

Important heat transfer processes occurring on soil surface control the thermal environment within the topsoil layer and the boundary layer above. Soil management practices such as the application of mulches or the formation of a soil micro relief through tillage modify the thermal regime of soils. The aim of this study was to compare the effects of soil tillage and the application of stubble mulch and different amounts of straw mulch on the thermal behaviour of a Luvisol. The experiments were performed from January to May 2007, in a field sown with winter wheat. Temperature was measured with copper-constantan thermocouples placed over straw and over stubble, at soil surface and at 2, 4 and 8 cm depths. Compared with tilled bare soil, the application of straw mulch seems to affect the soil thermal regime more significantly than that of stubble mulch. The topsoil under straw mulch showed the lowest thermal amplitudes and the highest minimum temperatures. From March to May, the mean temperatures in the profiles covered by straw were significantly lower than those recorded on the remaining plots. Implications of these techniques for soil temperature control in crop growing are discussed too.

Key words

crop establishment, soil temperature, soil tillage, straw mulch, stubble mulch

Introduction

Crop establishment is a major factor determining crop productivity in the field and is strongly controlled by soil temperature and soil moisture (Abreu, 1987; Andrade, 2001). Important heat energy transfers on soil surface control the thermal environment within the topsoil layer and the boundary layer above it (Arya, 1988). In practice, the soil thermal regime is usually modified by application of mulches and the creation of a soil micro-relief by tillage. Both methods affect net radiation and heat transfer on soil surface by means of affecting soil water evaporation (De Vries, 1975). Thus, investigation of the influence of surface treatments on soil thermal regime is useful for the evaluation of differences in the performance of crop growth and development.

Porous mulches such as straw or stubble mulches, affect soil moisture and soil temperature by influencing soil thermal parameters such as heat capacity, heat conductivity and vapour transport resistance (Sui et al., 1992; Bussière and Cellier, 1994). Although they may depress crop growth (Schaller and Evans, 1954; Van Wijk et al., 1959) by decreasing mean soil temperature, these mulches can help in the conservation of soil moisture, making it a very important practise in areas of low rainfall (Awan, 1964; Chakraborty et al., 2008). In addition, these mulches can be applied either to protect soil surface from excessive cooling or to avoid its excessive warming (Rosemberg et al., 1983; Nath and Sarma, 1992), having this latter feature special relevance in the context of the global warming (IPCC, 2007).

Extreme variations in soil temperature near the surface of bare soils and quick changes in soil water content due to irregular rainfall and high evaporative demands lead generally to poor crop establishment in Mediterranean areas (Abreu, 1987). Moreover, risks of frost are common either during the intermediate vegetative stages in winter crops or during the early stages in summer crops.

The aim of this study was to compare the effects of different types of soil surface treatments – soil tillage, stubble mulch and straw mulch applied in two different amounts, on the thermal performance of a Haplic Luvisol sown with a wheat crop. The results expected should enable us to discuss not only some possible consequences of soil and residue management for crop growth rates and the development of plants but also the risk of frost damage.

Material and methods

Field experiments were performed from January to May 2007 at Herdade da Revilheira, Reguengos de Monsaraz (lat.: 38º28' N; long.: 7º28' W), in a field sown with winter wheat (*Triticum aestivum* L.) in early December. The local climate is Csa, according to Köppen climate classification (Ahrens, 2003). At Reguengos de Monsaraz, about 5 km away from the experimental site, the mean annual temperature averages 16.1 ºC, ranging from a monthly mean of 8.7 ºC in January to 24.3 ºC in August, while the mean annual rainfall is 572 mm, 77.4% of which falls between October and March. According to the climate data supplied by a weather station located at the experimental site (CGE, 2009), mean monthly temperatures in March and April as well as the rainfall values in January and March were visibly lower than those correspondent Normal values but close to them in all the other cases (Table 1).

