Title

Effects of gravel mulch on surface energy balance and soil thermal regime in an unheated plastic greenhouse

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Abstract

This work analyses how a mulch layer of mostly gravel particles affected the soil thermal dynamics in an unheated plastic greenhouse in a Mediterranean area (South-East Spain), where suboptimal regimes of soil temperature usually prevail in winter crop cycles. Soil temperature and heat flux profiles were measured in two soil types: (i) a 0.1-m thick gravel mulch (GM) placed at the top of a 0.30-m layer of imported loamy soil and (ii) the latter without gravel mulch (NM). These measurements were conducted during a winter period (14-28 January) when the dominant source of energy in the soil root-zone was the heat from deeper soil layers. The higher albedo of the GM and its higher long-wave radiation losses reduced substantially the daily net radiation at the mulch surface by *ca.* 77 % with respect to NM. However, the soil root-zone maintained warmer under the GM than with NM in a period when soil temperatures are usually below the optimum. This was mainly caused by the insulating property of the mulch, which acted as heat barrier and increased the resistance to heat transmission from deep soil horizons towards the surface. This passive heating of the soil root-zone by using a gravel mulch was later confirmed in a summer-winter cycle of sweet pepper grown in an unheated plastic greenhouse. The gravel mulch also reduced the soil evaporation and increased the reflected short-wave radiation towards the plants, but the air temperature above the mulch fluctuated more strongly than in the absence of the mulch.

Keywords: albedo, heat and water barrier, heat storage, net radiation, soil heat flux, soil temperature.

Nomenclature

a	albedo
C	thermal heat capacity (MJ m^{-3} K^{-1})
DTR	diurnal temperature range (ºC)
G	soil heat flux (W m^{-2} or MJ m^{-2} per unit time)
GM	gravel mulch soil system
G_s	soil heat flux at –0.01 m depth (W m^{-2} or MJ m^{-2} per unit time)
H_s	sensible heat flux at the ground surface (W m^{-2} or MJ m^{-2} per unit time)
k	heat conductivity (W m^{-1} K^{-1})
L	soil sub-layers (-)
L_d	downward long-wave radiation (W m^{-2} or MJ m^{-2} per unit time)
L_n	net long-wave radiation at the ground surface (W m^{-2} or MJ m^{-2} per unit time)
L_u	upward long-wave radiation (W m^{-2} or MJ m^{-2} per unit time)
NM	no mulch soil system
Q	soil heat storage (MJ m^{-2})
Q_h	hourly integral of heat stored/released (MJ m^{-2} h^{-1})
R_n	net radiation at the ground surface (W m^{-2} or MJ m^{-2} per unit time)
S	incident short-wave radiation (W m^{-2} or MJ m^{-2} per unit time)
S_n	net short-wave radiation at ground surface (W m^{-2} or MJ m^{-2} per unit time)
S_r	reflected short-wave radiation (W m^{-2} or MJ m^{-2} per unit time)
T_a	greenhouse air temperature at 0.3 m aboveground (ºC)
T_s	soil temperature at –0.01 m depth (ºC)

T_{surf} surface soil temperature (ºC)

z soil depth (m)

1. Introduction

The use of gravel or mixtures of gravel and sand as mulch is a traditional farming technique practiced in some semiarid countries (Fainbourn, 1973; Gale, McColl, Fang, 1993; Nacthtergaele, Kjelgren, van Waswmael, 1998; Xie et al., 2010) aiming to improve water use efficiency, but also to increase soil temperature. In these zones, different mulch inorganic materials [sand (0.05 mm < ∅ < 2 mm), gravel (2 mm ≤ ∅ < 76 mm) and larger rock fragments] are used separately or mixed in different proportions based on local availability, but gravel is usually preferred, particularly in developing countries, because of its availability and low cost (Xie, Wang, Jiang, Wei, 2006). Mixed gravel-sand mulches have been widely adopted by local farmers in northwest China because they substantially improve soil temperature and decrease soil evaporation (Li, 2003).

Numerous open field studies have attempted to gain a deeper insight into this farming practice with the aim of adapting it to modern agricultural techniques. Poesen and Lavee (1994) stated that heat transfer in a dry soil, characterized by the thermal diffusivity, increases non-linearly with the content of rock fragment particles larger than 2 mm in diameter. Nacthtergaele et al. (1998) reported significant increases in gravel mulch topsoil temperature in vineyards in Switzerland. Li (2002) also found higher topsoil temperatures with gravel mulches, attributed to the lower heat storage capacity of the gravel layer compared to bare soil, resulting in a rapid increase in temperature and heat transfer to the underlying soil layers. Xie et al. (2010) found that the use of several gravel-sand mixtures increased soil temperature and decreased daily soil temperature fluctuation. They also concluded that in these mixtures small-size particles (∅ < 20 mm) were better for preserving heat in soil than large ones.

Gravel-sand mulches have also been used extensively for greenhouse vegetable production in countries of the Mediterranean Basin, particularly in Spain. In South-East Spain, one of the largest areas of greenhouses in the world (Castilla & Hernández, 2005), artificially layered soils with top gravel-sand mulches, known as *enarenados*, have played a fundamental role in the development of the greenhouse industry (Castilla & Hernández, 2005; Pardossi, Tognoni, Incrocci, 2004). This area is characterised by water scarcity, medium-to-low quality irrigation water, a mild winter climate and low-cost structures covered with plastic film and without climate control systems. The use of the *enarenado* technique by growers spread very rapidly from the outset (early 1960's) of this intensive agricultural sector because it offers several advantages to greenhouse production (Castilla & Hernández, 2005; Pardossi, Tognoni, Incrocci, 2004): (i) improving water use efficiency by lowering soil evaporation; (ii) mitigating soil salinity by avoiding superficial salt accumulation when irrigating with waters of moderate (1 to 2.5 dS m^{-1}) salinity; (iii) reducing weed infestation; and (iv) preventing soil compacting by farm workers and machinery. At present, gravel-sand mulches are employed in about 80% of this greenhouse area.

To our knowledge, no in-depth studies have been conducted to evaluate how the thermal and optical (e.g. albedo) properties of gravel-sand mulches affect the greenhouse microclimate, in particular with regard to soil and air temperature, radiation balance at ground surface, and heat storage capacity of the mulch and underlying soil layers. These issues are especially relevant to unheated greenhouses located in mild winter climates, where the microclimate, particularly air and soil temperature, is usually suboptimal for winter vegetable production (Bartzanas, Tchamitchian, & Kittas, 2005; López, Baille, Bonachela, Pérez-Parra, 2008). In these greenhouses, the use of soil mulching, such as gravel-sand mixtures, may represent a valuable option to substitute classical heating systems with fossil energy (Baille, López, Bonachela, González-Real, Montero, 2006; Bonachela et al., 2012). However, a deeper insight into the use of gravel-sand mulches in unheated greenhouses is required, particularly in early stages of crop cycles starting in winter (melon, cucumber and tomato), when canopy leaf area is small and most of the soil is uncovered. The use of passive heating systems, such as soil mulching, in unheated greenhouses located in mild winter climates has been highly recommended (Baille et al., 2006; Bonachela et al., 2012; Hernández et al., 2017).

This study focussed on the changes in heat transfer processes between the surface and the underlying soil layers, and on the heat storage/release dynamics in these layers. The objectives of the present experimental work were to characterise *in situ* the extent to which a mulch layer composed of gravel and sand particles (i) alters the surface energy balance and microclimate in an unheated plastic greenhouse, and (ii) modifies the thermal dynamics of the underlying soil layers with respect to a non-mulched soil.

2. Material and methods

2.1 Experiments and greenhouse facilities

Two greenhouse experiments were conducted at the "Palmerillas" research station (Fundación Cajamar, Grupo Cooperativo Cajamar) on the Almería coast, SE Spain. The main experiment was carried out in a three-span, arch-roofed greenhouse of 22.5 m wide and 28 m long. The greenhouse, of 4.5 m high to the ridges and 3.2 m to the eaves, was unheated and passively ventilated with one roof vent per span, and a sidewall rolling vent in the southern and northern sides. All vents, covered with insect-proof screens, were managed manually. The greenhouse, east-west oriented, was covered with a three-layer thermal polyethylene film (200 µm thickness) with a transmissivity of 89% to short-wave radiation and 25% to long-wave radiation (Sotrafa, Almería, Spain). The greenhouse was divided in two equal compartments of 22.5 m × 10 m. In order to minimize climate differences between compartments due to the outside surrounding environment, a 4 m wide buffer zone was maintained between the two compartments. Moreover, a 2 m buffer zone was established at each end of the greenhouse.

Before the start of this experiment, the soil system was identical in both greenhouse compartments: an *enarenado* soil, consisting of a 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 (Soil survey division staff, 2017). With time and use, the dried farmyard manure layer was practically mineralised and disappeared. The top gravel-sand mulch layer presented a bulk density of 1.42 g cm^{-3}, a particle density of 2.53 g cm^{-3} and a total porosity of 0.44.

One day before the start of this experiment (14 January 2009), the gravel-sand mulch layer was entirely removed from one compartment (NM treatment), while it was left intact in the second one (GM treatment, Fig. 1). At the start of this experiment, the vertical temperature profile in the imported soil layer and the original soil layer were therefore practically identical in the two greenhouse compartments. During the experimental period (from 14 to 28 January 2009), the greenhouse remained without crop and the soil was maintained dry. These conditions were representative of the period before and just after crop planting when plantlets have a very low leaf area. Greenhouse vents remained closed from the beginning of the experiment until 25 January, after which they were open during most of daytime.

