How plastic mulches affect the thermal and radiative microclimate in an unheated low-cost greenhouse

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Abstract

Suboptimal regimes of air and soil temperature usually occur under unheated greenhouses during winter crop cycles. This work analyses the effects of three soil surface treatments (no plastic mulch, NM; transparent mulch, TM, and black mulch, BM) on the air-soil heat exchanges and the resulting soil and aerial microclimate. Experiments were conducted in unheated greenhouse compartments located in an area of mild winter climate (South-East Spain) during autumn and winter periods. In all treatments, the soil consisted of an artificial layer of 0.10 m gravel-sand material placed above a 0.3 m layer of imported loamy soil. When vents were closed, soil heat flux, ground net radiation and both air and root-zone temperature were higher in BM than in TM, while NM presented intermediate performances between BM and TM. When vents were open, heat storage and soil warming were substantially reduced with respect to unventilated conditions. This reduction was greater in BM, and so the advantages of BM with respect to the other treatments were only marginal under ventilated conditions. The main conclusions were: (i) The combination of black mulch + greenhouse appears to be a simple and low-cost passive heating system that can be recommended for the early stages of crop cycles starting at the end of autumn or in winter, when canopy leaf area index is small and most of the soil surface is free of vegetation; and (ii) ventilation had a negative effect on the benefits of mulching, implying that greenhouse ventilation management should reflect a compromise between maximizing greenhouse heat storage and fulfilling ventilation requirements for suitable crop growth.

Abbreviations

BM: black mulch
NM: without plastic mulch
G: conduction heat flux rate in the soil (W m^{-2})
G_d: daily integral of conduction heat flux rate in the soil (MJ m^{-2} d^{-1})
L_c: longwave radiation emitted by the inner greenhouse cover (W m^{-2})
L_g: longwave radiation emitted by the ground (W m^{-2})
L_n: net longwave radiation (W m^{-2})
R_n: net radiation at the ground/soil surface (W m^{-2})
R_{nd}: daily integral of net radiation at the ground/soil surface (MJ m^{-2} d^{-1})
S_i: incident shortwave radiation (W m^{-2})

S_n: net shortwave radiation (W m^{-2})
S_r: reflective shortwave radiation (W m^{-2})
T_a: air temperature at 0.3 m aboveground (°C)
T_s: surface temperature (°C)
TM: transparent mulch

Keywords

Air temperature; Black mulch; Gravel-sand layer; Net radiation; Soil heat flux; Soil temperature; Transparent mulch.

1. Introduction

Plastic greenhouses have become widespread in mild-winter climates and other warm regions of the world (Castilla, 2002), such as the Mediterranean coast of South-East Spain, which represents the largest greenhouse area in Europe (Castilla and Hernández, 2005). Most greenhouses of this region are low-cost structures covered with plastic film, without climate control systems and with soil-grown crops (Pérez-Parra et al., 2004). Winter greenhouse microclimate is usually suboptimal for production of vegetable crops with edible fruits (Bartzanas et al., 2005, Montero et al., 1985), with a negative effect on yield and fruit quality (López et al., 2008). Suboptimal air temperatures (nighttime values ranging between 5 and 10 °C) are often associated with low soil temperatures. Castilla and Lopez-Galvez (1994) reported soil temperature as low as 13 °C in the typical gravel-sand mulched soil used in the greenhouses of this region. Despite these unfavourable conditions, crop cycles starting in late autumn (cucumber) or early winter (melon and watermelon) have been introduced in order to supply the market demand and benefit from higher prices.

Heating systems are not commonly used in these greenhouses because they are not considered economically viable (Bartzanas et al., 2005, López, 2003). An alternative is the use of passive solar heating methods and measures to enhance the greenhouse energy efficiency. In a typical plastic greenhouse with a bare gravel mulched soil, Baille et al. (2006) found that the soil acted as a substantial source of air heating during winter nights (about 20 W m^{-2} on average in February). They suggest that simple passive solar systems increasing solar heat storage in the soil during the day and releasing the energy during the night could significantly enhance the overall greenhouse efficiency, especially in areas that receive a significant input of solar radiation in winter.

Among the passive systems, mulching could be of interest for improving the air/soil thermal regime during the early stages of crop cycles starting in winter, such as melon and watermelon, when the leaf area index is small and most of the soil surface is free of vegetation. As greenhouses are semi-closed systems in which multiple feedback loops exist between soil, air, vegetation and cover flux and state variables (Aubinet et al., 1989), the presence of a mulch can substantially modify the behaviour of the whole greenhouse system. In particular, the optical properties of the mulch and the degree of contact between it and the underlying soil modify the partitioning of the available net energy at the air–mulch and mulch–soil interfaces, with direct consequences on the heat transfer processes – radiation, convection and conduction – at these interfaces. Moreover, the mulch acts as a barrier to evaporation (Liakatas et al., 1986), enhancing the predominance of sensible heat exchange and influencing the dynamics of the soil temperature and humidity, and the amount of heat stored in or released from the upper layer of the soil (Berninger, 1989).

Most studies have focussed on plastic mulching for greenhouse soil solarization in summer (Stapleton, 2000, Streck et al., 1996). Transparent plastics are usually considered to be more effective for soil heating, especially for soil solarization (Stapleton, 2000, Streck et al., 1996), but black mulches may increase soil temperature more than clear ones in some cases when plastic mulches are closely in contact with the soil enhancing the heat conduction at the mulch–soil interface (Ham and Kluitenberg, 1994, Ham et al., 1993). Black mulch can be also used for weed control, a practice adopted by some local growers in southeast Spain. In the case of autumn/winter crops, an interesting characteristic of plastic mulching is that it might increase the soil heat storage and the soil temperature during the period prior to planting (i.e. from November to January), as well as immediately after planting when plants cover only a small fraction of the ground and do not affect the soil energy balance and storage rate to a large extent. Such a “heat-storage” treatment might provide the greenhouse with (i) a surplus of energy that could be used to heat the greenhouse during the coldest period (January–February); and (ii) a higher soil temperature than that prevailing under non-mulched soils, with positive effects on root temperature and crop performance during the early stages of growth. However, there is only scant information on how optical mulch properties could affect the greenhouse thermal behaviour under winter conditions. Obviously, highly reflective mulches are not suitable for increasing soil heat storage and root zone temperature, as reported by Lorenzo et al. (2005), who concluded that white plastic mulching was inadequate for soilless crops in winter because it lowers air and substrate temperature.