The soil was classified as Haplic Luvisol (WRBS, 2006) and its profile was Ah-AB-Bt-C. The clay-loamy Ah (0–8 cm) and AB (8–24 cm) horizons had a bulk density of 1.51±0.12 Mg m^{-3} and 1.58±0.07 Mg m^{-3}, respectively, while the clayey Bt (24–53 cm) horizon had a bulk density of 1.63±0.04 Mg m^{-3}. In the Ah horizon, soil water content was 0.21±0.07 cm^3 cm^{-3} at 1500 kPa and 0.43±0.13 cm^3 cm^{-3} at 30 kPa.

Soil temperatures were measured in four profiles with copper-constantan thermocouples connected to a data-logger (*data Taker* 600). One profile was subject to a surface soil tillage only (modality A), another was covered by stubble mulch (mod B) and the remainder were covered by two different amounts of straws mulch (mod C – 2,500 kg ha^{-1} and mod D – 5,000 kg ha^{-1}). Thermocouples were placed at the middle of each profile, at its surface, at 2, 4 and 8 cm depth and over straw and stubble mulches. Hourly averaged temperatures were recorded for all thermocouples locations. Effects on soil thermal regime were evaluated by daily mean temperatures and daily minimum temperatures at 2 cm depth as well as by thermal amplitudes at 2 cm, at 4 cm depth and at the surface of the mulch.

Soil water contents were measured four times (1st March, 15th March, 28th March and 13th April) by the gravimetric method down to 20 cm depth, in each of the four plots. Crop height was also measured four times (1st March, 15th March, 13th April and 5th May) on five plants randomly chosen in each plot/modality.

Statistical differences between means were tested at 5% significance level (*P < 0.05) with paired Student's t-tests using least significant differences (LSD) procedures (Walpole and Myers, 2006).

Results

Soil moisture

Table 2 shows soil water contents measured on four dates in each of the four plots. Soil water content was about 50% of the available capacity (AC) either on the first date or on the last date, about 20–30% of the AC on the second and close to the wilting point on the third. At all dates, plots corresponding to the modalities C and D presented generally the highest contents of soil water while those referred to the others (A and B) presented the smallest values. Differences observed between the values found under straw mulch and those found under stubble mulch or tilled soil were about 0.02–0.03 cm^3 cm^{-3} at all dates and were statistically significant (*P < 0.05). On the other hand, neither the amount of

Table 1. Mean monthly air temperature [ºC] and monthly rainfall [mm] data recorded at Herdade da Revilheira, from January to May 2007 (in brackets, the corresponding Normal values referred to the period 1961–1990)

	Jan	Feb	Mar	Apr	May
Air temperature [ºC]	7.7 (8.7)	10.8 (10.0)	11.4 (12.6)	12.5 (14.2)	17.0 (17.3)
Rainfall [mm]	36.8 (77.6)	95.6 (76.7)	11.6 (83.3)	49.7 (44.9)	38.9 (33.5)

Table 2. Soil water contents ($cm^3\ cm^{-3}$) measured four times (1st March, 15th March, 28th March and 13th April) on four plots (modalities A, B, C and D)*

	Modality A	Modality B	Modality C	Modality D
1st March	0.33±0.012	0.32±0.035	0.37±0.051	0.34±0.053
15th March	0.27±0.025	0.25±0.025	0.28±0.031	0.29±0.004
28th March	0.20±0.045	0.21±0.053	0.24±0.049	0.22±0.039
13th April	0.30±0.012	0.27±0.012	0.32±0.012	0.30±0.018

*modality A: tilled soil; modality B: stubble mulch; modality C: straw mulch (2,500 kg ha^{-1}); modality D: straw mulch (5,000 kg ha^{-1})

straw mulch seems to affect significantly the soil water content nor stubble mulch seems to have any effect on it when compared with tilled soil. These results also show the usefulness of straw mulch in conservation of soil water pointed out by several authors, as Nath and Sarma (1992) and Ramakrishna et al. (2006).