An additional experiment was carried out during the 2016/17 cropping season in two identical, unheated, plastic greenhouses covered with a three-layer thermal polyethylene film of 200 µm thickness. Both greenhouses had an e*narenado* soil consisting of an imported 0.3 m layer of silty clay loam soil placed over the original sandy loam soil and a 0.1 m mulch layer placed on the imported silty clay loam soil (Granados, Thompson, Fernández, Martínez-Gaitán, Gallardo, 2013). This mulch was composed of fine gravel (85 %) plus coarse (13 %) and fine (2 %) sand particles (Soil survey division staff, 2017). The characteristics of this gravel-sand mixture were not exactly the same as those of the previous experiment, but both mixtures were similar as they were predominantly composed of fine gravel and coarse sand particles. Before the start of this experiment, the soil of one greenhouse was tilled with a plough and the mulch gravel layer was well mixed with the imported soil layer. In both greenhouses, with (GM) and without (NM) a top gravel mulch layer, a typical summer-winter cycle of sweet pepper (*Capsicum annuum* L. cv. Canción) was grown. The crop, which was transplanted at a density of 2.5 plants m^{-2}, started on the 28/08/2016 and ended on the 8/03/2017.

2.2 Measurements and calculations

2.2.1 Experiment without crop

Soil temperature was measured with Pt-100 reference thermistors (T107, Campbell Scientific Ltd., Delft, The Netherlands) and soil heat flux with flux plates (HFP01, Campbell Sci., Delft, The Netherlands). Sensors in the GM treatment were buried in the upper (0.01 m depth), middle (0.05 m) and lower (0.1 m) parts of the top mulch 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), whereas in the NM treatment the sensors were buried at 0.01 m, 0.05 m and 0.1 m depth of the imported soil layer, in the middle (0.15 m depth) of this layer and in the upper part of the original soil (0.35 m depth, Fig. 1). In both soil treatments, there were no heat flux plates in the upper part of the original soil. By convention, the soil heat flux, G, measured by the flux plates was considered positive when directed downwards and negative when directed upwards. Assuming that the reference level (z = 0) was the surface of the NM soil, the measurements in the gravel layer of the GM treatment corresponded to z = +0.05 and +0.10 m, the latter corresponding to the surface of the gravel layer (Fig. 1).

For soil heat storage calculations, the 0.35-m layer of explored depth in NM was divided into seven consecutive sub-layers of 0.05 m thickness (L_0 to L_{-6}) , while the explored 0.45-m depth layer in GM was divided into nine sub-layers (L_2 to L_{-6}) (Fig. 1). In NM as in GM, the sub-layer L_0 corresponded to the layer 0 > z > –0.05 m of the imported soil and sub-layers L_{-1} to L_{-6} referred to the six sub-layers beneath L_0 until the depth of 0.35 m. Sub-layers L_1 and L_2 corresponded to the lower and upper 0.05 m of the mulch layer, respectively (Fig. 1). Temperature in layers where measurements were not performed (at –0.20, –0.25 and –0.30 m in NM; at –0.05, –0.10, –0.20, –0.25 and –0.30 m in GM) were estimated by linear interpolation between the values measured in the adjacent layers.

Air dry and wet bulb temperatures were measured inside the greenhouse at 0.30 m height aboveground with ventilated capacitance psychrometers (mod. 1.1130, Thies Clima, Göttingen, Germany). Net radiation (R_n) at the ground/mulch surface was measured with a set of radiation sensors (CNR1, Kipp&Zonen, Delft, The Netherlands) located 0.30 m aboveground in each greenhouse compartment. These sensors provided measurements of incident short-wave radiation, S, its reflected component, S_r, and downward and upward long-wave radiation, L_d and L_u, respectively. The net radiation at the ground/mulch surface, R_n, was calculated as the sum of net short-wave ($S_n = S - S_r$) and net long-wave ($L_n = L_d - L_u$) radiation. The surface albedo, a, was obtained as $a = S_r/S$. Data were taken at 2-s intervals, averaged every 5 min and registered by data logging devices (mod. CR1000 and CR3000, Campbell Scientific Inc., Logan, UT, USA). Outdoor weather data were measured in an automatic meteorological station (AWOS 7770, Thies Clima, Göttingen, Germany) located on bare land about 100 m away from the experimental greenhouse.

Soil evaporation, E_s, was estimated by the soil water balance method. The volumetric soil-water content (m^3 m^{-3}) was measured over the observation period with a TDR system (TRASE 6005X1, Soil Moisture Corp., Santa Barbara, CA, USA). At each treatment, eight TDR probes of 30 cm length were randomly installed in the soil. They were inserted vertically in the loamy soil layer (Fig. 1). The mulch layer of the GM soil system was practically dry over the observation period.

2.2.1.1 Calculation of heat storage in the soil layers. The change in sensible heat content, Q_i, of each layer was calculated from the calorimetric equation (Eq. 1):

$$Q_i = V_i \, C_i \, \Delta T_i \qquad (1)$$

where i is the layer index, V_i the volume of the layer (m^3 m^{-2}) , C_i (MJ m^{-3} K^{-1}) the thermal volumetric capacity of the material of layer i, and ΔT_i (K^{-1}) the change in temperature of layer i during the considered time step. The thermal volumetric capacity considered was 1.70 MJ m^{-3} K^{-1} for the gravel material (Singh et al., 2010), 1.44 MJ m^{-3} K^{-1} for the dry loamy soil (De Vries, 1963; Kustas & Daughtry, 1990) and 4.18 MJ m^{-3} K^{-1} for water. Q_i values were calculated at 5-min intervals for each layer, and subsequently summed to provide mean hourly (Q_h, MJ m^2 h^{-1}) and the total energy stored/released over the period of observation.

2.2.1.2 Checking soil heat flux data. Measurements of soil heat flux by means of flux plates could lead to large experimental errors (Heuksinveld, Jacobs, Holtslag, Berkowicz, 2004; Ochsner, Sauer, Horton, 2006). We first checked the reliability of these sensors and the coherence of their flux data, with special focus on the surface soil heat flux (G_s), by using the combination method (Fuchs & Tanner, 1966; Kustas & Daughtry, 1990). This method combines soil calorimetry (section 2.2.1.1) and G measurements at a reference depth (in our case, the flux plate located at 5 cm below the surface). We tested the coherence of G data by calculating the daily integral of G at different depths and summing over the whole observation period. For the GM soil system, the comparison was rather satisfactory, as far as the sum of daily integrals of G_s and G at other depths supplied by the combination method were within 20 % of the values provided by the heat-flux plates. For the NM soil system the agreement was less satisfactory, as the G_s integral obtained by means of the combination method was more than twice the integral obtained from the flux plate at 1 cm depth. This was because small but systematic differences at a daily scale could lead to large cumulated errors over the observation period. We, therefore, discarded the flux measurements made at 1 cm depth, and chose the combination method with flux plate data at 5 cm depth as reference for both, the NM and GM soil systems. This provided the most reliable and coherent flux data set with respect to surface energy balance, soil temperature and heat storage in the different soil layers.

2.2.2 Crop experiment

The soil temperature profile in the cropped greenhouses with (GM) and without a top gravel layer (NM) was measured with Pt-100 reference thermistors (T107, Campbell Scientific Ltd.). Sensors were buried in the upper (0.05 m depth), middle (0.15 m) and lower (0.25 m) parts of the imported soil layer, and in the upper part of the original soil layer (0.40 m) in both greenhouses. These depths correspond to measurements taken from the bottom of the mulch layer for the greenhouse with GM, while they correspond to measurements taken from the ground surface for the greenhouse with NM. Thermistors were also installed at 0.01 m depth from the mulch/ground surface at both greenhouses. Measurements were taken twice, below a plant row and between two contiguous plant rows.

3. Results

3.1. Experiment without crop

3.1.1. Surface energy partitioning

3.1.1.1. Net radiation. The NM surface received more radiative energy than the GM surface. Over the observation period, the integral of R_n was 28.6 MJ m^{-2} for NM and 6.7 MJ m^{-2} for GM, that is, a difference of +21.9 MJ m^{-2} in favour of NM. On 24 h-average, daily R_n in GM was approximately 23 % of R_n in NM (Table 1). This large difference has to be ascribed (i) to greater losses by long-wave radiation at the GM surface when compared to the NM surface, and (ii) to greater albedo, *a*, of the GM (0.33) compared to the NM (0.17) surface (Table 1). It should be noted that greater albedo of GM led to greater solar radiation incidence on the surface in GM (Table 1) due to multiple reflections between surface and cover. There was a moderate correlation (R^2 = 0.36) between the daily R_n integrals in GM and NM ($R_{n,GM}$ = 0.36 $R_{n,NM}$ – 0.24; Fig. 2)

3.1.1.2. Soil heat flux. Daily integrals of the soil surface heat flux, G_s (MJ m^{-2} d^{-1}), in NM and GM were better correlated ($G_{s,GM}$ = 0.72 $G_{s,NM}$ + 0.11; R^2 = 0.77) than corresponding R_n values (Fig. 2). Mean daily G_s over the observation period was –0.48 ± 0.46 and –0.24 ± 0.37 MJ m^{-2} d^{-1} in NM and GM, respectively (Table 1). The negative sign of G_s indicated that the soil contributed to heat the greenhouse atmosphere in both soil systems. The total energy transferred from the soil surface of NM to the atmosphere during the observation period (7.17 MJ m^{-2}) was about twice the amount released by GM (3.54 MJ m^{-2}). The high standard deviation associated with the mean values (Table 1) indicated that daily G_s fluctuated considerably in both soil systems due to variable weather conditions. The daily G_s/R_n ratio, which underwent a similar high temporal variability, was –0.25 in NM and –0.53 in GM, indicating that, on a daily scale, the magnitude of the soil surface heat flux with respect to R_n was relatively small in NM (≈ 25%) and relatively high in GM (≈ 53%).

3.1.1.3. Latent and sensible heat flux. Volumetric soil-water content hardly changed in the GM soil system over the measured period: 0.228 ± 0.021 m^3 m^{-3} on January 15, 0.232 ± 0.011 m^3 m^{-3} on January 23 and 0.230 ± 0.014 m^3 m^{-3} on January 28. Therefore, evaporation in this soil system was minimal and the mean daily latent heat flux at the soil surface can be assumed negligible with respect to the other fluxes. By contrast, volumetric soil-water content in the loamy layer of the NM soil system clearly decreased over the measured period (from 0.256 ± 0.014 m^3 m^{-3} to 0.227 ± 0.012 m^3 m^{-3}), leading to a water loss of 8.7 mm. This is equivalent to a mean daily latent heat flux, E_s, of 1.65 MJ m^{-2} d^{-1}, assuming most evaporation occurred on the soil surface (Xiao, Horton, Sauer, Heitman, Ren, 2011). The sensible heat flux, H_s, can be derived as the residual term of the surface energy balance (Eq. 2):

$H_s = R_n - E_s - G_s$ (2)

Mean daily H_s was 0.68 MJ m^{-2} d^{-1} in GM and 0.74 MJ m^{-2} d^{-1} in NM (Table 1).

