Title:

Microclimate and agronomical effects of internal impermeable screens in an unheated Mediterranean greenhouse

Author names and affiliations

Joaquín Hernández[a,*], Santiago Bonachela[a], María R. Granados[a], Juan C. López[b], Juan J. Magán[b], Juan I. Montero[c]

[a] Departamento de Agronomía, Centro de Investigación en Biotecnología Agroalimentaria (BITAL), Campus de Excelencia Internacional Agroalimentario (CEIA3), Universidad de Almería, La Cañada de San Urbano s/n, 04120 Almería, España

[b] Estación Experimental Las Palmerillas (Fundación Cajamar-Grupo Cooperativo), 04710 El Ejido, Almería, España

[c] Centre de Cabrils. Institut de Recerca i Tecnologia Agroalimentaries, 08348, Cabrils, Barcelona, España

[*] Corresponding author. Fax: +34 950015939

E-mail addresses: jhrodri@ual.es (J. Hernández), bonache@ual.es (S. Bonachela), mgranado@ual.es (M.R. Granados), juancarloslopez@fundacioncajamar.com (J.C. López), juanjosemagan@fundacioncajamar.com (J.J. Magán), JuanIgnacio.Montero@irta.cat (J.I. Montero).

Abstract

In unheated greenhouses in mild-winter areas, low-cost, fixed, water-impermeable plastic screens are frequently installed in winter cycles of the vegetable crops more sensitive to fungal diseases. They are used to prevent rain and condensation falling on the crop and to improve the greenhouse air temperature. Two experiments were carried out to quantify how fixed and movable impermeable screens affect microclimate and crop behaviour in an unheated greenhouse in a mild-winter area**.** The fixed screen improved the night-time temperature and humidity of the air below the screen, and reduced the water condensation on its inner plastic surface or the proliferation of fungal diseases, but did not completely prevent it. Compared to the greenhouse without screen, the movable screen, usually unfolded at night, increased the night-time temperature of the air and the crop, reduced the night-time relative humidity of the air below the screen, prevented the water condensation on the screen or the crop, accelerated melon crop development, and significantly increased early marketable yield of melon fruits and their quality, but it did not substantially affect the substrate temperature, or the total marketable yield of melon fruits. In the comparison of the greenhouse with fixed *versus* movable screen, no substantial differences were found for a winter cucumber cycle in night-time temperature and relative humidity of the air below the screens, in shoot biomass or in fresh weight of total and marketable cucumber fruits. This can be mainly attributed to the small differences between both treatments in the shortwave radiation reaching the crop.

Keywords: Air temperature, air humidity, biomass, yield, cucumber, melon, net radiation, soil temperature.

1. Introduction

Environmental assessments of greenhouse production in Europe have shown that energy consumption is responsible for most of the environmental impact, particularly in North Western Europe where heating accounts for 81 to 96% of all impact categories (Montero, Anton, Torrellas, Ruijs & Vermeulen, 2011). Energy-saving technologies are increasingly used in the greenhouse industry to reduce fossil fuel consumption and associated environmental impacts. Most heated greenhouses in temperate regions have increased their airtightness (very low ventilation rate through leakages) and are equipped with thermal screens to reduce heat losses and energy consumption (Campen, Kempes & Bot, 2009). However, these changes usually increase and make more difficult the control of the greenhouse air humidity around the crop, which is usually conducted by heating and/or ventilation systems. Air humidity is often excessive during the heating period in these greenhouses, especially at night, and they have to be ventilated with cold outside air for dehumidification, which increases the heating energy consumption. In most of these greenhouses, thermal screens are commonly unfolded horizontally over the crop around sunset and folded around sunrise, although the optimal opening strategy depends on outside weather conditions, prices of energy and horticultural product, etc. (Bailey, 1988; Dieleman & Kempkes, 2006). These screens save energy influence the greenhouse microclimate and can therefore affect crop behaviour (Bailey, 1981; Baille, Baille & Laury, 1985; Dieleman & Kempkes, 2006; Kittas, Katsoulas & Baille, 2003).

In greenhouses from mild-winter areas, such as the coastal areas of the Northern and Southern Mediterranean Basin, the greenhouse air temperature and humidity in winter are usually outside the optimum range for fruit vegetable crop production, especially at night (Bartzanas, Tchamitchian & Kittas, 2005; Montero, Castilla, Gutierrez & Bretones, 1985), but active heating systems are not normally used because they are not considered economically viable (Bartzanas, Tchamitchian & Kittas, 2005; López, Baille, Bonachela & Perez-Parra, 2008). In these greenhouses, passive solar heating methods and measures to enhance the greenhouse energy efficiency are usually recommended (Montero, Anton, Torrellas, Ruijs & Vermeulen, 2011). In a typical plastic greenhouse with a bare gravel mulched soil on the SE Spanish Mediterranean coast, Baille, Lopez, Bonachela, Gonzalez-Real & Montero (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). For the same greenhouse system and area, Bonachela et al. (2012) concluded that using a black mulch was a simple and low-cost heating system recommendable 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, especially when the ventilation rate is low.

The roofs of most Spanish Mediterranean greenhouses consist of plastic sheets held in place between two galvanised steel meshes (Parra, Baeza, Montero, & Bailey, 2004). Wires puncture the covering, attaching the meshes to tension wires, which allows some rainfall to enter the greenhouse, especially in those with flat roofs. Moreover, during the winter period, especially at night, water often condenses and accumulates on the inner cover surface and may drop due to the slight slope. The fall of condensation and rainwater onto the crop creates more favourable conditions for the proliferation of fungal diseases (Baptista, 2007), which might reduce crop yield and quality. Although conventional thermal screens are commonly used in greenhouses in temperate regions, they are rarely used in Mediterranean greenhouses because they are relatively expensive. In addition, as they are not totally impermeable, they might not fully prevent the fall of rainwater and condensation onto the crops.

In Spanish Mediterranean greenhouses, low-cost, fixed, water-impermeable plastic screens are frequently installed during the colder cropping period (around winter), especially for the vegetable crops more sensitive to fungal diseases, like late cycles of cucumber crops. They consist of thin PE sheets joined hermetically by wires and located between the crop canopy and the greenhouse roof. Fixed screens affect greenhouse air temperature and humidity, and water condensation by reducing heat loss, natural ventilation and leakage rates, as well as air volume around the crop. These topics have generally received little attention, especially as regards impermeable, fixed screens, such as those commonly used in Mediterranean areas. Baille, Aries, Baille & Laury (1985) studied the role of optical screen properties for unheated greenhouses and concluded that the greatest heat loss reduction was obtained when an aluminised side faced directly upwards, but these conclusions cannot be directly applied to impermeable fixed screens. Moreover, the use of fixed screens may produce some unwanted daytime microclimate effects, such as reducing the greenhouse transmission of shortwave radiation, which usually limits crop production in winter (Soriano et al., 2004) and intensifying the daytime CO_2 depletion (Sánchez-Guerrero et al., 2005), as the greenhouse air volume directly in contact with crops is reduced. In order to reduce these drawbacks, the development and improvement of low-cost, impermeable movable screens could be of great interest for Mediterranean greenhouse areas.

Overall, little is known about the greenhouse microclimate effects of using fixed and movable impermeable screens for low-cost greenhouses in mild-winter areas (Montero, Castilla, Gutierrez & Bretones, 1985; Montero et al., 2013; Plaisier, 1992), and even less knowledge is available about the effect of these screens on crop response. Therefore, the main objective of the present study was to quantify how fixed and movable low-cost impermeable screens affect the microclimate and crop behaviour in an unheated greenhouse in a mild-winter climate area.