Crop height

Table 3 shows measurements of crop heights (in cm) at four different dates, corresponding to the four modalities in study. The highest mean crop height was always found in the plot where the biggest amount of straw mulch was applied (mod D). On the contrary, the smallest crop height was found in mod A, at the first date (1 Mar), in mod B, at the last one (4 May) and in the others (mod A and mod C) on 15th March and 13th April. Differences between the highest and the smallest mean values ranged from 14 cm on 1st March to 9–10 cm in the remaining dates.

Mean soil temperatures

Daily mean temperatures ($\overline{T}_{day}$) at the 2 cm depth ranged from about 3–4 ºC (end of January) to 23–28 ºC (middle of May), following closely the annual course of net radiation at the soil surface in areas of Mediterranean climates (Fig. 1). In January and February, differences between daily mean temperatures recorded in the four plots either at 2 cm or at 4 cm depth (not shown) were not generally greater than 1 ºC, while from March to May the plots covered by straw presented mean temperatures significantly lower than those covered by stubble mulch or subject to surface tillage, often reaching about 3–4 ºC or even more in some days. On a decennial basis (periods of ten days) these differences were statistically significant (*$P < 0.05$) during this period. In addition, the differences recorded during these last two months are more pronounced during warming periods than when mean daily temperatures decreased.

On the other hand, the increase of mean temperatures in soil profiles covered by straw (mod C and mod D), follows with some delay, mainly in April and May, the increase verified in the other profiles (mod A and mod B). This is probably due to the higher water holding capacity presented by straw mulch when compared with those presented by the other profiles. Furthermore, neither the amount of straw mulch seems to affect at topsoil layer, nor the maintenance of stubble mulch over soil surface seems to change significantly when compared with tilled soil only.

Daily minimum temperatures recorded at 2 cm depth were lower in profiles covered by stubble or subject to a surface tillage than in profiles covered by straw mulches, irrespective of their densities (Fig. 2). Differences between minimum temperatures recorded in modalities B (stubble mulch) and D (straw mulch – 5,000 kg ha^{-1}) were about 2 ºC (= 2.20 ± 1.05 ºC) on average, reaching up to 4–5 ºC at maximum. In a decennial basis (periods of ten days) these differences were statistically significant (*$P < 0.05$) during this period, except in the middle of January and April. Differences between minimum temperatures recorded in modalities C and D were generally lower than 1 ºC (= 0.63 ± 0.43 ºC), meaning that prevention of frost deposition on soil surface doesn't seem to depend significantly on the amount of straw

Table 3. Mean crop (winter wheat) heights [cm], measured on each of the four plots (modalities A, B, C and D) on four different dates (1st March, 15th March, 13th April and 4th May)*

	Modality A	Modality B	Modality C	Modality D
1st March	36±2.0	45±2.5	41±0.7	50±1.6
15th March	51±2.5	55±3.2	50±1.6	59±2.2
13th April	68±3.7	73±2.7	68±3.2	78±2.9
4th May	80±3.8	75±2.5	80±3.5	85±3.2

*modality A: tilled soil; modality B: stubble mulch; modality C: straw mulch (2,500 kg ha^{-1}); modality D: straw mulch (5,000 kg ha^{-1})

mulch; in the same way, differences found between modalities A and B (= 0.54 ± 0.47 ºC) means that stubble mulch doesn't increase protection against frost deposition when compared with tilled soil only.

Damping of thermal wave

Damping of thermal wave down to 4 cm depth was significantly higher in modality D (densest straw mulch) than in the remaining plots, while the lowest damping was found in the plots where stubble was applied (Fig. 3). In addition, damping of thermal wave was higher in mod C than in mod A. Mean differences between soil thermal amplitudes found in modalities C and D and those found in modalities A and B, either at 2 cm or at 4 cm depth, ranged from about 7 ºC to about 10 ºC, meaning that straw mulch is much more effective in damping the thermal wave into depth than the stubble mulch or the tilled soil only.