3.1.1.4. Day/night energy partitioning. The daily integral of soil surface heat flux was also calculated during the periods with $R_n > 0$ and $R_n < 0$, which correspond approximately to the daytime and night period, respectively (Table 2). During daytime, the mean R_n value in GM (1.94 MJ m^{-2} d^{-1}) represented approximately 60% of the value observed in NM (3.27 MJ m^{-2} d^{-1}), while the corresponding mean G_s value in GM (1.54 MJ m^{-2} d^{-1}) was approximately 21% greater than that found in NM (1.27 MJ m^{-2} d^{-1}). During the night, mean radiative loss was slightly lower in NM (–1.36 MJ m^{-2} d^{-1}) than in GM (–1.49 MJ m^{-2} d^{-1}). These radiative losses were more than compensated by a heat supply from the soil surface (G_s) of –1.75 and –1.77 MJ m^{-2} d^{-1} in NM and GM, respectively. These values indicated that the two surfaces released a similar amount of energy during the night. The residual term of equation 2, H_s, in the GM soil system was therefore positive for both periods: 0.40 MJ m^{-2} d^{-1} at daytime and 0.28 MJ m^{-2} d^{-1} at night (Table 2).

3.1.1.5. Daily pattern of surface fluxes. Time evolution of radiative surface fluxes at 5-min time intervals throughout a typical clear day (21 January) is presented in Fig. 3. As mentioned above, R_n was substantially lower in the GM than in the NM soil system throughout daytime. The maximum R_n value in the GM occurred at around 10:30, decreasing rather sharply thereafter (Fig. 3). Moreover, R_n became negative approximately one hour earlier in GM than in NM. The main cause for the lower R_n in GM was, besides its greater albedo (Table 1), the greater magnitude of net daytime long-wave radiation (L_n) in GM than in NM. The difference in L_n between the GM and the NM soil systems reached *circa* 60 W m^{-2} near noon (Fig. 3).

In contrast to R_n, the daily time course of G_s followed a similar pattern in NM and GM (Fig. 3). The main difference was the higher peak value of G_s in GM (about 130 Wm^{-2} in GM and about 90 Wm^{-2} in NM for the selected day), generally occurring in the morning near noon. During the afternoon G_s values were slightly lower in GM than in NM, while the opposite occurred at night (values of about –50 W m^{-2} for NM on the selected day).

3.1.2. Soil and air temperature

3.1.2.1. Soil temperature profiles. The vertical profile of soil temperature at the beginning and end of the observation period is shown by Figure 4a. The mean daily temperature in the imported soil layer was 18.1 ºC for GM and 18.0 ºC for NM at the beginning of the experiment (14/01), increasing to 19.4 ºC for GM and decreasing to 17.8 ºC for NM at the end of the observation period (28/01). That is, over the observation period, the average soil temperature increased +1.3ºC in GM, but decreased –0.2ºC in NM, resulting in a net gain of +1.5ºC for GM with respect to NM.

Moreover, soil temperature was higher inside than outside the greenhouse. Over the observation period, the mean daily temperature in the middle of the imported soil layer (at –0.15 m) of the GM and NM greenhouse soil systems was between 4 and 6 ºC greater than at the same soil depth outdoor (Fig. 4b). Similar results were found at –0.30 m depth (data not shown). In addition, the fluctuation of mean daily soil temperatures was clearly lower in greenhouse compartments than outdoors (Fig. 4b).

3.1.2.2. Daily pattern and diurnal temperature range of soil temperature. The temperature near the ground surface (at 0.01 m depth), T_s, was greater in GM than in NM during most of the daytime, especially for clear sky days (Fig. 4c). The opposite was found at night, with T_s

values approximately 2 ºC lower in GM than in NM. Consequently, the daily T_s temperature range, DTR_{Ts} (= $T_{s,max} - T_{s,,min}$), reached values that were approximately twice as great in GM than in NM, as shown by Fig. 4c for a clear sky day: DTR_{Ts} was about 26 ºC in GM and about 13 ºC in NM. Moreover, analysis of the DTR at greater soil depths indicated that the thermal wave in the middle of the imported soil layer (at –0.15 m) fluctuated less in GM than in NM (Fig. 4b).

3.1.2.3. Air temperature. Air temperature at 0.3 m aboveground, T_a, was greater in the GM than in the NM greenhouse compartment during daytime, with maximum differences of about 5 to 6 ºC near noon when greenhouse vents were closed (Fig. 5). The opposite occurred at night, when T_a was about 2 ºC lower in the GM greenhouse compartment. These differences were smaller when vents were open during daytime (Fig. 5). On a daily scale, the mean T_a averaged over the observation period was similar in both greenhouse compartments: 18.2 ºC in GM and 18.4 ºC in NM.

It should also be noted that high positive differences, up to +8 ºC, were found between T_a and T_s in GM during a large part of the morning (data not shown), suggesting that during this period there was a large temperature gradient in the upper centimeter of the mulch, probably close to or exceeding 10 ºC.

3.1.3. Soil heat storage/release

3.1.3.1. Period-averaged profile of heat storage at different hours of day. During the night (at 00:00 and 20:00 hours, Fig. 6), the gravel top mulch substantially slowed down the rate of heat loss of all underlying layers, while during daytime the reverse occurred. At sunrise (07:00 h), there was a much steeper increase in stored heat in the 0.1-m gravel layer compared to the 0.1-m top layer of the NM soil system, while the opposite was found at sunset (17:00 h). The maximum storage rate was observed at early morning (near 9:00 h) for both soil systems, with values close to 300 and 150 kJ m^{-2} h^{-1} in the surface layer of GM and NM, respectively. At noon, the storage rate was lower than at early morning (Fig. 6).

Vertical distribution of the heat storage/release accumulated over the observation period in each soil sub-layer (MJ m^{-2} per layer) indicated that the GM soil system presented a positive storage for all the sub-layers (Fig. 7a), which corresponds to the higher temperatures found in all the soil sub-layers at the end of the observation period (Fig. 4a). This trend contrasted with that observed for NM, where there was a small positive heat storage in the first three sub-layers, but a negative heat storage in the sub-layers underneath (Fig. 7a).

3.1.3.2. Profile of accumulated heat storage/release. Integrating over the vertical soil profile, the total heat storage was −0.07 MJ m^{-2} in NM and +1.03 MJ m^{-2} in GM (Fig. 7b). In the latter, 0.67 MJ m^{-2} were stored in the imported soil and 0.36 MJ m^{-2} in the 0.1 m mulch layer. That is, the mulch layer and the imported soil layer contributed to approximately 35% and 65% of the total heat stored in GM.

3.1.3.3. Heat extracted from the deep layers. Extracted heat from the original soil layer was calculated by adding to G_s the heat stored in all sub-layers above 30 cm depth, taking into account the heat stored in the water retained in these soil layers. Heat stored in the water retained above 30 cm depth was −0.06 MJ m^{-2} in NM and +0.38 MJ m^{-2} in GM. Therefore, over the observation period, the total energy extracted from the soil layers deeper than 30 cm (that is, from the original soil) was 7.11 and 4.89 MJ m^{-2} for NM and GM, respectively. These data correspond to a daily mean extraction rate of 0.47 MJ m^{-2} d^{-1} in NM and 0.33 MJ m^{-2} d^{-1} in GM.

3.2. Crop experiment

In the two greenhouses, the soil temperature decreased progressively from the beginning of autumn until practically the end of January (Fig. 8). This trend was observed at all the measured depths of the imported (at 0.05, 0.15 and 0.25 m depth) and the original (at 0.40 m depth) soil layer, regardless of whether measurements were conducted around the plant row or between two contiguous rows (data not shown). During this period, the soil temperature in each greenhouse was generally greater as soil depth increased. Thus, the temperature of the imported soil layer was lower than that of the original soil layer in both greenhouses (Fig. 8). Moreover, the temperature measured at each monitored depth of the greenhouse without gravel mulch was lower than that measured at the corresponding depth of the greenhouse with a top gravel mulch (Fig. 8). Thus, the mean temperature measured from October to January was 19.2 and 18.0 ºC for the imported soil layer (average of measurements at 0.05, 0.15 and 0.25 m depth) of the greenhouse with GM and NM, respectively, and 20.3 and 18.7 ºC for the corresponding original soil layers.

From the end of January the temperature of imported and original soil layers started to increase gradually in both greenhouses, and the temperature differences between soil layers and between greenhouses decreased substantially, almost disappearing in some cases (Fig 8). Thus, the mean temperature measured in February was 17.0 and 16.9 ºC for the imported soil layer of the greenhouse with GM and NM, respectively, as compared to 17.0 and 16.7 ºC for the corresponding original soil layers.

4. Discussion

4.1. Impact of the gravel mulch on the surface energy balance

4.1.1. Mulch impact on the net radiation

Correlation between net radiation at the ground of the GM and NM soil systems in the greenhouse experiment without crop was rather weak (Fig. 2). This was attributable to the differences in albedo and surface temperature between both soil systems. The greater albedo of GM, compared to NM (Table 1), has a negative effect on S_n, even though part of the reflected short-wave radiation was redirected by the greenhouse cover towards the mulch surface, meaning GM received somewhat more global solar radiation than NM (Table 1). The average reduction of S_n in GM due to its greater albedo represented approximately 11 % of the S_n received in NM (Table 1). Even more substantial was the effect of the greater T_{surf} on the upward long-wave radiation in GM, and consequently on the L_n, which was approximately 50% greater (more negative) in GM than in NM (Table 1). This was ascribed to the rapid heating of the surface of the gravel layer during the morning, and to the maintenance of high surface temperature differences with respect to NM during most of daytime, as illustrated by the daily pattern of the L_n in NM and GM (Fig. 3). In absence of direct T_{surf} measurements, soil temperature at 0.01 m depth can be used as a surrogate. However, this approximation might lead to large errors in a low heat conductivity medium, like gravel. We can also use L_n data as surrogate for T_{surf} estimation. The difference in L_n between the GM and the NM systems reached *circa* 60 W m^{-2} near noon during a clear sky day (Fig. 3), which might represent a difference of soil surface temperature of approximately 12 ºC, assuming a radiative heat transfer coefficient of 5 W m^{-2} K^{-1} (Nijskens, Deltour, Coutisse, Nisen, 1984).