2. **Materials and methods**

2.1 Greenhouse and experiments

Two greenhouse crop experiments were carried out at Las Palmerillas research station (2º 43' W; 36º 48' N; and 155 m elevation), Cajamar Caja Rural, El Ejido, (Almería, Spain). Experiments were conducted in two identical, arch-roofed (4.5 m high to the ridges and 3.0 m to the eaves), three-span, E–W oriented greenhouses of 630 m^2. Greenhouses were covered with a three-layer thermal polyethylene film (200 µm thickness), installed in January 2008, with a transmission of 89 % for shortwave radiation and 25 % for longwave radiation (manufacturer's data). The soil was a gravel-sand mulched soil, known as *enarenado*, and widespread in the region (Wittwer & Castilla, 1995). Greenhouses had one roof vent per span and a sidewall rolling vent in the southern and northern sides, with a high total ventilation area of 0.26 m^2 of vents per m^2 of ground.

Two screen systems of interest for low-cost Mediterranean greenhouses were studied: a fixed screen and a movable one. The plastic materials used in both screens were water-impermeable and covered the whole greenhouse ground surface in order to fully prevent rain and condensation water falling onto the crops, as rainwater might enter the roof of most Spanish Mediterranean greenhouses. The fixed screen was constructed following local practices. It consisted of 37.5 μm-thick PE sheets (Sotrafilm DC AF, Sotrafa, Spain) forming a symmetrical planar and impermeable roof of 9º slope and N-S oriented above the crop canopy (between 2.20 and 2.80 m height) and joined hermetically by wires. The sheets had a transmission of 97% for shortwave radiation and 60% for longwave radiation (manufacturer's data). Local greenhouse growers use very thin impermeable plastic films to prevent the fall of rainwater and condensation onto the crop, while also minimizing the loss of incoming shortwave radiation reaching the crop. The movable screen consisted of 200 μm-thick PE (Plastermic 3C, Sotrafa, Almería, Spain) sheets forming a symmetrical planar roof of 9º slope above the crop canopy (between 2.2 and 2.8 m height, Fig. 1) at each greenhouse span. PE sheets, which had a transmission of 88% for short wave radiation and 12% for long wave radiation (manufacturer's data), were supported by tensioned wires and managed automatically (Multima, HortiMax S.L.). The thin impermeable plastic materials in the fixed screen cannot be used in the movable one, as their mechanical resistance makes them unsuitable for folding and unfolding. Prior to the experiments, several PE materials were evaluated mechanically for use as impermeable movable screens, and the above- mentioned material was chosen. The movable screen was unfolded when the outside solar radiation was lower than 50 W m^{-2} (Dieleman & Kempkes, 2006) and the greenhouse air temperature was lower than 18ºC. The junctions between contiguous sheets were closed as much as possible but they were less airtight than those in the fixed screen.

The first experiment compared a melon crop (*Cucumis melo* L.) grown in a greenhouse with (MS) and without (NS) a movable impermeable screen. The melon crop (cv. Yalo) was transplanted on the 14 of January and the crop ended on the 1 of June 2010 (early cycle). The second experiment compared a winter cucumber cycle (*Cucumis sativus* L.) grown in a greenhouse with a movable (MS) and with a fixed impermeable screen (FS). The cucumber crop (cv. Dylan) was transplanted on the 28 of October 2010 and ended on the 4 of March 2011 (late cycle). Local crop practices were applied to each crop, which were grown in 40 L perlite grow-bags of type B12 (particle diameter 0.1–5.0 mm). The irrigation water had an electrical conductivity (EC) of 1.5 dS m^{-1} and the same nutrient solution was supplied in both treatments at each experiment with a non-recirculating drip irrigation system. Crop water uptake was calculated from daily measurements of irrigation water supplied from two drip emitters and leached nutrient solution from two representative perlite grow-bags at each treatment. Vents were automatically opened (Multima, HortiMax S.L., Almería, Spain) when the daytime greenhouse air temperature was higher than 24-28 ºC in the melon crop (depending on the crop stage) and higher than 22-26 ºC in the cucumber crop. In this latter crop, roof vents were opened first, and sidewall vents were also opened when the air temperature exceeded the set points by 2 ºC or more. Moreover, whenever the air humidity deficit (grams of water vapour that can be added to one kilogram of air to bring it up to saturation) exceeded the set point (6-9 g kg^{-1}, depending on the crop stage), the temperature set point was decreased 0.2°C for each 0.1 g kg^{-1} increment of air humidity deficit.

2.2. Measurements

Main climate variables of soil, substrate, crop, inside and outside air, and greenhouse cover were measured in both greenhouses at each experiment. Sensors were located in the middle of each greenhouse, below and above the southern part of the third span (Fig. 1).

Soil and substrate temperatures were measured with thermistors (T107, Campbell Scientific, Inc., Logan, UT, USA). At each greenhouse, two thermistors were buried in the middle of the imported soil layer (at 0.25 m depth) and three in the middle of representative perlite grow-bags.

Temperature and relative humidity of greenhouse air were measured at 0.3, 2.0 and 4.0 m above ground with ventilated capacitance psychrometers (mod. HMP45C, Vaisala, Campbell Scientific, Inc., Logan, UT, USA). Dry and wet bulb air temperatures were measured 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 greenhouses. Temperature of upper and lower surface of greenhouse covers and screens were measured with two contact thermocouples (type T, copper-constantan, RS Amidata, Madrid) at each surface. Shortwave radiation effects on daytime thermocouple measurements were corrected using a linear relationship obtained *in situ* in one experimental greenhouse. Under a wide range of greenhouse air temperature and radiation conditions, simultaneous temperature measurements of thermocouples subjected (T_{T_G}, ºC) and not subjected (T_T, ºC) to the incoming shortwave radiation (G, W m^{-2}) were related: $T_T = T_{T\_G} - 0.0032 \times G - 0.017$. Crop temperature was measured in the lower, middle and upper leaves of the canopy with three contact thermocouples at each height. Special caution was given to place the thermocouples among the leaves to protect them from shortwave radiation. Net radiation inside and outside each greenhouse was measured with net radiometers (CNR1, Kipp&Zonen, Delft, The Netherlands) located above the crop canopy (2.1 m above ground) and 0.3 m above the greenhouse roof cover, respectively. These sensors measured separately the total radiation fluxes reaching the upward and downward surfaces of each radiometer sphere. Net shortwave radiation (S_n) was obtained from the difference between incident and reflected solar radiation. Net longwave radiation (L_n) at the greenhouse cover surface was calculated as the difference between the measured atmospheric radiation and the measured radiation emitted by the outer surface of the cover, while at the crop surface it was calculated as the difference between the measured radiation emitted by the inner surface of the cover/screen and the measured radiation emitted by the crop/ground surface. All these sensors were sampled at 2-second intervals, averaged every 5 minutes and registered by several data logging devices (mod. CR10X, CR1000 and CR3000, Campbell Scientific Inc., Logan, UT, USA).

The mean daily greenhouse transmission for PAR radiation was measured at both greenhouses on two sunny days: 7th January and 3rd June 2010 for the melon crop, and 20th January and 23rd March for the cucumber crop. PAR was determined with linear sensors (mod. LP80 AccuPAR, PAR/LAI Ceptometer, Decagon Devices Inc., Pullman, WA, USA) every 2-3 hours during daytime inside and outside the greenhouses. Inside the greenhouses without screen, with fixed screen and with folded and unfolded movable screen, measurements were taken along transversal and longitudinal transects above the crop canopy and below the screen.

At each crop cycle, plant height (m) was measured every 1-2 weeks from six plants per replication (four replication per treatment), except for the final crop phase. Total aboveground, leaf, stem and fruit biomass, as well as leaf area index (LAI), were measured in two plants per replication at the onset, around flowering and at the end of each crop cycle. An additional measurement was taken in the middle of fruit growth period for the melon crop. LAI was measured with an electronic planimeter (AM7626, Delta T Device Area Meter, UK). Axillary stems and young fruits pruned before the sample date were included in the corresponding biomass fraction. Total and marketable yield, and yield components (fruit number and mean fruit weight) were measured in 8 (cucumber) and 6 (melon) plants per replication. Two fruits per replication were selected during each harvest to measure fruit dry matter. Soluble solids content (SSC, º Brix) and core firmness (N) of commercial melon fruits were also measured in two fruits per replication.