Amplitudes at 4 cm depth of soil profile covered by straw mulch (mod D) were about half ($\Delta T_{modD}/\Delta T_{modB}$ = 0.48 ± 0.09) of those verified in the soil profile covered by stubble mulch (mod B). The ratio between thermal amplitudes verified at 4 cm depth in tilled soil and those verified in the profile covered by stubble mulch ($\Delta T_{modA}/\Delta T_{modB}$) varied from 0.90 to 0.71 (0.86 ± 0.11), while that verified in covered profiles by straw ($\Delta T_{modD}/\Delta T_{modC}$) ranged from 1.05 to 0.72 (0.77 ± 0.13).

Thermal amplitudes at 2 cm depth were 44 ± 7% and 23 ± 4% of those observed at the top of the straw mulch layer, respectively in modalities C and D. On the contrary, stubble mulch damped the thermal wave in about 21 per cent only, i.e., the amplitudes at 2 cm depth are 79 ± 10% of those observed at the surface (Fig. 4). Since no trend was visible on the time course of the relationships plotted in Fig. 4, the damping of heat wave into the soil did not seem to be significantly affected neither by crop growth nor by the annual course of net radiation.

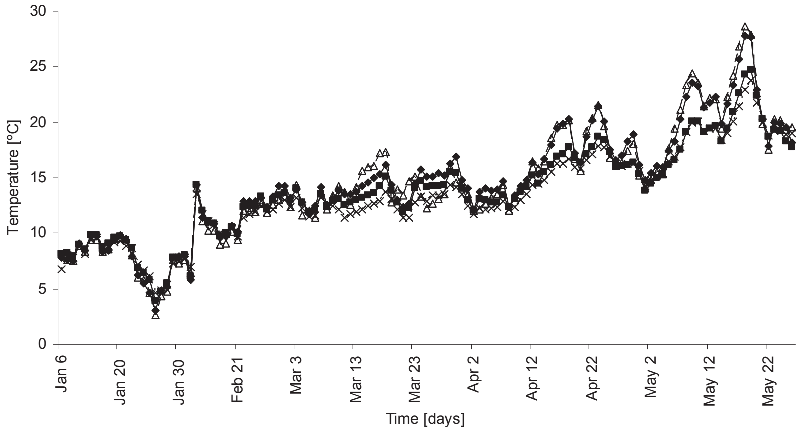

Fig. 1. Daily mean temperatures recorded at a 2 cm depth, from January to May 2007: modality A: tilled soil (—•—); modality B: stubble mulch (---Δ---); modality C: straw mulch – 2,500 kg ha–1 (—■—); modality D: straw mulch – 5,000 kg ha–1 (---x---)

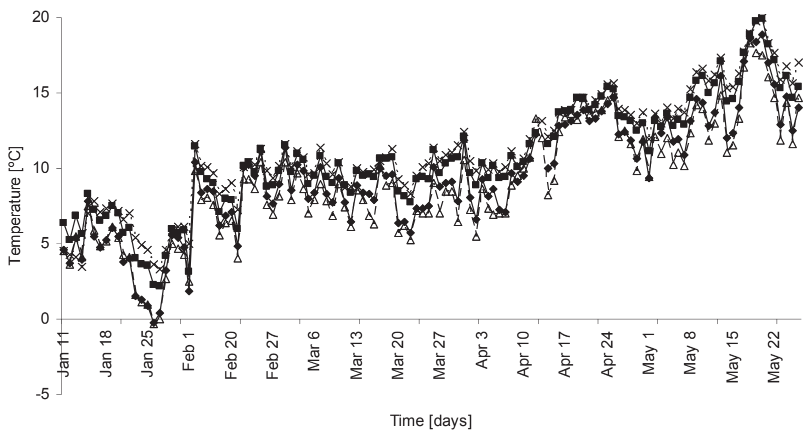

Fig. 2. Daily minimum temperatures recorded at a 2 cm depth, from January to May 2007: modality A: tilled soil (—•—); modality B: stubble mulch (---Δ---); modality C: straw mulch – 2,500 kg ha–1 (—■—); modality D: straw mulch – 5,000 kg ha–1 (---x---)