This work investigates how the two main standard plastic mulches (transparent and black) alter the greenhouse soil temperature at different depths and the rate of heat storage/release with respect to a non-mulched soil. A primary objective was to assess the potential of such materials to capture, store and retain the available energy incoming at the surface (i.e. net radiation) in the medium term (week). A secondary objective was to analyse the short-term (24 h) dynamics of the energy exchanges between the surface and the air, so as to assess the magnitude of the day-to-night heat exchanges and the heating capacity of the soil during the night, when air heating is deemed necessary.

2. Materials and methods

2.1. Greenhouse and experiments

Experiments were conducted in a three-span greenhouse of 630 m^2 (22.5 m × 28 m), oriented east–west and covered with a three-layer thermal polyethylene film (200 μm thickness), located at the “Cajamar Foundation” research station (2°43′W; 36°48′E; 155 m.a.s.l.) on the Almería coast in southeast Spain. The greenhouse was arch-roofed, 4.5 m high to the eaves and 3.0 m to the ridge, and had one roof vent per span and a sidewall rolling vent in the southern and northern sides.

Vents were covered with insect-proof screens (28 × 13 threads per cm; thread diameter 0.19 mm; porosity 32%) and they were managed manually.

The plastic film covering the greenhouse, installed in January 2008, had a transmissivity of 89% to shortwave radiation and 25% to longwave radiation (manufacturer's data). The transparent mulch was a three-layer anti-fog plastic film of 35 µm thickness (Sotrafilm NT, Sotrafa SA, Almería, Spain) with a shortwave transmissivity, reflectivity and absorptivity of 0.85, 0.10 and 0.05, respectively, and a longwave transmissivity of 0.74. The black mulch was a three-layer plastic film of 30 µm thickness (Sotrafilm NG, Sotrafa SA, Almería, Spain) with a shortwave transmissivity of 0.01, a reflectivity of 0.04 and an absorptivity of 0.95, and a longwave transmissivity of 0.15.

The greenhouse was divided in two equal compartments of 22.5 m × 10 m (A and B) in order to minimise climate differences between compartments due to the outside surrounding environment. A 4 m wide buffer zone was maintained between the two compartments, while a 2 m buffer zone was established at each end of the greenhouse (Fig. 1). The compartments were isolated by means of a north–south wall made of a three-layer thermal polyethylene plastic film.

The soil consisted of the naturally occurring, gravel sandy-loamy soil covered with a 0.3 m layer of imported loamy soil, a 0.02 m layer of dried farmyard manure, and finally a 0.1 m mulch layer of fine gravel (69%) plus very coarse (29%) and coarse (2%) sand particles. With time and use, the dried farmyard manure layer was practically mineralised and disappeared. This soil, known as “enarenado”, is widely used in this region (Wittwer and Castilla, 1995). The top gravel-sand mulch layer presented a total porosity of 0.44, a bulk density of 1.42 g cm^{-3} and a real density of 2.53 g cm^{-3}. During the experimental period (from 4 November 2008 to 11 January 2009) the greenhouse remained without crop and the soil was maintained dry. These conditions are representative of the period before and just after crop planting when plantlets have a very low leaf area index and the soil area wetted by drip emitters is small.

Two experiments were carried out, each comparing two treatments, one per greenhouse compartment. The first experiment, conducted from 4 November to 9 December 2008, compared a transparent plastic mulch (TM, compartment A) with a black one (BM, compartment B). Roof and sidewall vents remained closed from the beginning of the experiment until 16 November, when they were open during most of the daytime (from 9:00 h to 18:00 h). The second experiment, conducted from 10 December 2008 to 11 January 2009, compared the soil covered with the black mulch (BM, compartment B) to the non-mulched soil (NM, compartment A). Greenhouse vents remained closed from the beginning of the experiment until 29 December, after which they were open during most of the daytime. In both experiments plastic mulches covered the whole surface of each compartment and were manually stretched and installed in the closest possible contact with the soil fixing the plastic borders with staples.

2.2. Measurements

The main microclimate variables of soil, mulch, inside and outside air, and greenhouse cover were measured in the two compartments. The sensors were located in the middle of each greenhouse compartment (Fig. 1).

Soil temperature was measured with Pt-100 reference thermistors (T107, Campbell Scientific Ltd., Delft, The Netherlands) and conduction heat flux was measured with heat flux plates (HFP01, Campbell, Scientific, Delft, The Netherlands). The sensors were buried in the upper (0.01 m depth), middle (0.05 m) and lower (0.1 m) parts of the top gravel-sand layer, in the middle of the imported soil layer (0.25 m depth) and in the upper part of the original soil (0.45 m depth). By convention, the direction of each energy flux term was considered positive towards the surface, and negative away from the surface (e.g. the soil heat flux was negative when heat was transferred from the soil surface to the greenhouse atmosphere, and *vice versa*).

Dry and wet bulb temperatures were measured inside the greenhouse at heights of 0.3 m and 4.0 m aboveground with ventilated psychrometers (mod. 1.1130, Thies Clima, Göttingen, Germany), and in an automatic meteorological station (AWOS 7770, Thies Clima, Göttingen, Germany), mounted at 1.5 m height under open field conditions on bare land 100 m away from the experimental greenhouse. The temperature of the upper and lower surfaces of the plastic mulches was measured with contact thermocouples (type T, copper-constantan, RS Amidata, Madrid).

Net radiation at the ground/mulch surface was determined by means of a set of radiation sensors (CNR1, Kipp&Zonen, Delft, The Netherlands) located 0.3 m above the ground in each compartment. Shortwave and longwave net radiation components were determined separately. Incident (S_i) and reflected (S_r) shortwave radiation were measured by means of a pair of pyranometers, one in inverted position. Net shortwave radiation (S_n) was obtained from the difference between incident and reflected solar radiation. Net longwave radiation at the ground surface (L_n) was obtained as the difference between the radiation emitted by the ground (L_g) and that emitted by the inner cover (L_c). Net radiation at the ground/mulch surface (R_n) was calculated as the sum of net shortwave and longwave components.