3. Results

3.1 Microclimate

3.1.1 Substrate temperature

3.1.1.1 Melon crop. Greenhouse with (MS) and without (NS) movable screen

The substrate (perlite grow-bag) temperature was similar in both greenhouses throughout the melon cycle. The daily mean substrate temperature, averaged over this crop cycle, was 20.7 and 20.6 ºC in the greenhouses with MS and NS, respectively (Table 1). During the coldest month (February), the hourly mean substrate temperature in the daytime was slightly higher in the melon crop with MS, while the opposite occurred during part of the night (Fig. 2).

Temperatures in the middle of the imported soil layer were generally higher and more stable than inside the perlite grow-bag (Fig. 2). The daily mean temperature, averaged over the melon cycle, was between 0.9 and 1.1 ºC higher in the soil layer than inside the perlite grow-bag (Table 1).

3.1.1.2 Cucumber crop. Greenhouse with movable (MS) *versus* fixed (FS) screen

The daily mean substrate temperature was similar in both these greenhouses throughout the cucumber cycle. Averaged over the whole cycle, it was 18.2 and 18.0 ºC in the greenhouses with MS and FS, respectively (Table 1). However, during February (the coldest month) the hourly mean substrate temperature at night was slightly higher in the cucumber crop grown in the greenhouse with FS (18.5 *versus* 17.7 °C) and the opposite occurred during most of the daytime (17.3 *versus* 17.5 °C).

Temperatures in the middle of the imported soil layer were generally higher and more stable than inside the perlite grow-bag in the two crop cycles (Fig. 2). The daily mean temperature, averaged over the crop cycle, was between 2.3 and 2.4 ºC higher in the soil layer than inside the perlite grow-bag (Table 1).

3.1.2 Air and crop temperature, air humidity and water condensation

3.1.2.1 Melon crop. Greenhouse with (MS) and without (NS) movable screen

The hourly mean air temperature (T_a), averaged over the cycle, was similar at the three measured heights in the greenhouse with NS in the daytime (Fig. 3), while night-time values were slightly higher near the ground (at 0.3 m above ground). However, the hourly mean T_a in the greenhouse with MS was clearly higher below than above the screen at night (mean differences of about 1.5 ºC), when the screen was usually unfolded, and the opposite occurred in the daytime, when the screen was usually folded (Fig. 3). The hourly mean T_a, averaged over the cycle, at 0.3 m and 2.0 m above ground in both greenhouses, was clearly higher than outside (Fig. 3). However, during the coldest period of the cycle (February), the hourly mean T_a at 2.0 m above ground in the greenhouse with NS was similar to the outside air, while it was clearly higher in the greenhouse with MS (data not shown). The mean increment of night-time T_a produced by unfolding the screen over the crop was about 0.8 ºC at 2.0 m above ground for the melon cycle.

The movable screen also slightly increased the canopy temperature of the melon crop (T_c) at night (Fig. 4). The mean night-time T_c over the melon cycle was 0.6 ºC higher in the greenhouse with MS, and 0.9 ºC over the coldest month (13.7 ºC in the greenhouse with MS and 12.8 ºC in the greenhouse with NS). Additionally, the hourly mean T_c at night was similar to the hourly mean T_a around the crop (mean of measurements at 0.3 and 2.0 m aboveground) in both greenhouses (Fig. 4).

The absolute air humidity (AH) at night, averaged over the melon cycle, was similar at the three measured air layers in the greenhouse with NS: 8.6, 8.9 and 8.8 g kg^{-1} at 0.3, 2.0 and 4.0 m above ground, respectively. In the daytime, vents are frequently opened in winter in Mediterranean areas to control excessive air humidity: the roof and sidewall vents presented a daytime mean opening, averaged over the cycle, of between 27 and 32 % for both treatments. At night, particularly in unheated greenhouses, transpiration is a relatively weak source of water vapour to the air. As a consequence, the movable screen did not affect the AH below the screen at night, but it slightly reduced it above: the night-time mean values at 4.0 m above ground were 8.3 and 8.0 g kg^{-1} in the greenhouses with NS and MS, respectively. The cumulative water uptake throughout the melon cycle was slightly lower in the crop grown with MS (265 mm) than in that with NS (279 mm).

In the greenhouse with NS the mean hourly air relative humidity (RH), averaged over the crop, was higher over the melon canopy (2.0 m) and near the greenhouse roof (4.0 m) than near the ground (0.3 m) throughout the whole day (Fig. 5), whereas in the greenhouse with MS it was lower below than above the screen at night, and the opposite occurred in daytime (Fig. 5). Overall, the movable screen reduced the night-time RH in the air below the screen (Fig. 5). Averaged over the melon cycle, the night-time RH at 2.0 m above ground was 4.7% lower with MS than with NS because the AH was similar in both greenhouses but the air temperature was higher in the greenhouse with MS. This RH difference is slightly higher than the sensor accuracy (± 2 %). Additionally, the night-time RH was much higher inside both greenhouses than outside (Fig. 5).

Water condensation was not observed on the lower surface of the screen or the crop. The dew-point air temperature was lower than the temperature of the lower surface of the screen throughout the whole melon cycle and the crop temperature in a representative day. However, water condensation was frequently observed at night on the inner surface of the cover of the greenhouse with NS, as its temperature was often lower than the dew-point temperature of the surrounding air, especially during the second half of the melon cycle (Fig. 6).

3.1.2.2 Cucumber crop. Greenhouse with movable (MS) *versus* fixed (FS) screen

The greenhouse with FS presented a higher hourly mean T_a below than above the screen throughout the whole day (Fig. 3). The hourly mean night-time T_a values below both screens were substantially higher than outside (Fig. 3).

At night, the hourly mean T_c of the cucumber crop was slightly higher in the greenhouse with MS than in the greenhouse with FS (0.6 ºC averaged over the cycle, Fig. 4), and the opposite occurred in the daytime (0.7 ºC lower).

In the greenhouse with FS the mean hourly RH in the daytime was highest above the crop canopy (2.0 m) (Fig. 5). Compared to the fixed screen, the movable one slightly reduced the hourly mean RH above the crop canopy the whole day (Fig. 5), and these differences were greater in the winter period (data not shown). The small differences between both greenhouses might be associated to the higher ventilation rate observed in the one with FS: the daytime mean opening of the roof and sidewall vents was 29 and 14%, respectively, in the greenhouse with FS, as compared to 19 and 11 %, respectively, in the one with MS. Averaged over the crop cycle, the AH above the crop canopy (2.0 m) in the daytime was higher in the greenhouse with FS (mean daytime value of 10.7 g kg^{-1}) than in that with MS (mean daytime value of. 9.9 g kg^{-1}), and the opposite occurred in the air between the screen and the greenhouse cover: mean daytime AH values of 7.9 *vs.* 9.9 g kg^{-1}, respectively. The cumulative water uptake was similar in the cucumbers grown with FS and MS: 121 mm and 117 mm, respectively.

Water condensation was not found on the lower surface of the movable screen or on the crop. The dew-point air temperature was lower than the temperature of the lower surface of this screen throughout the whole cucumber cycle and the crop temperature (Fig. 6). However, water condensation did occur on the lower surface of the fixed screen during the second half of the cucumber cycle (Fig. 6). The fixed screen generally presented a lower surface temperature than the movable one, and a slightly higher dew-point air temperature (Fig. 6).

3.1.3 Radiation

The screens reduced the daily mean greenhouse transmission to incoming shortwave radiation (τ_{sw}). In the melon crop, τ_{sw} was 0.64 for the greenhouse with NS, and 0.53 and 0.49 for the greenhouse with folded and unfolded MS, respectively (Table 2). In the cucumber cycle, the τ_{sw} for the greenhouse with MS was 0.54 when the screen was folded and 0.48 when it was unfolded, as compared to 0.53 for the greenhouse with FS (Table 2).