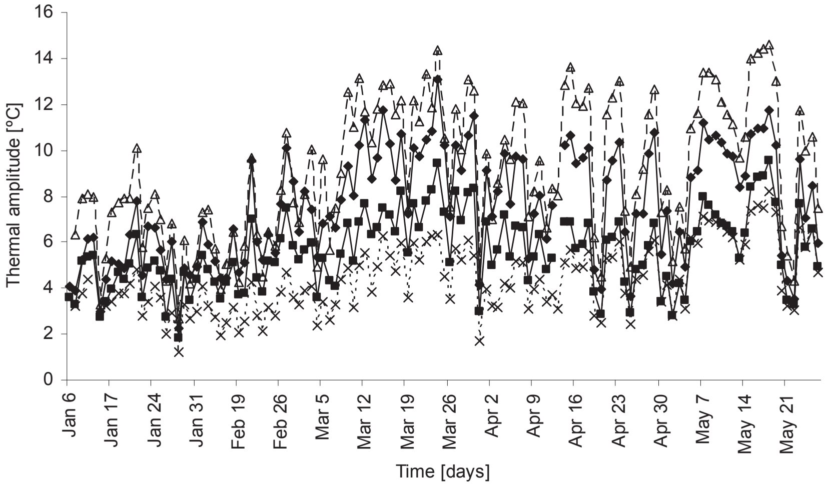

Fig. 3. Temperature amplitudes at a 4 cm depth, from January to May 2007: modality A: tilled soil (—•—); modality B: stubble mulch (---Δ---); modality C: straw mulch – 2,500 kg ha^{-1} (—■—); modality D: straw mulch – 5,000 kg ha^{-1} (---x---)

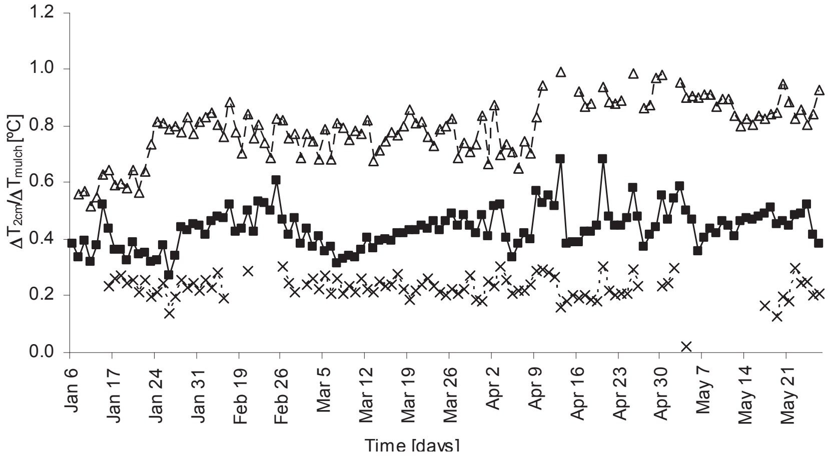

Fig. 4. Ratio thermal amplitudes at a 2 cm depth/thermal amplitudes over mulch, from January to May 2007: modality B: stubble mulch (---Δ---); modality C: straw mulch – 2,500 kg ha^{-1} (—■—); modality D: straw mulch – 5,000 kg ha^{-1} (---x---)

Discussion

Soil temperature is of utmost importance in the early development of grass crops because their apical meristem is below the soil surface till the 5–6 first unfolded leaves (Andrade, 2001; Chen, 2007). Comparing with tilled bare soil, the application of straw mulch seems to affect more significantly the soil thermal regime than that of stubble mulch. This fact was evident both with regard to mean and minimum daily temperatures and the damping of the thermal wave into the soil profile. On the contrary, no significant differences were found between the parameters measured in the plot covered by stubble mulch and those measured in tilled soil only. The effect of straw mulch is similar to that of a litter layer in pine stands (Andrade et al., 1993), both favouring the soil water retention and decreasing of thermal amplitudes in the topsoil.