All sensors were sampled at 2-s intervals, averaged every 5 min and registered by several data logging devices (mod. CR10X, CR1000 and CR3000, Campbell Scientific Ltd., Leicestershire, UK).

3. Results

3.1. Surface radiative balance

3.1.1. BM *vs*. TM

Solar radiation incident on the ground (S_i) was very similar in the BM and TM treatments, whereas reflected solar radiation (S_r) differed substantially. The mean daily albedo (S_r/S_i) of TM (0.34 ± 0.02) was much higher than that of BM (0.08 ± 0.01), leading to daily values of net shortwave radiation (S_n) that were *ca*. 30% higher for BM than for

TM (Fig. 2a). A close linear relationship was found between the daily means of S_n in the two treatments: $S_{n,TM} = 0.70S_{n,BM}$ ($n = 23$; $R^2 = 0.92$). This relationship was not affected by opening the vents.

Longwave radiative loss (L_n) during daytime reached about 100 W m^{-2} at the BM surface, which is clearly higher than that measured at the TM surface (Fig. 2a). The opposite trend was found for the nighttime period, when L_n values were slightly less negative for BM than for TM. The latter can be due to the higher longwave transmissivity of TM, compared to BM, as nighttime soil temperatures were greater in the upper part of the gravel-sand layer than in the plastic mulches. A close linear relationship was found between the daily means of L_n in both treatments: $L_{n,BM} = 1.18\ L_{n,TM}$ ($n = 23$; $R^2 = 0.80$), indicating that the longwave radiative loss was about 15–20% higher for BM than for TM on a 24 h scale, irrespective of whether the vents were open or closed.

The balance between radiation inputs (S_n) and outputs (L_n) indicates that BM received higher net radiation ($R_n = S_n + L_n$) than TM (Fig. 2b). The daily integral of R_n (R_{nd}) expressed in MJ m^{-2} d^{-1} (Fig. 3a) was on average approximately 1 MJ m^{-2} d^{-1} higher at the BM surface than at the TM surface, the two integrals being closely correlated through the linear regression (Fig. 3a): $R_{nd,BM} = 1.10R_{nd,TM} + 0.96$ ($n = 23$; $R^2 = 0.91$). Higher R_{nd} in the BM-treatment was due to the lower albedo of this material with respect to TM.

Opening the vents had a substantial effect on the absolute values of R_{nd} in both BM and TM compartments (Fig. 3a). R_{nd} was higher with open than with closed vents in both compartments. When vents were open, they produced more air movement inside the greenhouse, enhancing the sensible convective heat exchange from the warm plastic surface to the air, decreasing the plastic surface temperature and increasing net radiation at the mulch surface. However, the latter increase was not beneficial to the air temperature close to the surface, nor to the energy storage by the soil (Sections 3.2 Surface and air temperature, 3.3 Soil heat flux), which appeared to depend more on the temperature than on the net radiation at the surface.

3.1.2. BM *vs*. NM

The soil without plastic mulch (NM) had an albedo value (0.33 ± 0.03) close to that measured for TM, providing similar values of S_n to those observed for TM. Net longwave radiation at the surface of NM was lower than that of BM and the values were closely correlated ($L_{n,BM} = 1.14L_{n,NM}$; $n = 33$; $R^2 = 0.99$), as were those of $L_{n,BM}$ and $L_{n,TM}$ (see Section 3.1.1). As a result, in the second experiment $R_{nd,BM}$ was approximately 20% higher in absolute values than $R_{nd,NM}$ (Fig. 3b; $R_{nd,BM} = 1.18R_{nd,NM} + 0.27$; $n = 33$; $R^2 = 0.84$), indicating that, on a daily scale, the radiative balance of NM was closer to that of TM than to that of BM.

3.2. Surface and air temperature

3.2.1. Vents closed

When greenhouse vents were closed, the surface temperature of plastic mulch (T_s) was clearly higher for BM than for TM during daytime (Fig. 4a), up to 14 °C near midday. At night, T_s was slightly higher in the BM treatment (about 0.5 °C). On a daily scale, the mean difference in surface temperature between BM ($T_{s,BM}$) and TM ($T_{s,TM}$) was 3.7 °C. A similar trend was observed for the T_s difference between BM and NM.

The air temperature at 0.3 m above the ground (T_a), the most representative when considering low-height vegetable crops or tall crops at their early stages, was clearly higher in the BM than in the TM compartment during daytime (Fig. 4b). The difference in T_a between the two treatments peaked near noon (about 7 °C) while it was slightly negative during the night (about −0.5 °C), and it presented a close similarity to the evolution of the difference in surface temperature, T_s (Fig. 4a). On a daily scale, the mean gain in T_a induced by BM was 1.4 °C.

In the second experiment the difference in T_a between BM and NM presented a similar evolution (Fig. 4c) to that observed between BM and TM (Fig. 4b), with a mean daily air temperature gain of 1.0 °C in BM.

3.2.2. Vents open

When vents were opened during daytime, the surface temperature of the two mulches decreased by a similar amount and the daily evolution of difference in T_s between BM and TM was similar to that observed for closed vents (Fig. 4a). However, T_a decreased more with BM than with TM during daytime, resulting in substantially smaller differences in T_a between the BM and TM compartments than those observed with closed vents (Fig. 4b). On a daily scale, the mean T_a at 0.3 m was similar for both compartments, indicating that BM did not induce a significant gain in air temperature with respect to TM when vents were open. A similar behaviour was observed when the air temperature of BM and NM was compared (Fig. 4c), with the difference that BM induced a mean daily air temperature gain of 0.8 °C when vents were open.