In the melon crop, the net longwave radiation at the melon canopy was slightly higher in the greenhouse with MS than in that with NS (hourly mean night-time values were about 5 W m^{-2} higher in the greenhouse with MS during the cold growth period). At the cover, the net longwave radiation was similar for both greenhouses (Fig. 7). In the cucumber crop, the net longwave radiation was similar in the greenhouses with MS and FS, except for daytime greenhouse cover values, which were slightly higher in the latter (Fig. 7).

3.2. Crop growth and productivity

3.2.1 Winter melon cycle

The crop grown in the greenhouse with MS presented a more generative growth pattern than that grown in the greenhouse with NS. At the end of the cycle, the melon crop grown under MS produced a significantly lower vegetative biomass and LAI than the crop with NS (Table 3), but a significantly higher harvest index. The early marketable yield of melon fruits was significantly higher in the crop grown under MS, while the total marketable yield was similar in both greenhouse treatments (Table 4). Moreover, the content of soluble solids was significantly higher in the melon fruits grown under MS (Table 4) and the screen also decreased the incidence of powdery mildew on melon plants, although the incidence was low in both treatments (data not shown).

3.2.2 Winter cucumber cycle

No significant differences were found between the greenhouses with FS and MS for shoot and fruit biomass at the end of the cucumber cycle (Table 3), although the crop grown under MS presented a more vegetative growth pattern: the vegetative biomass was significantly higher in the crop under MS (Table 3). No significant differences were found for the fresh weight of either total or marketable cucumber fruits (Table 4). However, the fresh weight of first class cucumber fruits was significantly higher in the crop under MS (Table 4), which was due to a higher number of fruits. Moreover, non-marketable fruit weight was significantly higher in the crop under FS (Table 4).

4. Discussion

4.1 Greenhouse microclimate

This study has presented the benefits of impermeable movable screens, in comparison with unscreened greenhouses, in unheated Mediterranean greenhouses. Particular benefits were observed at night during the coldest period of the growing cycle (February), when the hourly mean air temperature below the screen was clearly higher than that of the outside air. On the contrary, air temperature was similar to the outside air in the greenhouse without screen (Fig. 3).

The results presented in this study are within the range reported by Piscia, Montero, Baeza & Bailey (2012), who found air temperature differences of up to 1.5 °C between screened and unscreened greenhouses. Therefore, the movable screen avoided the risk of thermal inversion (lower greenhouse air temperatures than the outside air), which frequently occurs in Mediterranean greenhouses on clear nights during the cold growth period (Montero, Castilla, Gutierrez de Ravé, & Bretones, 1985; Montero et al., 2013). The effect of the screen on the night-time greenhouse climate is usually stronger on clear nights, since the main greenhouse heat loss is due to the exchange of Far Infrared Radiation, FIR (Baille, López, Bonachela, González-Real, & Montero, 2006), which is higher on clear nights. The screen acts as a barrier to FIR and so reduces the heat loss. In terms of crop temperature, the movable screen also slightly increased the mean night-time temperature of the melon crop (Fig. 4), as was previously found by Teitel, Barak and Antler (2009). This benefit can also be associated to the reduction of radiative losses from the crop when the screen is unfolded at night. This might have helped to prevent crop water condensation (Fig. 6) and to reduce the risk of chilling injury (Graham & Patterson, 1982).

A valuable result of our study is that, in unheated greenhouses, water impermeable PE screens can produce most of the benefits of conventional thermal screens in terms of night-time climate. Both impermeable and conventional screens are effective shields to mitigate thermal radiation losses, though aluminised screens outperform impermeable PE screens since they are more FIR reflective, and so minimise FIR losses (Baille, Aries, Baille & Laury, 1985).

Perlite grow-bag and soil temperatures hardly varied between the greenhouses with and without movable screen (Table 1). However, the temperature of the soil where most root growth and water and nutrient uptake usually occur (Orgaz, Fernandez, Bonachela, Gallardo & Fereres, 2005) was generally higher and more stable than that measured inside the perlite grow-bag for the two studied crop cycles (Table 1), regardless of the presence and type of screen. Moreover, the mean temperature difference between soil and perlite grow-bag was higher in the cucumber cycle (about 2 ºC), which mostly developed throughout the colder period of the year (winter), than in the melon cycle (about 1 ºC), which developed throughout the winter and the spring period. In unheated plastic greenhouses in Mediterranean areas, root media temperatures during the cold growth period are usually below the optimum range (Lorenzo, Sánchez-Guerrero, Medrano, Soriano, & Castilla, 2005). Therefore, increments of the root media temperature of 1 to 2 ºC might represent a significant agronomical advantage of soil-grown *versus* substrate-grown crops.

The movable screen also reduced the night-time relative air humidity below the screen (Fig. 5), especially above the crop canopy (about 5% at 2.0 m above ground), which was mainly attributable to the higher night-time air temperature (Fig. 3), since the air absolute humidity was similar with and without screen.

Moreover, no water condensation was found on the lower surface of the screen in the two studied crops (Fig. 6): the dew-point temperature of the air below the screen was lower than the temperature of the lower surface of the screen throughout both crop cycles (Fig. 6). On the other hand, water condensation was frequently observed at night on the inner surface of the greenhouse cover without screen, especially during the second half of the melon cycle (Fig. 6), which may in part be due to the relatively high temperature set point used for opening the vents in this crop cycle. This led to water droplets falling onto the crop at night and in the early morning, and might explain the higher incidence of powdery mildew observed in the melon grown in this greenhouse (data not shown).

The above-mentioned microclimate effects produced by the movable screen may be greater in commercial Mediterranean greenhouses (Teitel, Barak & Antler, 2009), where the ratio of total cover area to floor area is lower than in the greenhouse used in this work. This lower ratio might reduce relatively the cover radiation loss, the major component of the energy losses at night in low-cost plastic greenhouses (Baille, López, Bonachela, González-Real, & Montero, 2006), and, therefore, it might increase the night-time thermal effect of the screen. Water condensation on cover and crop surfaces might also be more frequent and relevant in commercial Mediterranean greenhouses, which are usually larger and less ventilated (mean ventilation area of about 0.13 m^2 vents (m^2 ground)$^{-1}$) than the greenhouse used in this work (0.26 m^2 vents (m^2 ground)$^{-1}$). Furthermore, the night-time thermal effects produced by this movable screen could be improved by increasing its airtightness (e.g. reducing the separation between adjacent plastic sheets when they are unfolded).

A negative point was that the movable screen clearly reduced the shortwave radiation entering the greenhouse, even when it was folded (Table 2). This reduction was higher than that usually found in heated greenhouses with conventional thermal screens in temperate regions (Campen, Kempkes & Bot, 2009), because impermeable materials do not fold and unfold as easily as conventional thermal screen materials and produce more shading, especially when folded. This fact might be relevant for winter vegetable cycles in Mediterranean greenhouses, in which the photo-synthetically active radiation often limits crop production (Soriano et al, 2004). Greenhouse transmission of shortwave radiation should be improved in new movable screen prototypes for Mediterranean greenhouses.

The fixed screen, a low-cost structure (impermeable plastic sheets joined hermetically by wires) often installed in Mediterranean greenhouses during the cold period, modified the greenhouse microclimate during a typical winter cucumber cycle. The greenhouse with fixed screen presented a higher temperature and absolute humidity in the air below the screen than above it throughout the whole day, especially in the daytime (Fig. 3), while the relative air humidity below the screen was lower than above it at night-time and higher in the daytime (Fig. 5). A similar observation was made by Piscia, Montero, Baeza, & Bailey (2012) based on CFD simulations. These microclimate effects may be positive for winter vegetable cycles in Mediterranean greenhouses with good ventilation characteristics (able to rapidly evacuate excess heat or water vapour during the daytime), but not for poorly ventilated ones. In the latter, by reducing the ventilation rate and the internal air movement, the fixed screen might intensify problems of excessive heat or water vapour. In fact, the daytime mean opening of roof and sidewall vents in the cucumber crop was higher in the greenhouse with fixed screen than in that with movable screen in order to keep the prefixed set points of temperature and humidity. Natural ventilation studies show that ventilation efficiency is improved by combining both sidewall and roof vents, rather than using only one of them (Baeza et al., 2009). Moreover, the fixed screen reduced the daily greenhouse transmission of shortwave radiation from about 0.61 to 0.53 in winter (Table 2), when radiation normally limits Mediterranean greenhouse crop production (Soriano et al., 2004).