All together, the greater albedo and surface temperature in GM led to a decrease of R_n of 1.33 MJ m^{-2} d^{-1}, on average over the daytime period ($R_n > 0$, Table 2), of which 0.41 MJ m^{-2} d^{-1} was due to albedo and the remaining 0.90 MJ m^{-2} d^{-1} to surface temperature. On daily scale, the net radiation in GM (0.44 MJ m^{-2} d^{-1}) was only about 23 % of the value measured in NM (1.91 MJ m^{-2} d^{-1}). Thus, regarding the daily available radiative energy the surface of the NM soil system presented a clear advantage over the GM system. However, the greater albedo of GM might increase the available photosynthetically-active radiation available to the crop (Lorenzo, Sánchez-Guerrero, Medrano, Soriano, Castilla, 2005), which might represent an advantage of GM over NM in periods of low radiation, such as the winter season in Mediterranean climates.

4.1.2. Mulch impact on G_s and H_s

The partitioning of R_n between sensible and latent convective fluxes, and conductive heat flux was based on the assumption that evaporation in the NM soil system mostly occurred in the soil surface (Xiao, Horton, Sauer, Heitman, Ren, 2011). Evaporation in the GM soil system was considered negligible with respect to the other fluxes because the soil water content hardly changed during the observation period. From the results presented in Tables 1 and 2, we can highlight the following:

(i) Daily G_s values in NM and GM were positively correlated ($R^2 = 0.77$, Fig. 2), indicating that both fluxes varied in the same direction, independently of outdoor conditions. In both soil systems, G_s was only moderately correlated to R_n ($R^2 \approx 0.45$, data not shown), suggesting that G_s was mostly driven by the dynamics of heat conduction in the underlying soil layers, and the temperature gradient in the upper soil layers.

(ii) Mean daily G_s was slightly negative (−0.48 and −0.24 MJ m^{-2} d^{-1} for NM and GM, respectively, Table 1), indicating that both systems were supplying heat to the greenhouse environment. The NM soil system lost more energy compared to the GM system. However, the relative contribution of G_s to the surface available radiative energy was rather small in NM, as indicated by the G_s/R_n ratio (= −0.25). The relative contribution of G_s to the surface available radiative energy in GM was greater (G_s/R_n = −0.53).

(iii) During the diurnal period ($R_n > 0$), in absolute terms, GM collected about 0.27 MJ m^{-2} d^{-1} more than NM (mean G_s values of 1.54 and 1.27 MJ m^{-2} d^{-1}, respectively, Table 2), but the G_s/R_n ratio (i.e. the storage efficiency of the soil system) was equal to 0.39 and 0.79 for NM and GM, respectively. This indicates that GM was much more efficient in absorbing and storing the available radiative energy. In desert climates, the diurnal average of G_s/R_n was generally found to range between 0.20 and 0.60 (Santanello & Friedl, 2003; Singer & Martin, 2008).

(iv) At night ($R_n < 0$), G_s values indicated that each surface delivered approximately the same amount of energy to the greenhouse atmosphere (Table 2) for compensating for the greenhouse nocturnal losses.

(v) Sensible heat flux in the GM soil system was slightly greater during daytime (0.40 MJ m^{-2} d^{-1}) when compared to night (0.28 MJ m^{-2} d^{-1}, Table 2), and during both periods the GM surface delivered sensible heat flux to the greenhouse atmosphere.

To summarize, the GM soil system was more effective than the NM system in capturing and storing available radiative input, as previously found under open field conditions (Li, 2003; Xie et. al., 2010). One explanation might be the very large variation in the surface temperature in GM during the diurnal period (section 4.1.1; Li, 2003; Xie et al., 2010). On this point, more insight would be required into the heat conduction processes occurring in the surface sub-layer 0-0.01 m, and their role in the storage and transmission of heat towards the lower part of the mulch layer. A further point to clarify would be the influence of the 'fractal' nature of the gravel mulch surface, whose particles present a rougher surface than the smooth NM. In other words, the larger effective area of the GM surface might also contribute to greater storage efficiency.

4.2. Impact of the gravel mulch on soil evaporation

The gravel-sand mulch also acted as an effective water barrier by minimizing greenhouse soil evaporation and, therefore, latent heat losses, as previously found in studies carried out under field conditions (Nachtergaele et al., 1998; Xie et al., 2006, 2010). Compared to other heat fluxes, the latent heat loss in the GM soil system was practically negligible, as the soil water content of the imported soil layer hardly changed over the observation period and the gravel mulch layer was dry (section 3.1.1.3). However, at the surface of the NM soil system most of the available radiative energy (about 1.65 MJ m^{-2} d^{-1}) was used in the evaporation process. This process also contributed to the lower daytime soil surface temperatures found in the NM soil system, as was found under open field conditions (Lü et al., 2013).

4.3. Impact of the gravel mulch on greenhouse aerial microclimate

4.3.1. Air temperature

Values of T_a, the greenhouse air temperature around low-height vegetable crops or tall crops at their early stages, were greater in GM than in NM during daytime, especially on clear sky days when greenhouse vents were closed (Fig. 5). T_a values reached up to 35 ºC in the GM greenhouse compartment and up to 30 ºC in the NM one (data not shown). These differences, which were higher than those found under open field conditions (Li, 2003), could be attributed to the greater daytime surface temperature in the GM soil system (section 4.1.1, Bonachela et al., 2012; Li, 2003) and to the low ventilation rate of naturally-ventilated greenhouses. However, the greenhouse air temperature during the night was about 2 ºC greater in NM than in GM (Fig. 5). This result was supported by the T_s values, which were about 2 ºC higher in NM during most of the night (Fig. 4c), and by the differences in night-time L_n losses, which were lower in NM (Table 2), suggesting that the night soil surface temperature was higher in NM. On the daily scale, T_a was similar in NM and GM (section 3.1.2.3). Hence, the greenhouse air temperature regime might be considered similar for the NM and GM systems regarding vegetable growth, as most growth processes respond to the long-term integration of air temperature (De Koning, 1990). Lower air temperatures at night in the GM soil system were compensated by higher air temperatures at daytime, when crop photosynthesis occur. Notwithstanding, the lower night air temperatures might be problematic in some greenhouse areas with winter night-time air temperatures close to freezing (López, Baille, Bonachela, Pérez-Parra, 2008). Hence, the GM soil system accentuated the desert characteristics of non-cropped greenhouses, amplifying the daily temperature range of air temperature, and of the soil layer near the surface (Figs. 3 and 4c). Moreover, the GM soil system reduced the daily temperature fluctuation in the layers underneath the surface more than the NM system (Fig. 4b).

4.4. Impact of the gravel mulch on greenhouse soil temperature

Higher soil temperatures in gravel-sand mulches, compared to non-mulched soils, have been previously observed in studies carried out under open field conditions (Li, 2002 and 2003;

Xie et al., 2010). The measurements carried out in our study in greenhouses with and without crop (Figs. 4 and 8) confirm this result for winter Mediterranean conditions when the dominant source of energy in the soil root-zone was the heat from deeper soil layers.

On the other hand, the mean daily soil temperature was between 3 and 6 ºC greater in both greenhouse compartments (NM and GM) when compared to outdoors (Fig. 4b). Besides, the amplitude range of the mean daily temperature was substantially lower in both greenhouse compartments than outdoors (Fig. 4b). Hence, it appears that the greenhouse increased the seasonal soil heat storage and damped the heat wave amplitude in the soil.

The soil temperature profile, and the heat storage and extraction rate found in the GM greenhouse soil (section 3.1.3) can be ascribed in great part to the low heat conductivity of the gravel mulch, k_{GM}, compared to that of the imported loamy soil. Values of k_{GM} for gravel mulch reported in the literature ranged from 0.18 W m^{-1} K^{-1} (Singer & Martin, 2008) to 0.46 W m^{-1} K^{-1} (Montague & Kjelgren, 2004). Differences in k_{GM} likely depend on the diameter of particles and type of mixture (Xie et al., 2010). Heat conductivity of the loamy soil could be estimated to range between 1.0 and 1.50 W m^{-1} K^{-1}. In our study, the mulch thermal conductivity played a determinant role in the dynamics of heat transfer throughout all the explored layers, but probably also at deeper soil horizons. The low value of k_{GM} indicates that the mulch acted as an efficient insulating material or heat barrier (Lie, 2003; Xie et al., 2010). In winter, as the dominant energy supply came from the deeper soil layers, the heat barrier had a greater influence on upward fluxes (the heat was extracted from the deeper soil horizons mostly during the night-time, Fig. 6) than on downward fluxes (there was heat transmitted from the mulch to the underlying layer during daytime). Hence, the mulch decoupled substantially the underlying layers from the surface conditions, making the former less sensitive to changes in the surface energy balance and surface temperature, and more dependent on the temperature gradients prevailing in the deep soil layers. Thus, the gravel mulch improved significantly the storage of the heat extracted from the lower soil layers (original soil) within the imported soil layers (Figs. 6 and 7). The non-mulched soil did not benefit from such a heat barrier, and the relatively high thermal conductivity of the imported loamy soil made the first 0-0.30 m a mere free-transmission zone where practically no heat flux divergence occurred (Fig. 7). The heat extracted from the original soil layer was greater in NM than in GM (section 3.1.3.3). Most of this energy was transferred to the greenhouse atmosphere in the NM soil system, and contributed to heat the greenhouse atmosphere, especially at night, leading to higher nocturnal air temperatures in NM than in GM (Fig. 5). Hence, the NM soil system was more efficient than the GM soil system as a passive system to heat the greenhouse air at night, while the GM soil system was more efficient than the NM in heating the soil root-zone and increasing the daytime T_a. This also explains why the low amount of available radiative energy at the surface of GM (about 23 % of the net radiation in NM) had only a weak influence on the heat transfer processes in the underlying layers.