Since the decreasing of mean temperatures was more visible in soil profiles covered by straw mulch than in soil profiles covered by stubble mulch or tilled only, mainly when temperatures are higher (after March–April in Mediterranean climates in Northern hemisphere), the rhythm of the latest development stages of winter crops (booting, heading, flowering, grain filling and stage, maturity stages) should be more affected than their early development under these conditions. On the contrary, all the development stages of summer crops should be affected by the incorporation in soil profile of this type of mulch.

On the other hand, the decreasing in soil temperature due to the application of straw mulch did not seem to affect crop growth. In fact, the highest values for crop height were even found in the plots of modality D (Table 3), probably due to the higher soil water contents retained under straw mulch (especially that of highest density) (Table 2). Thus, any delay in crop development seems to be compensated by a stronger growth.

Straw mulch seems to be more efficient to avoid damage due to frost deposition on soil surface than the other modalities (A and B) while the maintenance of stubble on soil surface does not seem to provide the thermal moderating effect of the straw mulch layer.

In spite of its influence on damping of thermal wave into soil surface, the amount of straw do not affect significantly the accumulation of temperature (degrees-day) by crops and hence the rhythm of their development. However, the amount of straw mulch seems to affect crop height which might be related to the higher capacity to hold water in profiles covered with high densities of straw mulches (in the case, 5,000 kg ha^{-1}).

Conclusions

The more evident is the soil warming that reflects the annual course of net radiation, the more evident is the cooling as a result of the application of straw. The application of straw mulch at the soil surface increases daily minimum temperatures in the topsoil layer by about 2º C, avoiding often the occurrence of frost in the very topsoil layer. Despite the lack of significance of the influence of the amount of straw mulch on daily mean and minimum temperatures, it affects significantly the damping of thermal wave into topsoil layer. The maintenance of stubble mulch at the soil surface is not an efficient practice to decrease thermal variations in the topsoil layer.

Acknowledgement

The authors acknowledge the support by the European Union (FEDER) through the Foundation for Science and Technology (FCT): project POCTI/AGG/46545/2002.

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Vplyv orby a mulčovania na teplotný režim vo vrchných vrstvách pôdy

Súhrn

Významné procesy toku tepla na povrchu pôdy určujú tepelné pomery v povrchovej vrstve pôdy ako aj v hraničnej vrstve nad pôdnym povrchom. Postupy používané v pôdohospodárstve – ako je mulčovanie a modelovanie mikroreliéfu pomocou orby modifikujú teplotný režim pôd. Cieľom tejto práce je porovnať účinky orby a strniska ako aj rozličných množstiev slameného mulču aplikovaného na pôdu na tepelný režim luvisolov. Experimenty prebiehali na poli osiatom ozimnou pšenicou, od januára do mája 2007. Teplota bola meraná pomocou medeno-konštantánových článkov, umiestnených vždy v súboroch – nad slamou a nad strniskom, na povrchu pôdy a v pôde v 2, 4 a 8 cm. Ukázalo sa, že slamený mulč aplikovaný na holú oráčinu ovplyvňoval teplotný režim pôdy významnejšie ako ponechané strnisko. V povrchovej vrstve pôdy boli zistené najmenej výrazné teplotné amplitúdy a najvyššie minimálne teploty. Od marca do mája boli priemerné teploty zaznamenané v pôdnych profiloch pokrytých slamou významne nižšie ako na plochách ošetrených iným spôsobom. V práci sa uvádza aj možné využitie týchto prístupov za účelom kontroly pôdnej teploty pri pestovaní plodín.

Received March 3, 2010
Accepted March 24, 2010