Regarding the comparison of movable and fixed screens, daytime and night-time conditions have to be differentiated. In the daytime, shortwave radiation, transpiration and ventilation are usually the main factors controlling the greenhouse microclimate, while FIR properties play a secondary role. The impermeable screens modified the greenhouse microclimate by influencing both the greenhouse ventilation requirements, especially the fixed screen, and the radiation transmission. However, small daytime microclimate differences were observed between the greenhouses with fixed and movable screens, with a slightly higher temperature and absolute and relative air humidity below the screen in the former. As mentioned earlier, the impermeable material used in the movable screen produces more shading as it does not fold or unfold as easily as conventional thermal screen materials, which leads to poor greenhouse shortwave transmission. In the case of the fixed screen, the loss in transmission was due to the screen itself. Regarding the greenhouse ventilation, the daytime mean opening of the vents was higher in the greenhouse with fixed screen, which might have improved the exchange of air below and above the screen.

At night, small microclimate differences were observed between the greenhouses with fixed and movable screens: i) the temperature of the cucumber crop was slightly higher in the greenhouse with movable screen; ii) water condensation was not found on the lower surface of the movable screen at night, but it did occur on the lower surface of the fixed screen during the second half of the cucumber cycle (Fig. 6); and iii) the fixed screen generally presented a lower surface temperature than the movable one (Fig. 6). As mentioned earlier, at night the FIR exchange is one of the main factors controlling the climate of unheated Mediterranean greenhouses (Baille, López, Bonachela, González-Real, & Montero, 2006). Therefore, the observed microclimate differences might be, at least partially, associated to the lower FIR transmission of the movable screen. Nevertheless, in spite of the large differences between screens concerning FIR properties the microclimate differences were small (Montero et al., 2013). Two main reasons may have contributed to these slight differences: on the one hand the night-time climate might have also been affected by the higher airtightness of the fixed screen. The lower airtightness of the movable screen might have led to a greater exchange of air above and below the screen. On the other hand, the occurrence of condensation on the inner surface of the fixed screen during part of the cucumber cycle (Fig. 6) might have changed its optical properties (e.g. Pieters & Deltour (1997) reported a loss of FIR transmission in PE films with water condensation). The occurrence of condensation might have reduced the transmission of the fixed screen to FIR, a fact that was supported by the minor differences in night-time net radiation measured in the movable and fixed screen greenhouses (Fig. 7).

It should be highlighted that the lack of condensation on the movable screen was its major advantage over the fixed screen, since condensation might lead to a higher risk of fungal disease proliferation (Baptista, 2007). With respect to substrate temperature, no differences were found between the fixed and movable screens, either in the temperature of the perlite grow-bags or in the soil layer throughout the cycle (Fig. 1 and Table 1).

4.2 Crop response

The use of a movable screen during an early melon cycle (starting in January) slightly accelerated crop development (full crop flowering occurred about a week earlier), leading to a more generative crop growth pattern (Table 3), and significantly increased the early marketable yield of melon fruits and their quality (Table 4). This crop response may be mainly attributed to the higher air temperature below the screen, especially at night (Fig. 3). Moreover, the screen, by reducing the air relative humidity below it (Figs. 5 and 6), decreased the incidence of powdery mildew on melon plants, which was low in both greenhouse treatments. The melon grown in the greenhouse without screen developed a higher vegetative biomass and leaf area index (Table 3), which may be attributed to its lower development rate and to the higher amount of solar radiation entering this greenhouse (Table 2): However, no significant difference in total marketable yield accumulated at the end of the cycle was found between the crop with and without screen (Table 4).

In the comparison of the greenhouse with fixed *versus* movable screen, no differences were found for a winter cucumber cycle in shoot biomass (Table 3) or in fresh weight of total and marketable cucumber fruits (Table 4). The movable screen only increased the marketable yield of first class fruits. This response could be attributed to the similar temperatures found in the substrate and the air below both screen types (Table 1, Fig. 2), and to the similar shortwave radiation reaching both crop treatments (Table 2). The reduction in shortwave radiation produced by the folded movable screen was similar to that produced by the fixed one, but higher than that produced by conventional thermal screens in high-technology greenhouses from temperate regions (Campen, Kempkes & Bot, 2009), where the light loss is always lower than 5 % (Plaisier, 1992). This was mainly due to the requirement of a screen material that was both impermeable and easy to fold. The use of an impermeable movable screen that prevents the fall of rain or condensation water on the crop is paramount for some Mediterranean winter cycles, but the films available with these characteristics substantially increased the shortwave radiation loss (Table 2). Therefore, to minimize this radiation loss, future commercial efforts might seek to develop impermeable, transparent and easily folding films, systems of rolling instead of folding the film, optimal location of the screen structures inside the greenhouse or improved airtightness of the unfolded screen.

5. Conclusions

Both impermeable screens produced advantages over the unscreened greenhouse in terms of air and crop temperature, air relative humidity, formation of condensation water on the inner surface cover, fall of cover water condensation onto the crop, incidence of powdery mildew and early yield, but no significant differences were found between screened and unscreened greenhouses on total marketable vegetable yield.

The fixed screen was less effective than the movable one in reducing the formation of condensation water on the lower plastic surfaces and controlling the proliferation of fungal diseases. However, no significant differences were found regarding total marketable vegetable yield between the crops grown under fixed screen or movable screens.

Further developments of impermeable movable screens (materials, deploying mechanisms, airtightness and greenhouse location) are needed to explore all their potential advantages over the fixed screen, particularly concerning shortwave radiation transmission.

Acknowledgments

Authors would like to acknowledge the financial support of the Spanish Ministries of Science and Innovation, and Economy and Competitiveness, the INIA and FEDER funds in the framework of the projects AGL2007-64143/AGR and RTA2012-00039-C02-02.

References

Baeza, E. J., Pérez-Parra, J. J., Montero, J. I., Bailey, B. J., López, J. C., & Gázquez, J. C. (2009). Analysis of the role of sidewall vents on buoyancy-driven natural ventilation in parral-type greenhouses with and without insect screens using computational fluid dynamics. *Biosystems Engineering, 104*(1), 86-96.

Bailey, B. J. (1981). The reduction of thermal radiation in glasshouses by thermal screens. *Journal of Agricultural Engineering Research, 26*(3), 215-224.

Bailey, B. J. (1988). Control strategies to enhance the performance of greenhouse thermal screens. *Journal of Agricultural Engineering Research, 40*(3), 187-198.

Baille, A., Aries, F., Baille, M., & Laury, J. C. (1985). *Influence of thermal screen optical properties on heat losses and microclimate of greenhouses*. *Vol. 174. Acta Horticulturae* (pp. 111-118).

Baille, A., López, J. C., Bonachela, S., González-Real, M. M., & Montero, J. I. (2006). Night energy balance in a heated low-cost plastic greenhouse. *Agricultural and Forest Meteorology, 137*(1-2), 107-118.

Baptista, F. J. F. (2007). *Modelling the climate in unheated tomato greenhouses and predicting Botrytis cinerea infection.* (Ph. D. Thesis), Universidade de Evora, Portugal.

Bartzanas, T., Tchamitchian, M., & Kittas, C. (2005). Influence of the heating method on greenhouse microclimate and energy consumption. *Biosystems Engineering, 91*(4), 487-499.

Bonachela, S., Granados, M. R., López, J. C., Hernández, J., Magán, J. J., Baeza, E. J., & Baille, A. (2012). How plastic mulches affect the thermal and radiative microclimate in an unheated low-cost greenhouse. *Agricultural and Forest Meteorology, 152*(1), 65-72.