Heating the soil root-zone by using a top gravel mulch layer in an unheated greenhouse in the Mediterranean winter was confirmed in a summer-winter cycle of sweet pepper crop (section 3.2). From the beginning of autumn until nearly the end of January, soil temperatures progressively decreased at all the studied depths in the greenhouses with crops for both GM and NM soil systems (Fig. 8). In this period, when the main source of energy in the soil root-zone appears to be the heat from deeper soil layers (soil temperatures increased progressively as the depth increased), the gravel mulch layer acted as an efficient heat barrier by slowing down soil energy losses and maintaining higher soil root-zone temperatures compared to the NM soil system (Fig. 8).

Overall, this work present new insight into the impacts of gravel-sand mulches on surface energy balance, soil evaporation, and aerial and soil temperatures of unheated greenhouse crops, which have been analysed and compared with related results under open field conditions. In unheated greenhouses located in areas with mild winter climates and water scarcity, such as the Mediterranean basin, the use of gravel-sand mulches appears to be of interest for increasing daily soil and daytime air temperatures during winter crop cycles, and for reducing crop water requirements by lowering soil evaporation losses. The effects of gravel-sand mulches on growth and productivity of greenhouse vegetable crops with high thermal requirements, such as tomato, sweet pepper, cucumber, etc. (Bartzanas, Tchamitchian, & Kittas, 2005; López, Baille, Bonachela, Pérez-Parra, 2008), are complex because they depend on many interrelated factors: crop species, variety and cycle, crop and greenhouse management, and local weather conditions. The use of gravel-sand mulches in greenhouse crops improved the vegetable production in the few related works found in the literature (Abubaker, Qrunfleh, Hasan, 2014; Hernández et al., 2001; Zhang et al., 2009), but further and more detailed research is required to optimize the use and characteristics of gravel-sand mixtures. Moreover, gravel-sand mulches should be studied in combination with other low-cost, passive heating systems of interest, such as plastic mulches (Bonachela et al., 2012), fixed, water-impermeable screens (Hernández et al., 2017) or water filled plastic sleeves (Mavrogianopoulos & Kyritsis, 1993).

5. Conclusions

This research demonstrates substantial changes in the surface energy balance and soil thermal behaviour when implementing a gravel-sand mulch over the existing soil in an unheated Mediterranean greenhouse at winter. The greater albedo and daytime surface temperature in the GM soil system, compared to the NM soil system, changed the surface energy partitioning, reducing the available radiative energy by about 77 %. Despite this reduction, the temperature in the soil root-zone was higher under the mulch during the winter period, when the heat from deeper soil layers appears to be the dominant energy source. Soil temperature differences were mainly caused by the insulating property of the mulch, which acted as a heat barrier and increased the resistance to heat transmission from deep soil horizons towards the surface. A secondary conclusion was that greenhouse air temperature above the GM soil system fluctuated more strongly than in the absence of the mulch.

Thus, the gravel-sand mulch appears to provide a more suitable soil thermal environment for root growth than non-mulched soils during the winter period when soil temperatures might be frequently below the optimum. Moreover, the gravel-sand mulch reduced soil evaporation and increased the reflected photosynthetically-active radiation towards the plants.

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Table 1. Mean daily (24 h) values (MJ m^{-2} d^{-1}) over the observation period (14/01 to 28/01/2009) of the components of the radiative and energy balance at the surface of the NM and GM soil systems. S = incident short wave radiation, S_n = net shortwave radiation, a = albedo, L_n = net long wave radiation, R_n = net radiation, G_s = soil heat flux, H_s = sensible heat flux at the surface. In parenthesis, standard deviation

	S	***S*_n**	***a***	***L*_n**	***R*_n**	***G*_s**	***H*_s**	***G*_s/*R*_n**
NM	4.75 (± 1.34)	3.92 (± 1.05)	0.17 (± 0.02)	–2.01 (± 0.44)	1.91 (± 0.74)	–0.48 (± 0.47)	0.74	–0.25 (± 0.37)
GM	5.32 (± 1.36)	3.51 (± 0.80)	0.33 (± 0.04)	–3.06 (± 0.68)	0.44 (± 0.41)	–0.24 (± 0.26)	0.68 (± 0.35)	–0.53 (± 0.84)

Table 2. Mean values and standard deviation (MJ m^{-2} d^{-1}) of components of the surface energy balance during daytime ($R_n > 0$) and nighttime ($R_n < 0$). R_n = net radiation; G_s = soil heat flux; H_s = sensible heat flux.

	***R*_n**	***G*_s**	***H*_s**	***G*_s/*R*_n**
Daytime				
NM	3.27 (± 0.93)	1.29 (± 0.51)	-	0.39 (± 0.05)
GM	1.94 (± 0.47)	1.55 (± 0.52)	0.38 (± 0.35)	0.80 (± 0.20)
Nighttime				
NM	-1.36 (± 0.31)	-1.77 (± 0.41)	-	1.31 (± 0.08)
GM	-1.49 (± 0.33)	-1.79 (± 0.47)	0.30 (± 0.09)	1.20 (± 0.08)

Figure captions

Figure 1. Experimental set-up. Numbering and depth of the 5 cm sub-layers considered in the explored soil layers in the NM and GM soil systems. All sub-layers were 5 cm thick. The six 5 cm sub-layers of the imported soil in NM and GM were numbered L_0 to L_{-5}, by descending order. Layer L_{-6} corresponded to the top layer of original soil, and layers L_2 and L_1 to the top and bottom layer of the gravel mulch, respectively. The reference depth (z = 0 cm) was the surface of the imported soil in NM, and the interface gravel/soil in GM. Depths z were numbered starting from $z = 10$ cm (surface of the gravel layer) to $z = -30$ cm (interface imported soil/original soil). El Ejido, Almería, Spain.

Figure 2. Comparisons and regression lines of (i) the daily (24 h-integral) surface net radiation (MJ m^{-2} d^{-1}) in GM ($R_{n,GM}$) and NM ($R_{n,NM}$), (ii) the daily surface soil heat flux (MJ m^{-2} d^{-1}) in GM ($G_{s,GM}$) and NM ($G_{s,NM}$).

Figure 3. Daily time course of (i) net radiation (R_n, continuous lines) and net long wave radiation (L_n, dashed lines) at surface of the NM (thick lines) and the GM (continuous lines) soil systems, (ii) surface soil heat flux (G_s) in the NM (thick line) and GM (thin line) soil system on a clear sky day (21 January 2009).

Figure 4. (i) Mean daily temperature, averaged over the observation period, at different soil depths in the NM (squares) and GM (circles) soil systems (bars are standard deviations); (ii) Mean daily temperature profile in the NM and GM soil systems at the beginning (14/01, close symbols) and the end (28/01, open symbols) of the observation period.

Figure 5. Mean daily soil temperature in the NM (at −0.15 m, squares) and GM (at −0.15 m below the mulch layer, circles) greenhouse soil systems, and outdoor the greenhouse (at −0.15 m).

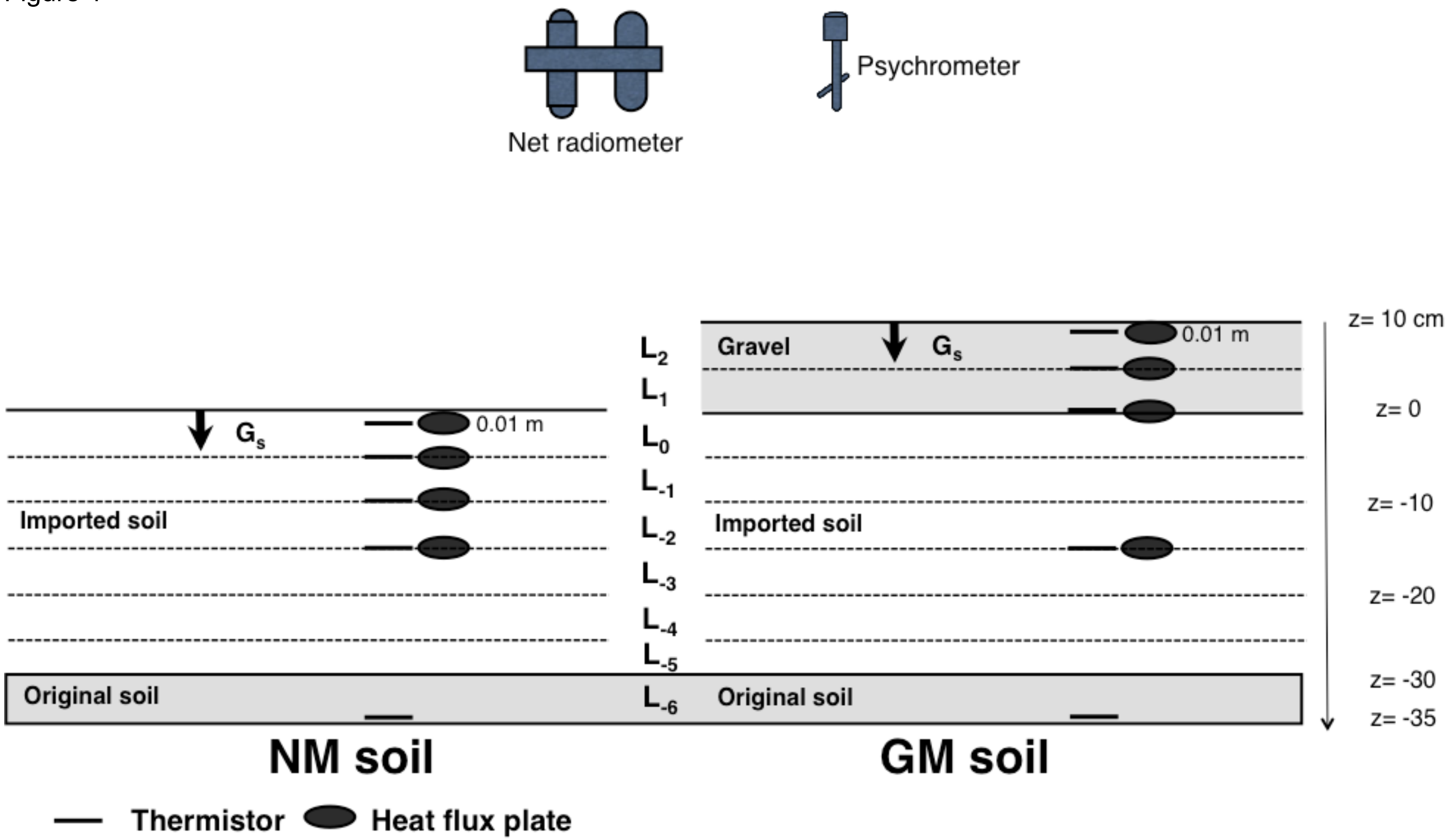
Figure 6. Time course of (i) soil temperature at −0.01 m depth (T_s) for two sunny days (20 and 21/01/09) in GM (thick line) and NM (dashed line), and (ii) soil temperature at −0.15 m depth.