3.3. Soil heat flux

3.3.1. BM *vs*. TM

The conduction heat flux rate at 0.01 m depth in the superficial gravel-sand layer (G) was more positive (heat storage) during daytime and less negative (heat release) during the night with BM than with TM (Fig. 5a). Maximum instantaneous values (15-min average) of *ca*. 150 W m^{-2} were observed for G near midday with BM, whereas these values were approximately 20 W m^{-2} lower with TM. The release rate during the night ranged between −55 and −40 W m^{-2} for TM, while for BM the values were approximately 10 W m^{-2} lower in absolute values. The soil heat flux evolution at 0.05 and 0.25 m depth presented the characteristic time-lag with respect to the uppermost layer (Fig. 5a). A close relationship between the daily integral of G (G_d) of the two treatments was found when pooling data of closed and open vents (Fig. 5b): $G_{d,BM} = 1.37G_{d,TM} + 0.98$ ($n = 22$; $R^2 = 0.80$). The mean daily gain in heat storage induced by BM with respect to TM was 0.66 MJ m^{-2} d^{-1} for the measurement period, but it was higher in the period with closed vents

(0.81 MJ m^{-2} d^{-1}; $G_{d,BM} = 1.65G_{d,TM} + 0.87$; $n = 13$; $R^2 = 0.87$) than in the period with open ones (0.45 MJ m^{-2} d^{-1}; $G_{d,BM} = 0.79G_{d,TM} + 0.66$; $n = 9$; $R^2 = 0.75$).

3.3.2. BM *vs.* NM

With regard to soil heat storage, BM performed slightly better than NM. G at 0.01 m depth was more positive (heat storage) during daytime and less negative (heat release) during the night with BM than with NM (Fig. 6a), but the differences were smaller than those observed for the BM *vs*. TM comparison (Fig. 5a). A close relationship between the daily G integrals at 0.01 m in BM and NM was also found (Fig. 6b): $G_{d,BM} = 1.06G_{d,NM} + 0.12$ ($n = 32$; $R^2 = 0.86$). The mean daily loss of heat storage in BM was 0.15 MJ m^{-2} d^{-1} lower than in NM for the period without ventilation, but similar for the period with ventilation.

The daily integrals of G at 0.01 m depth (G_d) and of R_n at the mulch surface (R_{nd}) were represented for the BM and TM treatments (Fig. 7) and data were pooled into two clusters: days with closed vents and days with open vents. With the exception of some outliers (4 paired values), two distinct clusters of points clearly emerged (Fig. 7), highlighting the substantial effect of ventilation on the G_d–R_{nd} relationship in greenhouses with plastic mulches. When data of G_d and $R_{n,d}$ for BM and NM were compared, the effects of ventilation were not so clear because the differences in G_d between the two treatments were small, as reported above.

3.5. Soil temperature

The analysis was restricted to the upper gravel-sand layer (0–0.1 m depth), as the soil surface temperature affects the air and soil energy exchanges, and the imported soil layer (at 0.25 m depth), as this layer concentrates most roots, and water and nutrient uptake by protected fruit vegetable crops (Orgaz et al., 2005).

3.5.1. BM *vs.* TM

The mean temperature (T_{s1}) in the top gravel-sand layer (averaged over 0.01, 0.05 and 0.1 m depth) was higher throughout the day with BM than with TM (Fig. 8a), except for the morning hours when slightly faster soil heating appeared to occur in the TM compartment, which can be observed for the upper part (0.01 m depth) of top gravel-sand layer in Fig. 9. The mean daily T_{s1} in the BM and TM compartments at the beginning of the experiment was 22.1 °C and 21.9 °C, respectively, as compared to 25.4 °C and 23.9 °C at the end of the period with closed vents, and 22.6 °C and 21.9 °C at the end of the experimental period. That is, the mean daily T_{s1} increase was 1.3 °C greater with BM than with TM at the end of period without ventilation, and 0.5 °C greater at the end of the experiment. The temperature in the middle of the soil layer (T_{s2}) at 0.25 m depth also increased more and was higher with BM than with TM, with a mean daily difference of about 1.0 °C at the end of the period without ventilation (Fig. 8a). A similar response was observed in the upper part of the original soil layer, at 0.45 m depth.

3.5.2. BM *vs.* NM

T_{s1} was higher in the compartment with BM than with NM during daytime (except for a short period after midday) and especially during the night, with maximum differences of about 3 °C (Fig. 8b). The mean daily T_{s1} in BM and NM, respectively, were 19.4 °C and 18.5 °C at the beginning of the treatment, as compared to 19.3 °C and 17.6 °C at the end of the period without ventilation, and 16.1 °C and 13.6 °C at the end of the experiment. Therefore, the mean daily T_{s1} decrease in this layer was 0.7 °C greater in NM than in BM at the end of period without ventilation, and 1.6 °C greater at the end of the experiment. T_{s2} also increased faster and was higher with BM than with NM (Fig. 8b): the temperature decrease in this layer was 1.6 °C greater with NM than with BM. A similar response was observed in the upper part of the original soil, at 0.45 m depth.

Overall these soil temperature patterns were in line with the daily heat storage values (G_d) observed in BM with respect to TM and NM (Section 3.4).

4. Discussion

4.1. The role of soil–mulch contact in driving soil heat storage

In our experimental conditions (late autumn and early winter period in an unheated plastic greenhouse in a Mediterranean climate) an opaque black mulch (BM) performed better than a transparent one (TM) when considering both the air and soil temperature regimes within the space occupied by low-height or young vegetable crops (0–0.3 m aboveground for the shoot and 0–0.4 m below ground for the root-zone). Similar results were obtained by Ham et al. (1993) in open-field for a fine sandy loam soil in summer. However, other studies dealing with the influence of the type of mulching material in open field crops showed the opposite: a better soil/air microclimate with transparent mulches. The latter was ascribed to the higher net radiation at the soil surface and the higher soil heat flux with a transparent mulch than with an opaque one (Liakatas et al., 1986, Rosenberg, 1974). That is why transparent mulch is generally recommended in order to reach higher soil temperatures, especially for soil solarization, including greenhouse soils (Stapleton, 2000). Ham and Kluitenberg (1994) simulated temperature and heat flux in soils under different plastic mulching and explained the contradictory results of transparent and black mulches. The heating capability of the black mulch is greater as the degree of *physical contact* between mulch and soil surfaces increases. A black mulch, stretched tightly on the soil surface, absorbs most of the shortwave radiation, heats up and transfers energy to the soil more efficiently, mostly by conduction, than a loose-contact film. The opposite occurs with the transparent mulch: the soil absorbs most of the shortwave radiation, and the larger the air gap between mulch and soil surfaces, the more effectively the soil is insulated from conduction/convection heat loss. Moreover, the heating capability of transparent mulch increases in wet soils when water condenses as droplets on its inner surface, reducing the mulch transmissivity to longwave radiation and increasing its emissivity, while its transmissivity to shortwave radiation is almost unaffected (Streck et al., 1996).