Campen, J. B., Kempkes, F. L. K., & Bot, G. P. A. (2009). Mechanically controlled moisture removal from greenhouses. *Biosystems Engineering, 102*(4), 424-432.

Dawson, J. R., & Winspear, K. W. (1976). The reduction of glasshouse heat losses by internal blinds. *Journal of Agricultural Engineering Research, 21*(4), 431-438.

Dieleman, J. A., & Kempkes, F. L. K. (2006) Energy screens in tomato: Determining the optimal opening strategy. *Vol. 718. Acta Horticulturae* (pp. 599-606).

Graham, D., & Patterson, B. D. (1982). Responses of Plants to Low, Nonfreezing Temperatures: Proteins, Metabolism, and Acclimation. Annual Review of Plant Physiology, 33(1), 347-372.

Kittas, C., Katsoulas, N., & Baille, A. (2003). Influence of an aluminized thermal screen on greenhouse microclimate and canopy energy balance. *Transactions of the American Society of Agricultural Engineers, 46*(6), 1653-1663.

López, J. C., Baille, A., Bonachela, S., & Pérez-Parra, J. (2008). Analysis and prediction of greenhouse green bean (Phaseolus vulgaris L.) production in a Mediterranean climate. *Biosystems Engineering, 100*(1), 86-95.

Lorenzo, P., Sánchez-Guerrero, M. C., Medrano, E., Soriano, T., & Castilla, N. (2005). Responses of cucumbers to mulching in an unheated plastic greenhouse. Journal of Horticultural Science and Biotechnology, 80(1), 11-17.

Montero, J. I., Castilla, N., Gutierrez de Ravé, E., & Bretones, F. (1985). Climate under plastic in the almeria area. *Vol. 170. Acta Horticulturae* (pp. 227-234).

Montero, J.I., Antón, A., Torrellas, M., Ruijs, M., & Vermeulen, P. (2011). Environmental and economic profile of present greenhouse production systems in Europe. Deliverable nº 5. Euphoros consortium. http://www.wur.nl/en/Research-Results/Projects-and-programmes/Euphoros-1/Reports.htm

Montero, J. I., Muñoz, P., Sánchez-Guerrero, M. C., Medrano, E., Piscia, D., & Lorenzo, P. (2013). Shading screens for the improvement of the night-time climate of unheated greenhouses. *Spanish Journal of Agricultural Research, 11*(1), 32-46.

Orgaz, F., Fernández, M. D., Bonachela, S., Gallardo, M., & Fereres, E. (2005). Evapotranspiration of horticultural crops in an unheated plastic greenhouse. *Agricultural Water Management, 72*(2), 81-96.

Parra, J. P., Baeza, E., Montero, J. I., & Bailey, B. J. (2004). Natural ventilation of parral greenhouses. Biosystems Engineering, 87(3), 355-366.

Pieters, J. G., & Deltour, J. M. (1997). Performances of greenhouses with the presence of condensation on cladding materials. *Journal of Agricultural Engineering Research, 68*(2), 125-137.

Piscia, D., Montero, J. I., Baeza, E., & Bailey, B. J. (2012). A CFD greenhouse night-time condensation model. *Biosystems Engineering, 111*(2), 141-154.

Plaisier, I. H. F. (1992). Energy saving and climate improvement with thermal screens of ludvig svensson. *Vol. 312. Acta Horticulturae* (pp. 137-137).

Sánchez-Guerrero, M. C., Lorenzo, P., Medrano, E., Castilla, N., Soriano, T., & Baille, A. (2005). Effect of variable CO2 enrichment on greenhouse production in mild winter climates. *Agricultural and Forest Meteorology, 132*(3-4), 244-252.

Soriano, T., Montero, J. I., Sánchez-Guerrero, M. C., Medrano, E., Antón, A., Hernández, J., Morales, M.I., & Castilla, N. (2004). A Study of direct solar radiation transmission in asymmetrical multi-span greenhouses using scale models and simulation models. *Biosystems Engineering, 88*(2), 243-253.

Teitel, M., & Segal, I. (1995). Net Thermal Radiation Under Shading Screens. *Journal of Agricultural Engineering Research, 61*(1), 19-26.

Teitel, M., Barak, M., & Antler, A. (2009). Effect of cyclic heating and a thermal screen on the nocturnal heat loss and microclimate of a greenhouse. Biosystems Engineering, 102 (2), 162-1.

Wittwer, S. H., & Castilla, N. (1995). Protected cultivation of horticultural crops worldwide. *HortTechnology, 5*(1), 6-23.

Table 1. Mean daily temperature, averaged over the crop cycle, in the middle of the soil layer (at 0.25 m depth) and inside the perlite grow-bag in a melon grown in a greenhouse with (MS) and without a movable impermeable screen (NS); and in a cucumber grown in a greenhouse with a movable (MS) and a fixed impermeable screen (FS).

	Melon		Cucumber	
	NS	MS	FS	MS
Soil	21.6	21.7	20.5	20.4
Perlite	20.7	20.6	18.2	18.0

Table 2. Mean daily greenhouse transmission of short wave radiation in a melon crop grown in a greenhouse with (MS) or without movable impermeable screen (NS), and in a cucumber crop grown in a greenhouse with movable (MS) or fixed impermeable screen (FS). Measurements carried out with the MS folded and unfolded.

Melon			**Cucumber**		
NS	**MS**		**FS**	**MS**	
	Folded	**Unfolded**		**Folded**	**Unfolded**
0.64	**0.53**	**0.49**	**0.53**	**0.54**	**0.48**

Table 3. Aerial biomass and partitioning, leaf area index (LAI), plant characteristics (mean number and length (cm) of internodes) and harvest index (HI) values at the end of: i) a melon crop grown in a greenhouse with (MS) or without (NS) movable impermeable screen; ii) a cucumber crop grown in a greenhouse with a fixed (FS) or movable (MS) impermeable screen. Different letters in the same column indicate significant differences (P < 0.05).

Melon	Biomass ($g\ m^{-2}$)				LAI	Plant internodes		HI
	Aerial	Leaf	Stem	Fruit	$m^2\ m^{-2}$	Number	Length	
NS	781.8 a	197.7 a	111.4 a	472.8 a	2.4 a	56.5 a	3.9 a	0.60 b
MS	755.6 a	144.9 b	66.6 b	544.1 a	1.6 b	49.8 b	3.6 b	0.72 a
Cucumber	**Biomass ($g\ m^{-2}$)**				**LAI**	**Plant internodes**		**HI**
	Aerial	Leaf	Stem	Fruit	$m^2\ m^{-2}$	Number	Length	
FS	530.4 a	128.2 b	75.4 b	326.8 a	1.6 a	45.0 a	3.6 a	0.62 a
MS	554.1 a	169.4 a	87.0 a	297.7 a	2.0 a	45.0 a	3.4 a	0.54 b

Table 4. Total, marketable and early yield and yield components of a melon crop grown in a greenhouse with (MS) or without (NS) movable impermeable screen. Total, marketable and first class yield, and yield components of a cucumber crop grown in a greenhouse with fixed (FS) or movable (MS) impermeable screen. Different letters in the same column indicate significant differences (P<0.05).