Figure 7. Time course of air temperature difference between the GM and the NM greenhouse compartment for a clear sky day with greenhouse vents closed (21/01) and with vents open during daytime (27/01). Measurements carried at 0.3 m aboveground.

Figure 8. Mean hourly stored heat ($\sum Q_h$, kJ m^{-2} h^{-1}) along the soil profile in the NM (squares) and the GM (circles) soil systems over the period of observation at 00.00, 07:00, 09:00, 12:00, 17:00 and 20:00 hours.

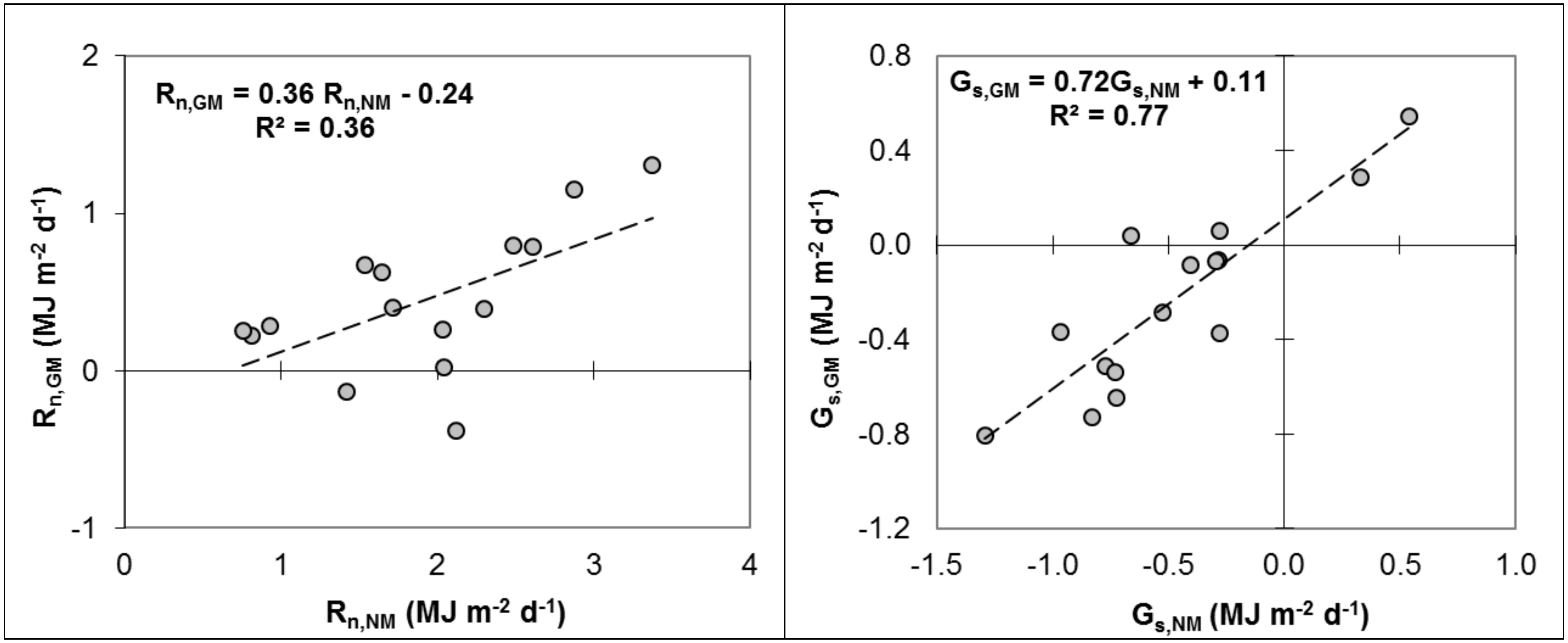
Figure 9. Accumulated heat stored over the observation period in the NM (squares) and the GM (circles) soil systems for each soil sub-layer (ΣQ, MJ m^{-2} layer^{-1}) and for all sub-layers, from the bottom to the top layer.

Figure 1



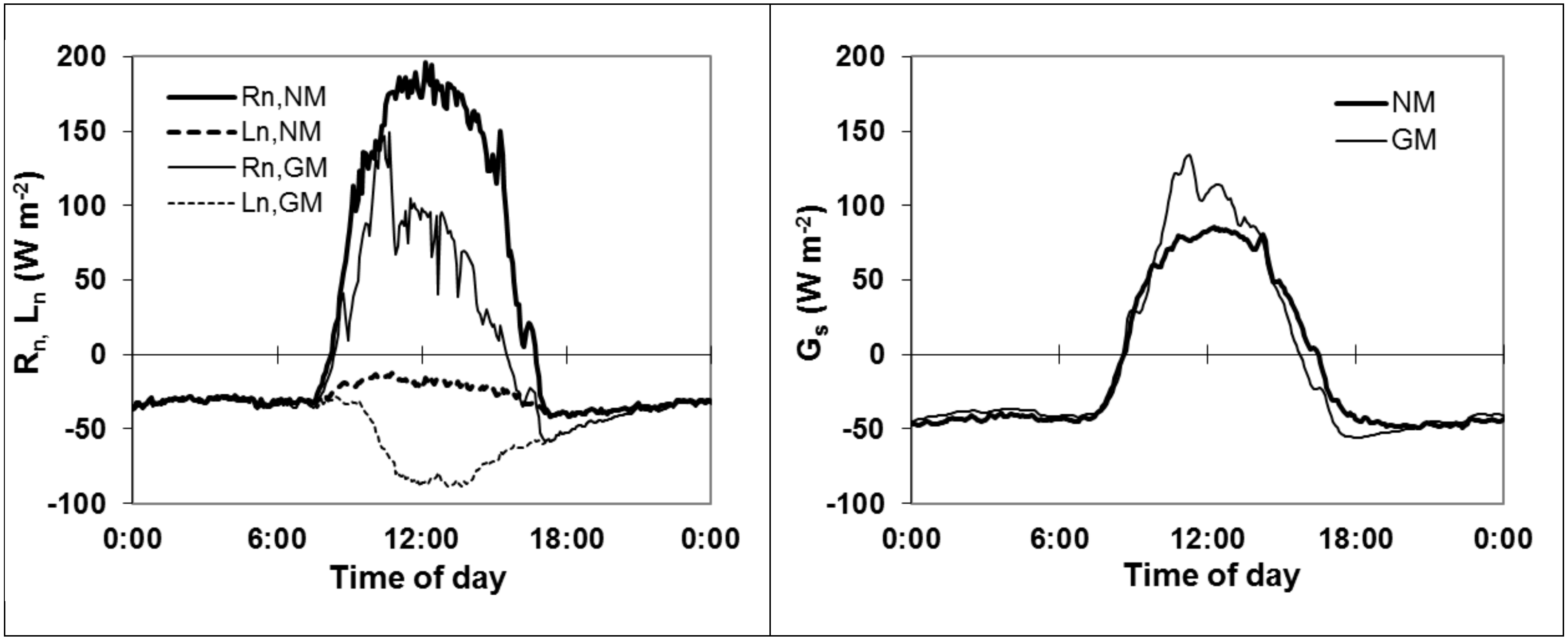
Net radiometer
Psychrometer
Gravel
G_s
0.01 m
G_s
0.01 m
L_2
L_1
L_0
L_{-1}
L_{-2}
L_{-3}
L_{-4}
L_{-5}
L_{-6}
Imported soil
Imported soil
Original soil
Original soil
z= 10 cm
z= 0
z= -10
z= -20
z= -30
z= -35
NM soil
GM soil
Thermistor
Heat flux plate

Figure 2



$R_{n,GM}$ = 0.36 $R_{n,NM}$ - 0.24
R^2 = 0.36
$R_{n,GM}$ (MJ m^{-2} d^{-1})
$R_{n,NM}$ (MJ m^{-2} d^{-1})
2
1
0
-1
0
1
2
3
4
$G_{s,GM}$ = 0.72$G_{s,NM}$ + 0.11
R^2 = 0.77
$G_{s,GM}$ (MJ m^{-2} d^{-1})
$G_{s,NM}$ (MJ m^{-2} d^{-1})
0.8
0.4
0.0
-0.4
-0.8
-1.2
-1.5
-1.0
-0.5
0.0
0.5
1.0

Figure 3



200
150
100
50
0
-50
-100
Rn,NM
Ln,NM
Rn,GM
Ln,GM
Rn, Ln (W m-2)
0:00
6:00
12:00
18:00
0:00
Time of day
NM
GM
Gs (W m-2)
Time of day