In our study, the net radiation integral at the mulch surface (R_{nd}) was higher (≈1 MJ m^{-2} d^{-1}) in the greenhouse compartment with BM than with TM (Fig. 2a), especially during the daytime. This was mainly due to the lower albedo of the BM surface. The conduction heat flux at the surface (0.01 m depth) of the upper gravel-sand layer was also higher with BM (Fig. 5a and b), with an average net daily gain of 0.66 MJ m^{-2} d^{-1} with respect to TM. It could be concluded that our mulch materials were installed in close contact with the underlying soil, a necessary condition to maximize the soil heat storage during daytime, especially for the black mulch material. Another factor that can contribute to the better thermal behaviour of BM in greenhouses is the very low inside air speed prevailing in greenhouses (Fernández et al., 2010), compared to outdoors. In such conditions the convective heat exchange between the plastic mulch and the air is small, and leads to a substantially higher increase in mulch surface temperature than that observed outdoors. This behaviour is expected to be enhanced by the use of plastic films with high emissivity, such as BM. It can also explain the smaller soil temperature differences observed between the BM and TM compartments when vents were open (Fig. 8a).

4.2. Black mulch improves the aerial and soil microclimate

BM increased soil and air temperature significantly more than TM. When greenhouse vents were closed, mean daily air temperature at 0.3 m was 1.4 °C higher in the BM compartment, with maximum differences of about 7 °C around midday (Fig. 4b). In terms of temperature integral, the black mulch provides a surplus of *ca*. 85 °C day with respect to the transparent mulch over a 2-month cropping period. These results were to be expected, as it is well known that a black surface is the most appropriate to increase the efficiency of air solar collectors (Duffie and Beckman, 1974), especially in greenhouses (Boulard and Baille, 1987). However, a slightly lower air temperature was found in the compartment with BM during the night. Despite the air nighttime temperature differences were very small, the possible agronomical effects, if any, have to be further evaluated in cultivated greenhouse experiments. The use of floating row covers in the early stages of crop cycles starting in early winter, a normal practice in the area, should be simultaneously considered. BM also induced a higher soil temperature regime than TM. This positive influence of BM was especially marked in the top 0–0.1 m layer and to a lesser degree in the deeper soil layers (Fig. 8a and b) where most fruit vegetable roots usually grow (Orgaz et al., 1995). This was a logical consequence of the differences observed in the daily integral of soil heat storage (G_d) mentioned above (Section 4.1).

4.3. Ventilation has a negative effect on soil heat storage efficiency

An original finding of this study is that the enhancement of soil heat storage induced by BM with respect to TM was substantially reduced when the greenhouse was ventilated during daytime. The analysis of the relationship between G_d and R_{nd} for BM and TM, distinguishing between days with and without ventilation, revealed the substantial effect of greenhouse ventilation on the parameters of this relationship (Fig. 7). Although R_{nd} was higher in both BM and TM when vents were open, G_d was consistently higher when vents were closed. Therefore, it seems recommendable to minimize the ventilation periods when the main aim is to maximize greenhouse soil heat storage. This is feasible in greenhouses that are void of crops (pre-planting period), which can be kept closed throughout the whole day. During the cropping period, some ventilation should be provided to ensure CO_2 and humidity control, and therefore the soil heat storage efficiency might be lower in post-planting than in pre-planting periods.

In conclusion, the combined effect of BM + greenhouse significantly improved the greenhouse microclimate and heat storage capacity of the system with respect to the combination of TM + greenhouse. Installing BM inside the greenhouse appears to be of interest for the early stages of fruit vegetable crop cycles starting at the end of autumn and in winter, when crop leaf area index is small and most of the soil is uncovered.

4.4. Comparison of BM and NM

The second experiment, comparing BM with the non-mulch soil (NM), showed that BM provided the same advantages over NM as those found in the comparison between BM and TM, but quantitatively the differences were not so marked. The mean daily temperature in the top gravel-sand layer and in the deeper soil layers was clearly higher with BM than with NM, especially when greenhouse vents were closed (Fig. 8b). R_{nd} was higher (0.5 MJ m^{-2} d^{-1}) with BM (Fig. 3b) particularly during daytime, as was G_d, especially when vents were closed (Fig. 6a and b). BM also increased the greenhouse air temperature at 0.3 m for most of the daytime compared with NM (Fig. 4c), but the daytime temperature gain was smaller than that measured in the BM and TM comparison. During the night the greenhouse air temperatures were similar for the BM and NM compartments (Fig. 4c).

Overall, regarding the thermal microclimate and soil heat storage capacity, the 0.1 m gravel-sand top layer currently used by growers in unheated greenhouses of Southern Spain (NM) presented an intermediate performance between BM and TM.

4.5. Additional agronomic considerations

The improved air/soil temperature regimes in passive greenhouses equipped with black mulching during the coldest period of the cropping season could be beneficial for vegetable production regarding crop processes related to plant growth, development and early yield, or to prevent weed proliferation. One shortcoming could be the low albedo, compared to that of greenhouses with transparent or without plastic mulch, which might result in a lower availability and interception of photosynthetically active radiation (PAR) by the plants. The higher reflection of PAR, expected in greenhouses without mulch or with transparent mulch, might compensate for their lower soil and air greenhouse temperatures. A previous work carried out on a cucumber crop in the same region and type of greenhouse but using a highly reflective white plastic mulch (Lorenzo et al., 2005) concluded, however, that the increase in intercepted PAR by the cucumber plants did not compensate for the reduction in air/soil temperature with respect to a non-mulched soil, and that yield was lower in the mulched crop than in the non-mulched one. The latter result notwithstanding, a comprehensive study on the respective advantages of opaque non-reflective mulch *vs*. highly reflective mulch would provide more information and criteria for selecting the greenhouse mulch with the most appropriate optical properties.