Melon	Yield (kg m^{-2})				Yield components		Fruit quality	
	Total	Marketable		Non-marketable	Fruit number (fruit m^{-2})	Fruit weight (g $fruit^{-1}$)	Soluble solids (ºBrix)	Firmness (N)
		Early	Total					
NS	5.7 a	0.0 b	5.0 a	0.7 a	4.3 a	1168 a	11.8 b	2.0 a
MS	5.3 a	2.7 a	4.7 a	0.7 a	4.3 a	1097 a	13.3 a	2.0 a

Cucumber	Yield (kg m^{-2})					Yield components			
	Total	Marketable			Non-marketable	Marketable fruits		First class fruits	
		Fist class	Second class	Total		Number (fruit m^{-2})	Weight (g $fruit^{-1}$)	Number (fruit m^{-2})	Weight (g $fruit^{-1}$)
FS	8.7 a	6.2 b	1.0 a	7.2 a	1.5 a	17.6 a	412 a	14.6 b	424 a
MS	8.4 a	7.0 a	0.6 a	7.6 a	0.8 b	18.9 a	401 a	17.1 a	408 a

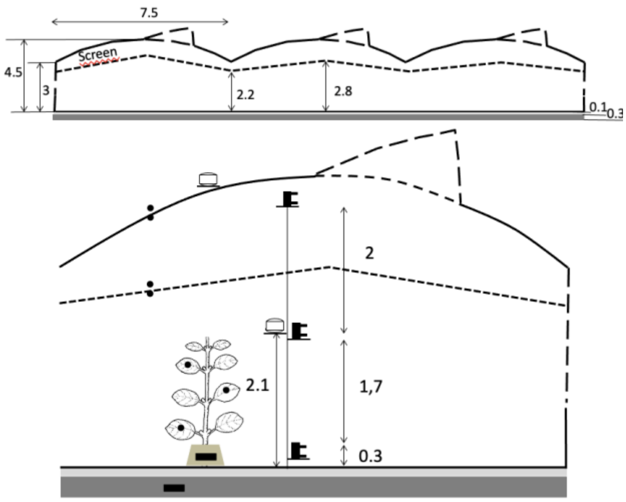

Fig. 1. Greenhouse transversal section and location of climate sensors. : Thermocouple; : Thermistor; : Psicrometer; : Radiometer; : Perlite grow-bag; : Sand-gravel layer; : Soil layer.

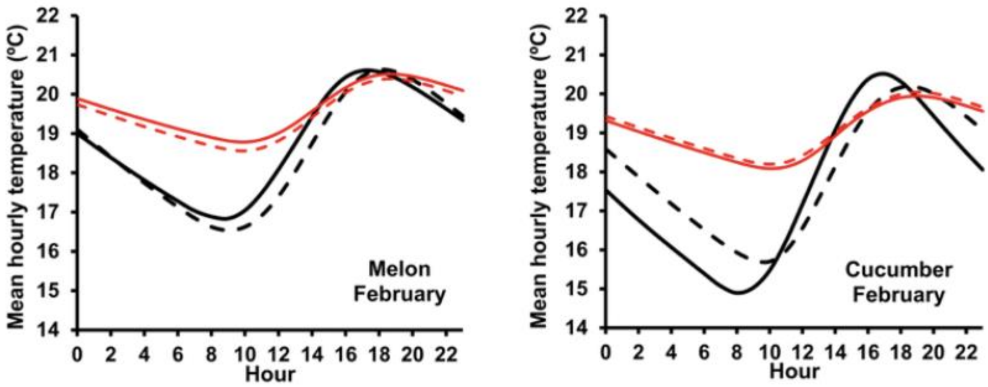

Figure 2. Hourly mean values, averaged over the month of February, of perlite and soil temperatures in a melon grown in greenhouses with (MS) or without (NS) movable screen, and in a cucumber grown in greenhouses with a movable (MS) or a fixed (FS) screen. El Ejido, Almería, Spain. Melon: MS (perlite): ; NS (perlite): ; MS (soil): ; NS (soil): . Cucumber: MS (perlite): ; FS (perlite): ; MS (soil): ; FS (soil): .

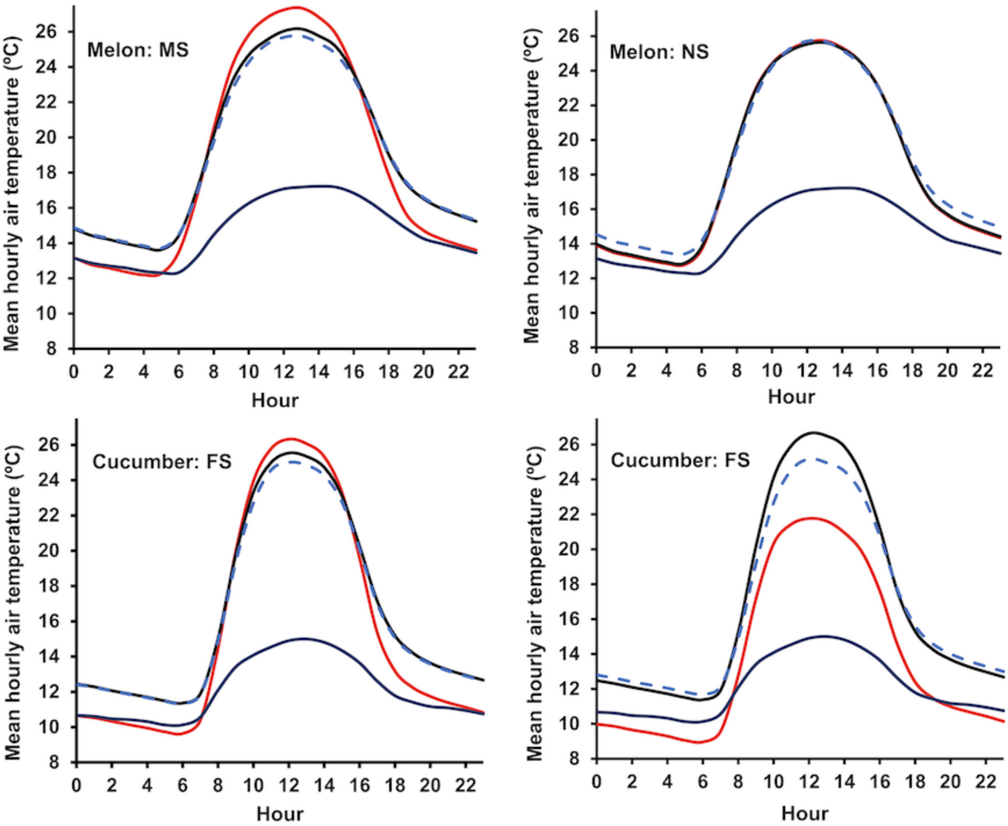

Figure 3. Hourly mean values, averaged over the crop cycle, of greenhouse air temperatures at 0.3 m, 2.0 m and 4.0 m above ground and outside the greenhouse in a melon grown in a greenhouses with (MS) or without (NS) a movable screen, and in a cucumber grown in greenhouses with a fixed (FS) or a movable (MS) screen. 4.0 m: ; 2.0 m: : 0.3 m: ; Outside: .

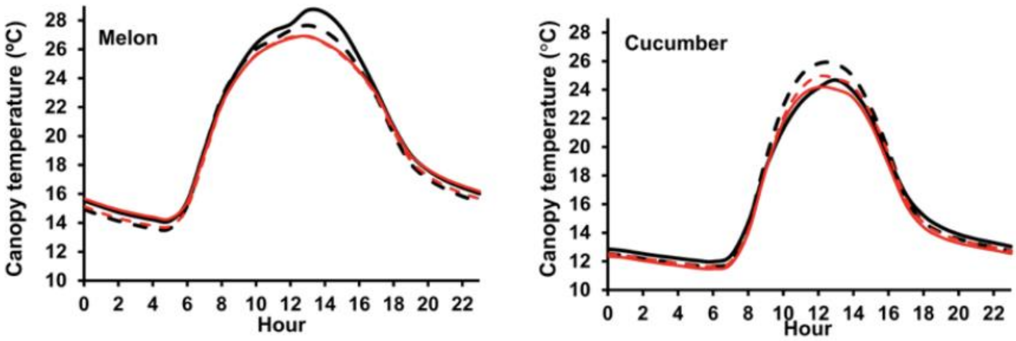

Figure 4. Hourly mean values, averaged over the corresponding cycles, of crop and air temperatures in a melon grown in greenhouses with (MS) or without (NS) a movable screen, and in a cucumber grown in greenhouses with a movable (MS) or a fixed screen (FS). Air temperatures correspond to hourly mean values of measurement taken at 0.3 and 2.0 m above ground. Melon: MS (crop): ; NS (crop): ; MS (air): ; NS (air): . Cucumber: MS (crop): ; FS (crop): ; MS (air): ; FS (air): .