Figure 4

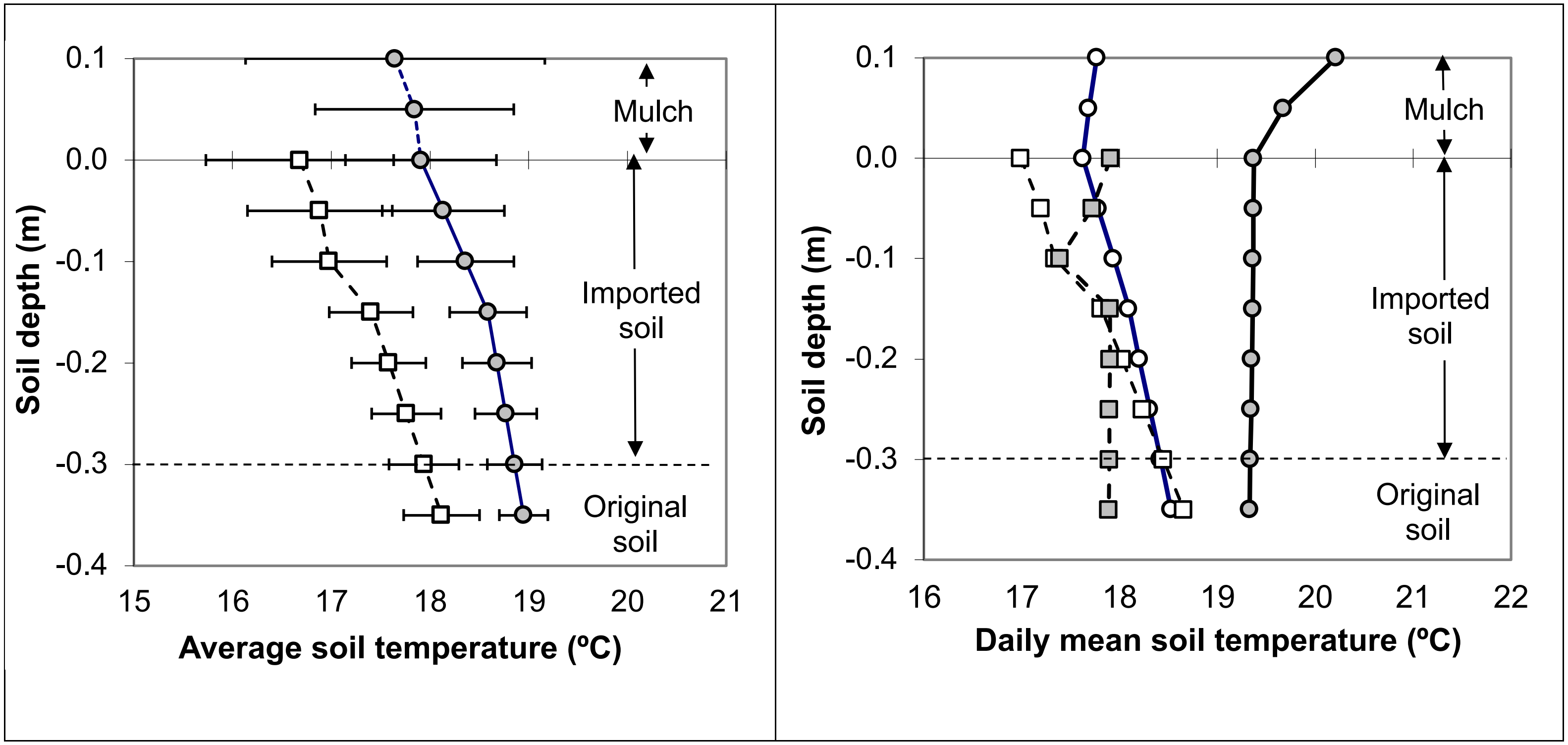

0.1
0.0
-0.1
-0.2
-0.3
-0.4
Soil depth (m)
15
16
17
18
19
20
21
Average soil temperature (ºC)
Mulch
Imported soil
Original soil
0.1
0.0
-0.1
-0.2
-0.3
-0.4
Soil depth (m)
16
17
18
19
20
21
22
Daily mean soil temperature (ºC)
Mulch
Imported soil
Original soil

Figure 5

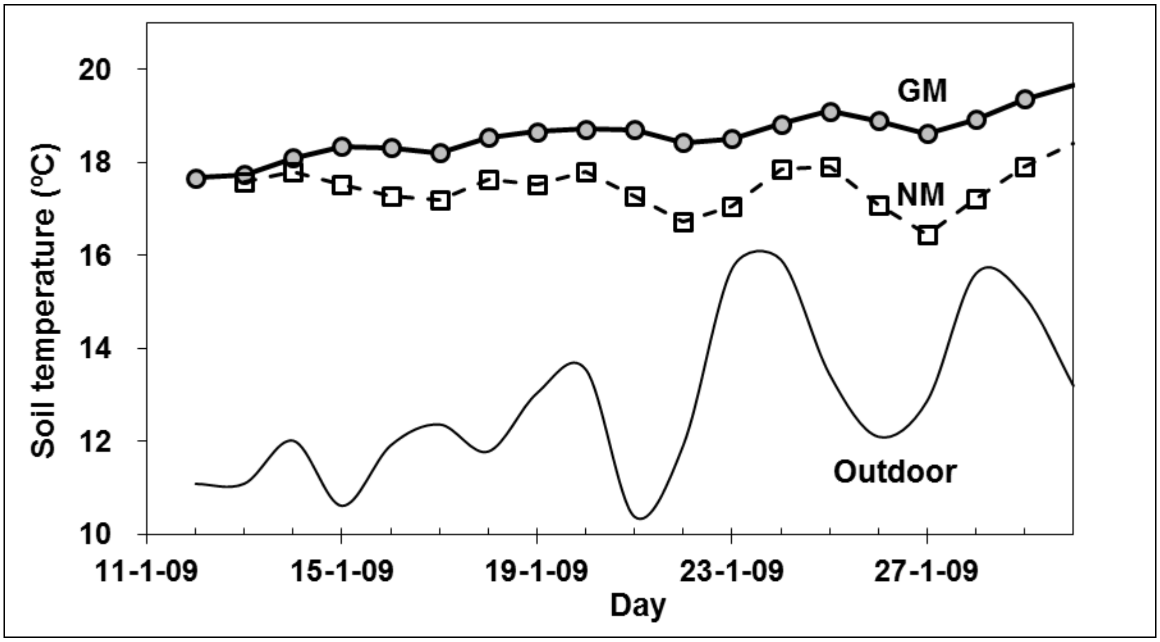
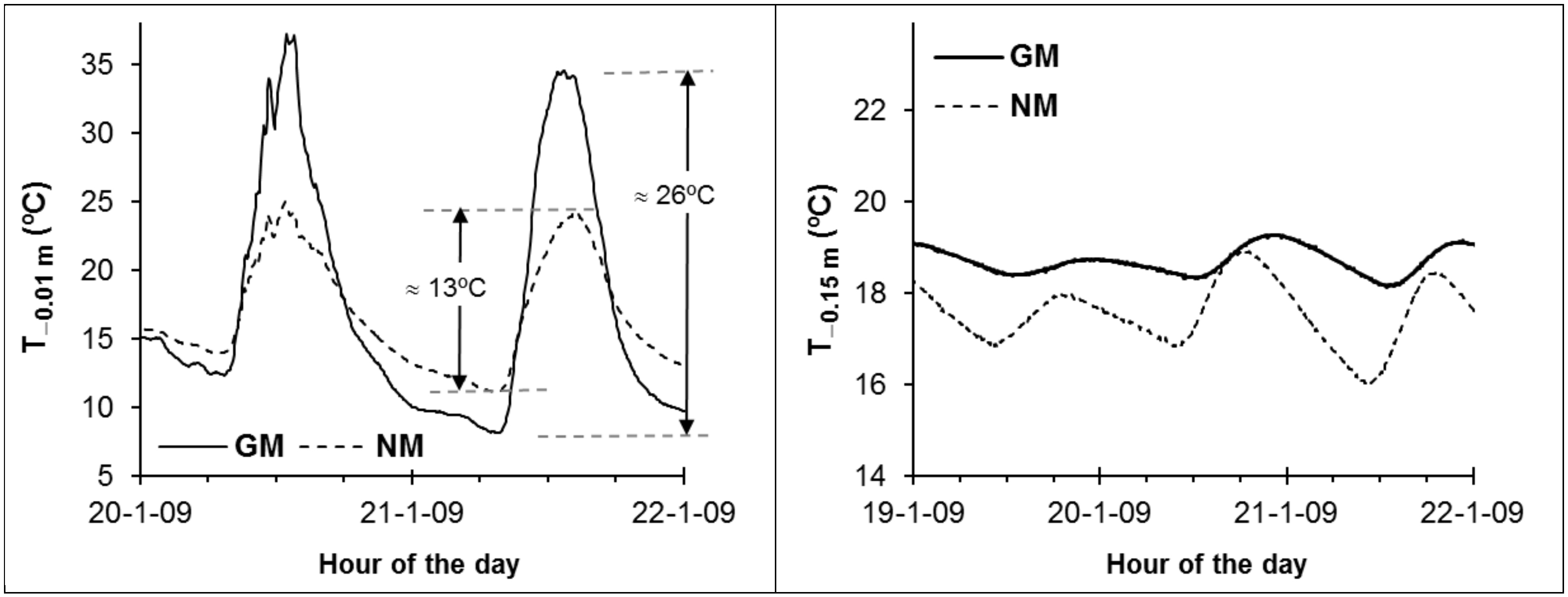

GM
NM
Outdoor
Soil temperature (ºC)
20
18
16
14
12
10
11-1-09
15-1-09
19-1-09
23-1-09
27-1-09
Day

Figure 6



$T_{-0.01\,m}$ (ºC)
35
30
25
20
15
10
5
≈ 13ºC
≈ 26ºC
GM
NM
20-1-09
21-1-09
22-1-09
Hour of the day
$T_{-0.15\,m}$ (ºC)
22
20
18
16
14
19-1-09
20-1-09
21-1-09
22-1-09
Hour of the day