4.6. Conclusions

Our study demonstrated that a black mulch installed in close contact with the soil in an unheated greenhouse substantially increased energy recovery and soil heat storage efficiency, and improved soil and surrounding air temperatures during a cold period (late autumn and early winter) with respect to a transparent one or a non-mulched soil. The combination black mulch + greenhouse appears to be a simple and low-cost passive heating system that can be recommended for the early stages of crop cycles starting at the end of autumn or in winter, such as cucumber, melon and watermelon, when the canopy leaf area index is small and most of the soil surface is free of vegetation. Other relevant findings of the study were:

- (i) The energy efficiency and improvement of the thermal microclimate induced by BM with respect to both TM and NM was negatively affected when greenhouse ventilation was operating during the day. This implies that greenhouse ventilation management should reflect a compromise between maximizing greenhouse heat storage and fulfilling ventilation requirements for suitable crop growth.
- (ii) The 0.10 m gravel-sand layer currently used by growers in unheated greenhouses of Southern Spain appears to play a positive role regarding the thermal microclimate and the day-night soil heat storage cycle, presenting an intermediate performance between the BM and the TM.

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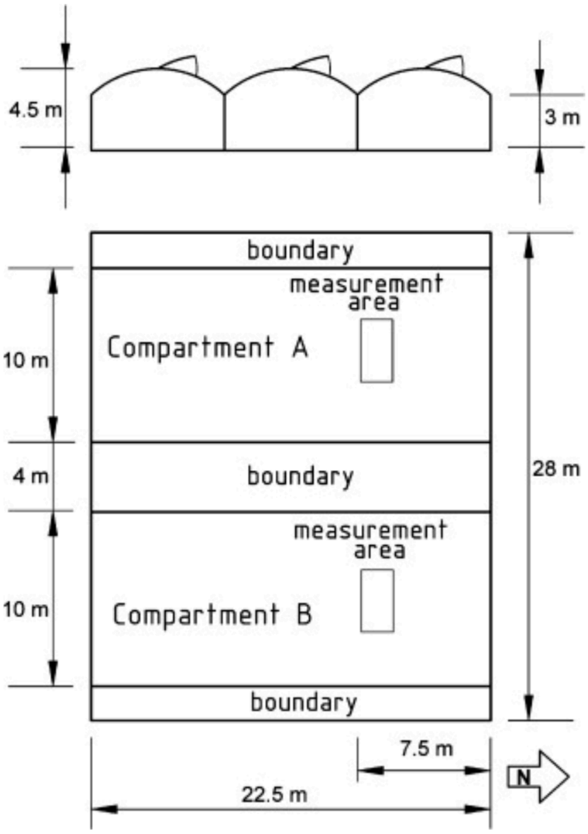

Fig. 1. Experimental greenhouse divided in two identical compartments. Small squares represent the area where microclimate measurements were carried out.

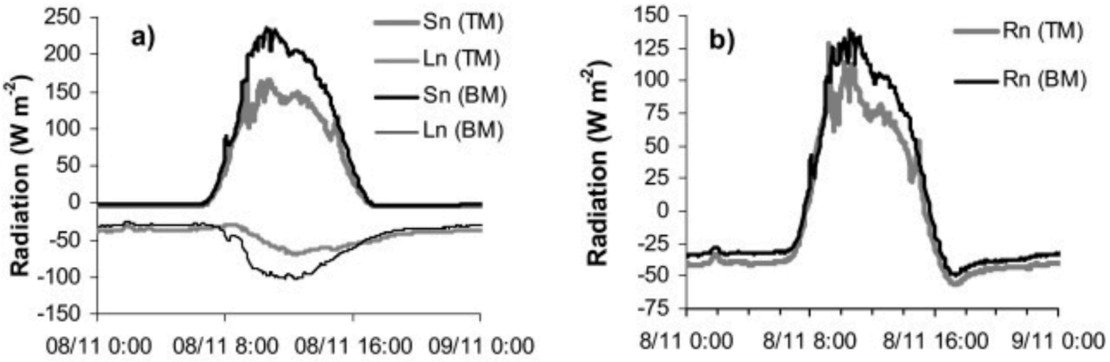

Fig. 2. Daily (24 h) evolution of (a) net shortwave, S_n and net longwave, L_n, radiation, and (b) net radiation, R_n, at the mulch surface of a greenhouse with black (BM) *vs*. transparent mulch (TM) on a representative sunny day (8 Nov. 2008) with closed vents.

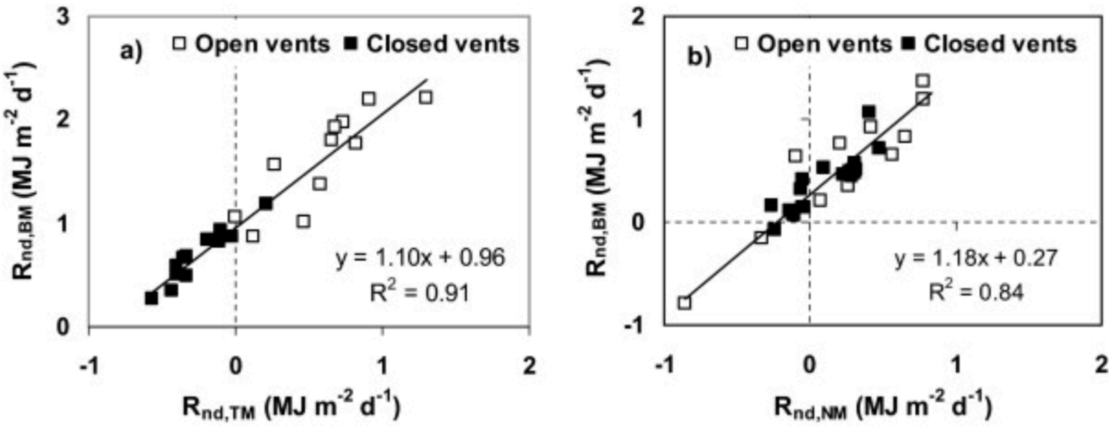

Fig. 3. Linear relationship between daily integrals of net radiation at the black mulch ($R_{\mathrm{nd,BM}}$) (a) *vs*. the transparent mulch ($R_{\mathrm{nd,TM}}$); and (b) *vs*. no plastic mulch conditions ($R_{\mathrm{nd,NM}}$).