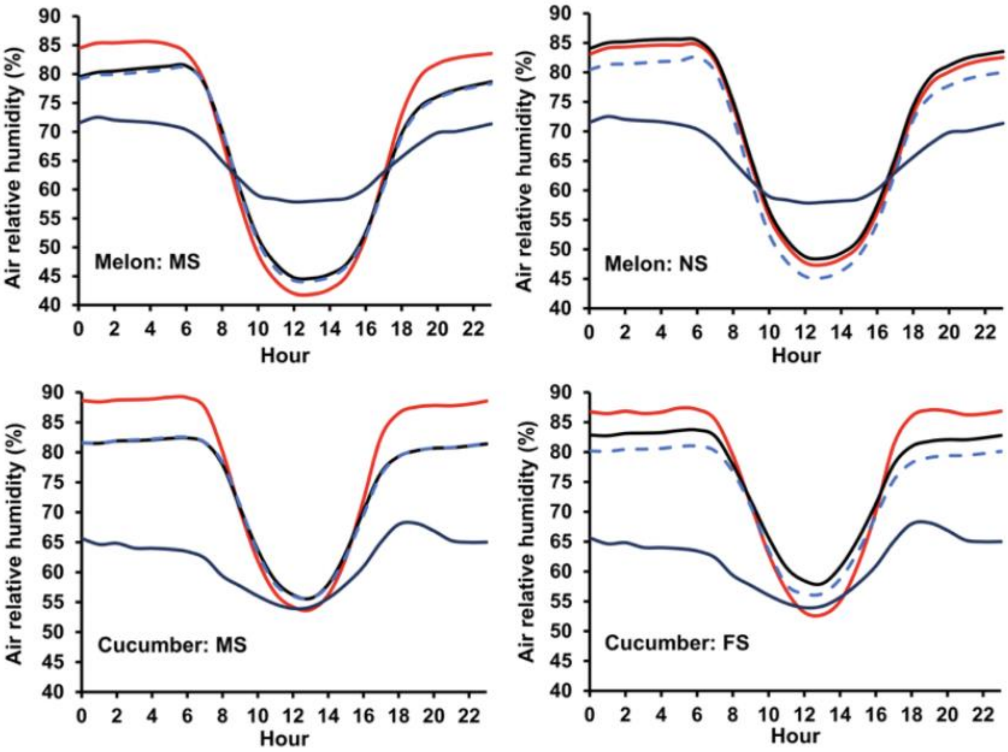

Figure 5. Mean hourly values, averaged over the crop cycle, of greenhouse air relative humidity at 0.3 m, 2.0 m and 4.0 m above ground and outside the greenhouse in a melon grown in greenhouses with (MS) or without (NS) a movable screen, and in a cucumber grown in greenhouses with a movable (MS) or a fixed screen (FS). 4.0 m: ; 2.0 m: : 0.3 m: ; Outside: .

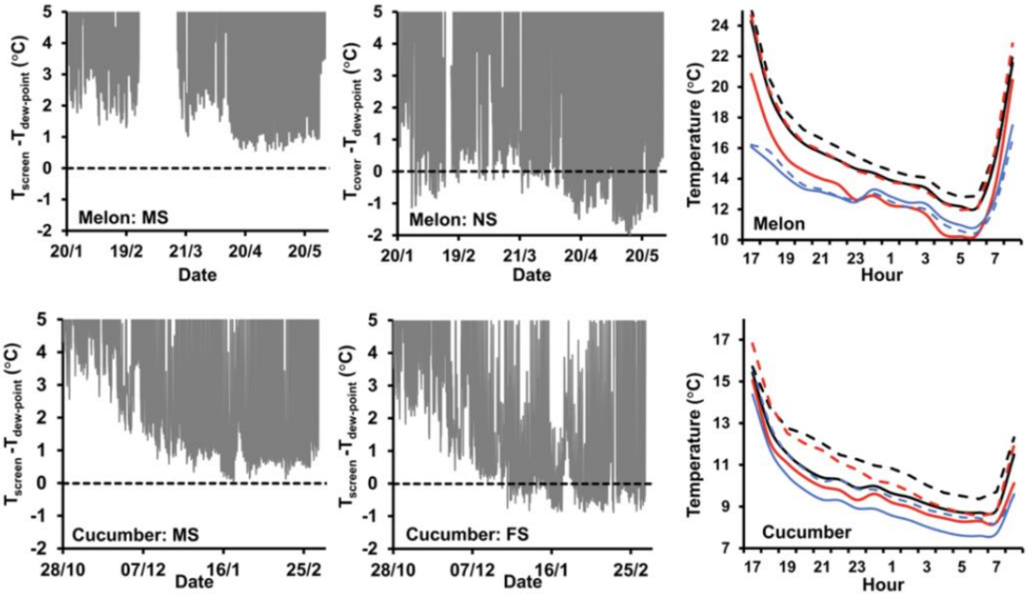

Figure 6. Upper part: temperature differences between the lower surface of the movable screen or the greenhouse cover and the dew-point of the air surrounding the screen or the greenhouse cover, respectively, throughout a melon crop grown in greenhouses with (MS) or without (NS) a movable screen; and hourly mean values for a representative day (22/3/2010) of lower surface temperature of the movable screen or greenhouse cover, dew-point temperature of the air surrounding the screen or the greenhouse roof and crop temperatures. Lower part: temperature differences between the lower surface of the movable or fixed screen and the dew-point of air surrounding the screens throughout a cucumber crop grown in a greenhouses with a movable (MS) or a fixed (FS) screens; and hourly mean values for a representative day (4/1/2011) of the lower surface temperatures of movable and fixed screens, dew-point temperatures of the air below both screens and crop temperatures. Melon: Screen_MS: ——; Cover_NS: ——; Crop_MS: – –; Crop NS: – –; Dew-point_MS: ——; Dew-point_NS: – – . Cucumber: Screen_MS: ——; Screen_FS: ——; Crop_MS: – –; Crop_FS: – –; Dew-point_MS: —— ; Dew-point_FS: – – .

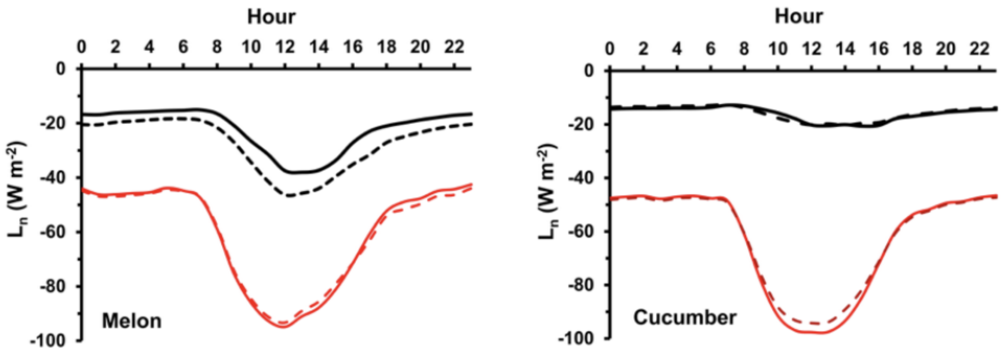

Figure 7. Hourly mean values, averaged over the crop cycle, of net longwave radiation at the crop and greenhouse cover surfaces in a melon crop grown in greenhouses with (MS) or without (NS) a movable screen, and in a cucumber crop grown in greenhouses with a movable (MS) or a fixed (FS) screen. Melon: MS (crop): ——; NS (crop): – –; MS (cover): ——; NS (cover): – – . Cucumber: MS (crop): ——; FS (crop): – –; MS (cover): ——; FS (cover): – – .