Figure 7

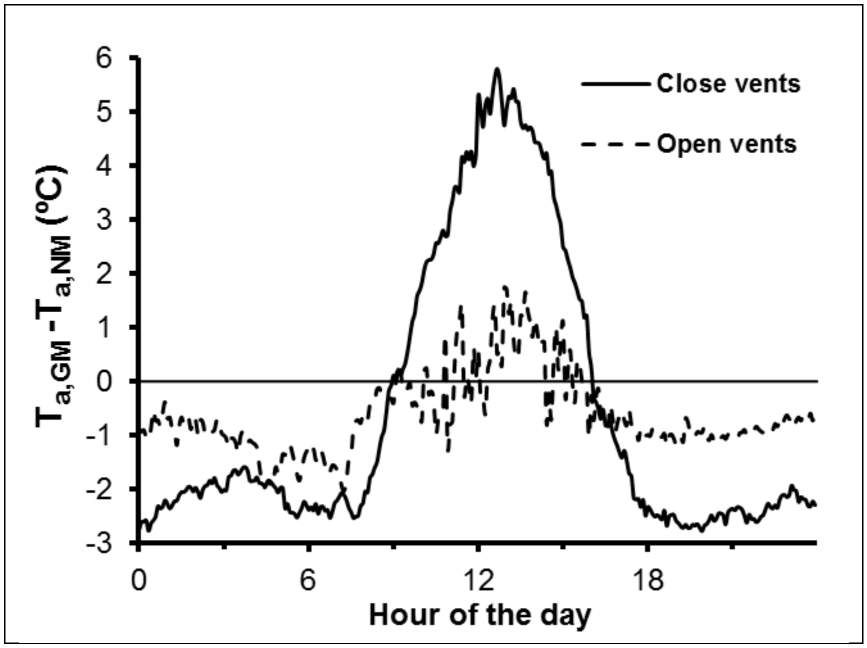

Close vents
Open vents
$T_{a,GM}$ - $T_{a,NM}$ (ºC)
6
5
4
3
2
1
0
-1
-2
-3
0
6
12
18
Hour of the day

Figure 8

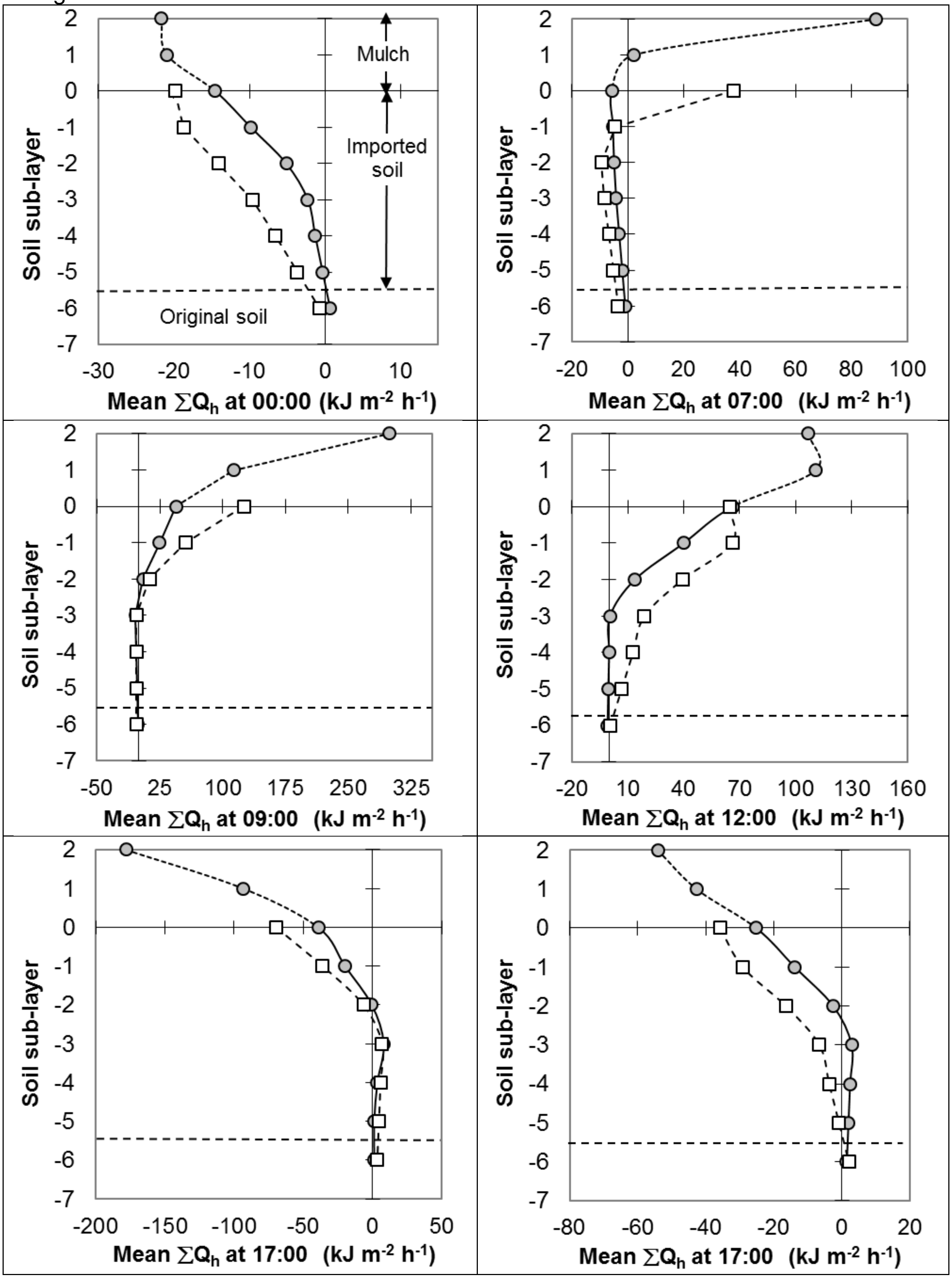
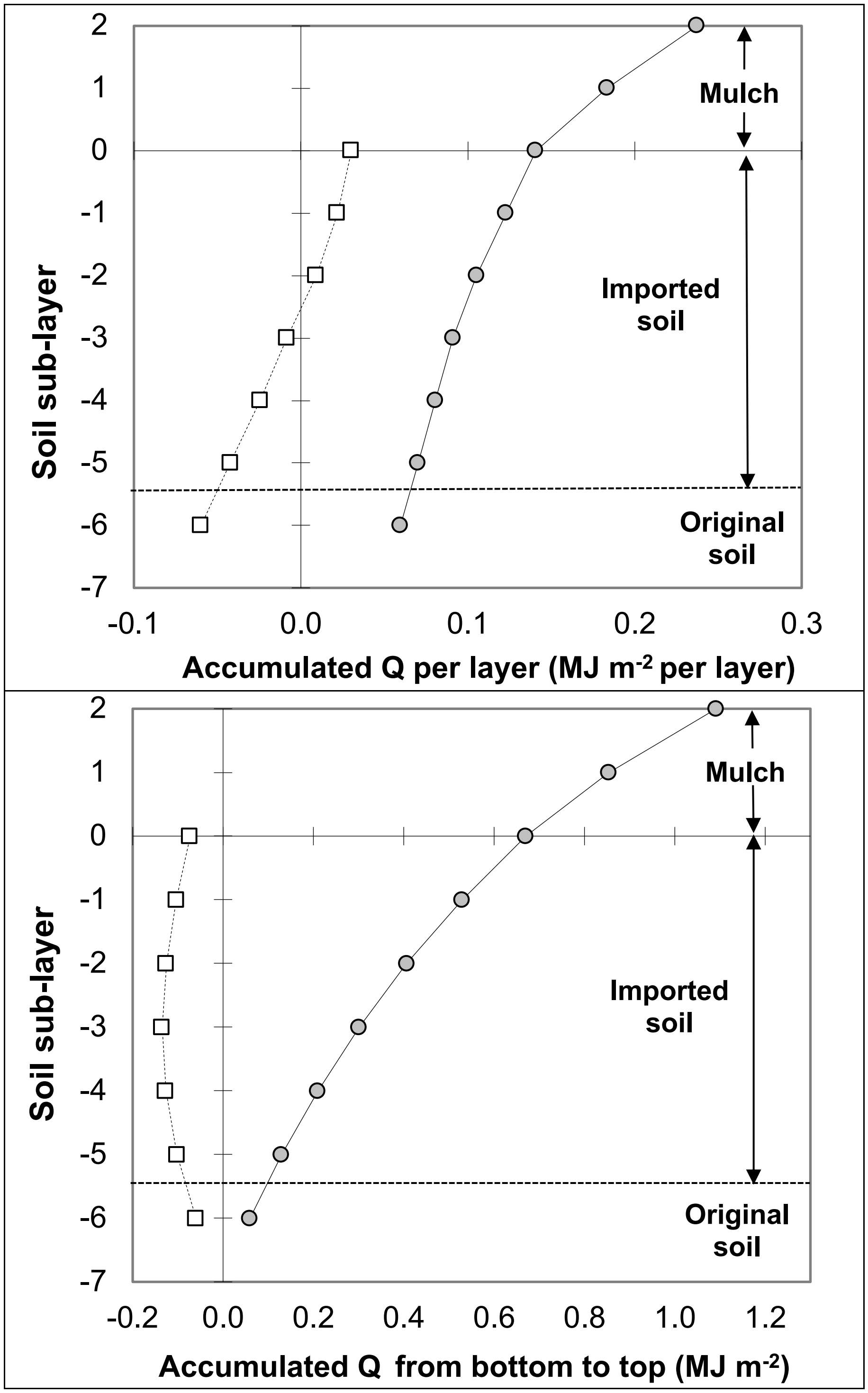

Mulch
Imported soil
Original soil
Soil sub-layer
Mean ∑Q_h at 00:00 (kJ m^{-2} h^{-1})
Mean ∑Q_h at 07:00 (kJ m^{-2} h^{-1})
Mean ∑Q_h at 09:00 (kJ m^{-2} h^{-1})
Mean ∑Q_h at 12:00 (kJ m^{-2} h^{-1})
Mean ∑Q_h at 17:00 (kJ m^{-2} h^{-1})
Mean ∑Q_h at 17:00 (kJ m^{-2} h^{-1})

Figure 9


Soil sub-layer
Mulch
Imported soil
Original soil
Accumulated Q per layer (MJ m-2 per layer)
-0.1
0.0
0.1
0.2
0.3
2
1
0
-1
-2
-3
-4
-5
-6
-7
Soil sub-layer
Mulch
Imported soil
Original soil
Accumulated Q from bottom to top (MJ m-2)
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2