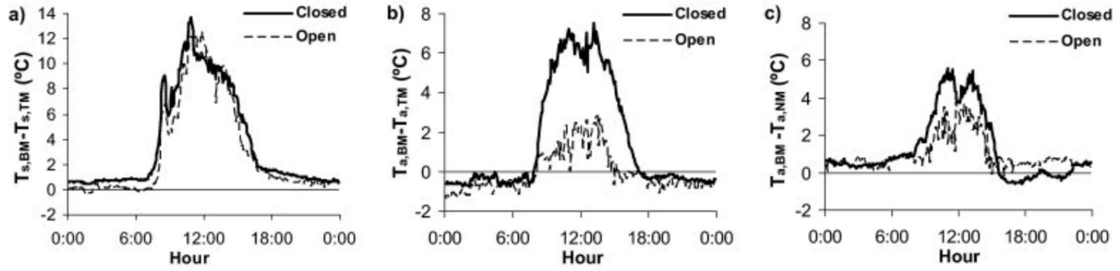

Fig. 4. Daily evolution of the temperature difference between: (a) the surface of BM ($T_{\mathrm{s,BM}}$) and TM ($T_{\mathrm{s,TM}}$), and (b) the air 0.3 m above the ground surface of BM ($T_{\mathrm{a,BM}}$) and TM ($T_{\mathrm{a,TM}}$) compartments on representative sunny days with closed (12 Nov. 2008) and open vents (18 Nov. 2008); (c) between the air 0.3 m above the ground surface of BM ($T_{\mathrm{a,BM}}$) and NM ($T_{\mathrm{a,NM}}$) compartments on representative sunny days with closed (18 Dec. 2008) and open vents (30 Dec. 2008).

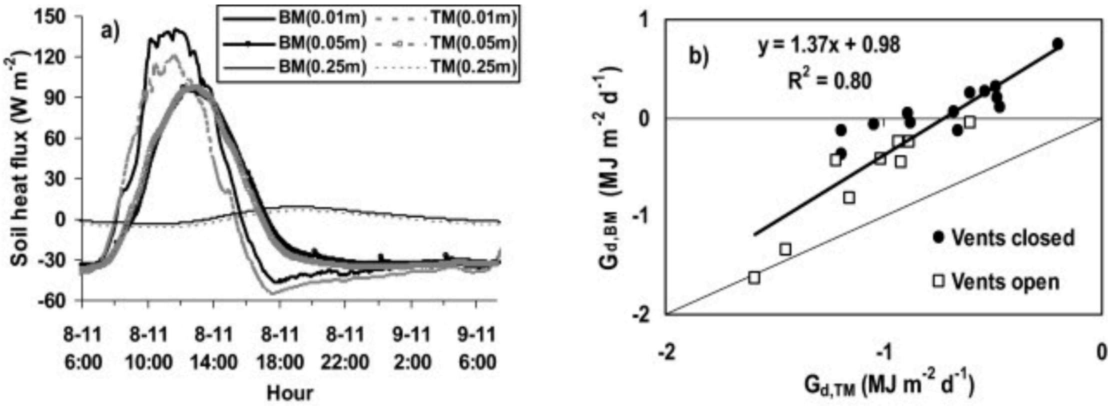

Fig. 5. (a) Daily evolution of the conduction heat flux rate at different soil depths in the BM and TM compartments on a representative sunny day with closed vents (8 Nov. 2008). (b) Linear relationship between daily integrals of conduction heat flux rate at 0.01 m depth in the BM ($G_{\mathrm{d,BM}}$) and the TM ($G_{\mathrm{d,TM}}$) for the whole experimental period.

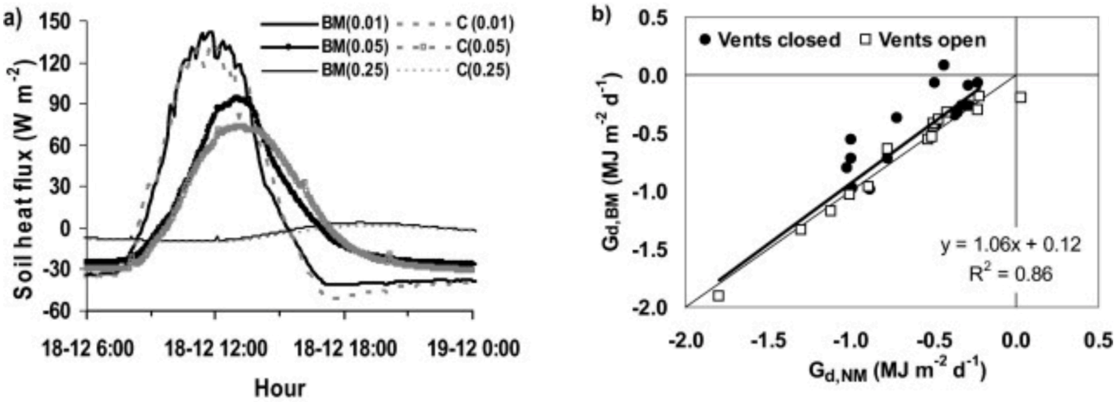

Fig. 6. (a) Daily evolution of the conduction heat flux rate at different soil depths in the BM and NM compartments on a representative sunny day with closed vents (18 Dec. 2008). (b) Linear relationship between daily integrals of conduction heat flux rate at 0.01 m depth in the BM ($G_{\mathrm{d,BM}}$) and the NM ($G_{\mathrm{d,NM}}$) for the whole experimental period.

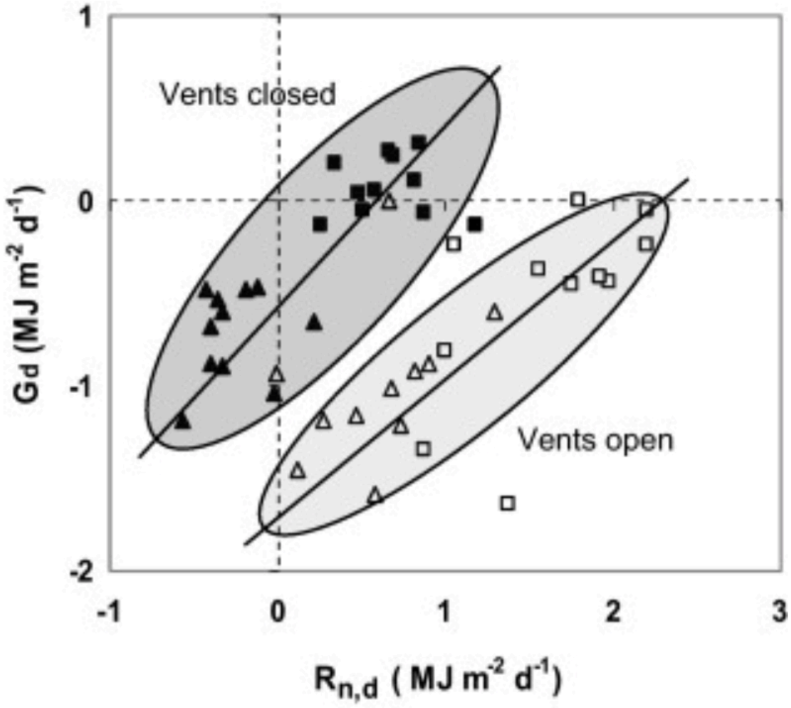

Fig. 7. Relationship between daily integrals of soil heat flux rate at 0.01 m depth (G_{d}) and net radiation at the mulch surface (R_{nd}) in the greenhouse compartment with black (BM) and transparent (TM) mulches. Data are pooled into two clusters: Black symbols: days with closed vents; blank symbols: open vents. Square: BM compartment; triangle: TM compartment.

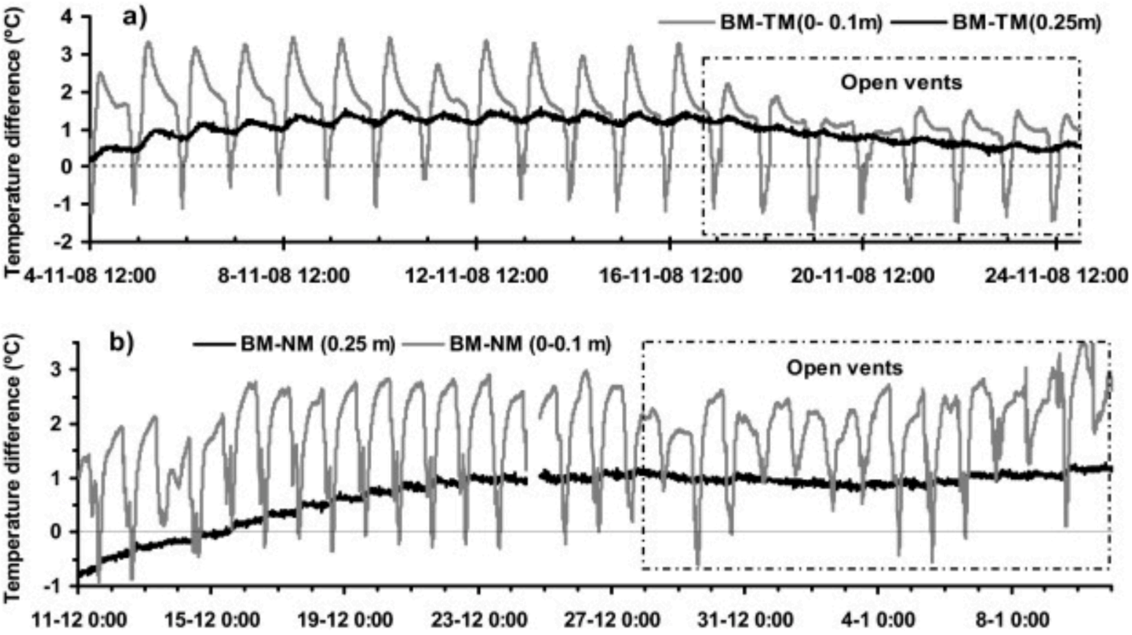

Fig. 8. Time course of the temperature difference in the gravel-sand layer (averaged over 0.01, 0.05 and 0.1 m depth) and in the middle of the soil layer (at 0.25 m depth) between: (a) BM and TM; (b) BM and NM.

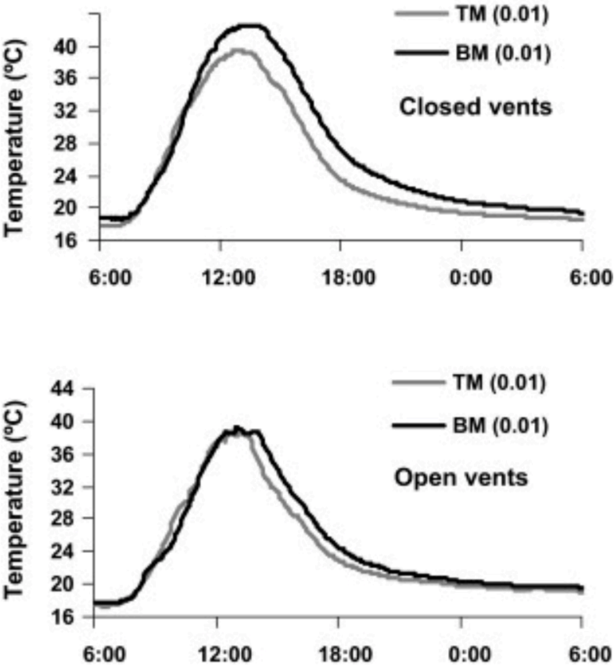

Fig. 9. Time course of the soil temperature in the upper part of the gravel-sand layer (at 0.01 m depth) during a day with closed (8/11/2008) and open (18/11/2008) vents in the greenhouse compartments with BM and TM.