Title

How mulching and canopy architecture interact in trapping solar radiation inside a Mediterranean greenhouse

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Abstract

This work evaluates roles and interactions of ground albedo (a_g) and canopy architecture in capturing solar radiation inside Mediterranean greenhouses. Both incident and reflected solar radiation were measured over the ground surface and the greenhouse roof cover during a series of greenhouse experiments where common types of mulch and crop architecture were combined. In the experiments without crop around winter, changes in the daily mean a_g from 0.06 to 0.38 induced changes in the greenhouse cover albedo (a_c), which ranged from about 0.20 to 0.42. In measurements carried out around winter, both the a_g and a_c decreased when the ratio of the outdoor diffuse-to-solar radiation increased, independently of the ground surface, indicating that a higher percentage of solar radiation was trapped by the greenhouse under diffuse than under sunny conditions. In crops grown horizontally (not vertically trained), the effect of ground mulching over a_g vanishes progressively with the increase in leaf area of the crops, resulting in an asymptotic trend of a_g close to 0.23 at full ground covering, independently of the mulch type. In crops grown with high-wire production systems (plants grown in separated rows with the canopy distributed vertically up to 1.5-4.0 m high), asymptotic a_g values were also reached but they were lower and dependent on the mulch type and the canopy architecture (0.08 for with black mulch and 0.12 to 0.19 with a gravel mulch). Then, crops with high-wire production systems, common in greenhouses, presented a higher efficiency in trapping solar radiation inside greenhouses. A model, which predicts fairly well the a_c from the knowledge of a_g and the cover shortwave reflectance, was proposed and used.

Keywords: gravel-sand mulch; horticultural crops; modeling; net shortwave radiation; plastic mulch.

Abbreviations

BGM	black plastic and gravel-sand mulches
GM	gravel-sand mulch
LAI	leaf area index (m^2 m^{-2})
NM	no mulch
TGM	transparent plastic and gravel-sand mulches
WGM	white plastic and gravel-sand mulches
a	albedo (-)
D	diffuse shortwave radiation (W m^{-2} or MJ m^{-2} day^{-1})
S	shortwave radiation (W m^{-2} or MJ m^{-2} day^{-1})
S_n	net shortwave radiation (W m^{-2} or MJ m^{-2} day^{-1})
ρ	greenhouse cover shortwave radiation reflectance (-)
τ	greenhouse shortwave radiation transmission (-)

Subscripts

c	measured above the greenhouse roof cover
g	measured above the ground surface (soil, mulch or crop)
i	inside the greenhouse
o	outdoor
r	reflected radiation (greenhouse roof, ground surface)
u	uncorrected

1. Introduction

The albedo, or fraction of incident solar radiation reflected by a surface, influences the shortwave radiation availability and the energy balance at this surface, which may affect microclimate, production and water use of agricultural systems. Albedo may also affect the climate regionally: increasing land surface reflectance by modifying the albedo of deserts, grasslands and croplands has been proposed as a local bio-geoengineering approach for mitigating global warming effects (Kaye and Quemada, 2017; Lenton and Vaughan, 2009).

The albedo is mainly determined by surface properties and solar radiation incidence angles. The latter depends on the solar elevation angle (which varies with time of day, latitude and season) and the atmospheric scattering properties (Pinty et al., 2005; Yang, 2006). Solar radiation (S_o) is composed of a diffuse and a direct component. The diffuse radiation (D_o) arises from the scattering of solar radiation by molecules or larger particles in the atmosphere and comes from many directions simultaneously, while direct radiation arrives in a straight line from the sun without being scattered. Diffuse radiation, and consequently the ratio of outdoor solar diffuse-to-global radiation (D_o/S_o), change diurnally and seasonally depending on the sun angle and the atmospheric scattering properties (Pinty et al., 2005), affecting solar radiation incidence angles. The solar elevation angle is the principal influence on diurnal and seasonal trends of the surface albedo (Yang, 2006), while the D_o/S_o ratio is one of the main factors driving the day-to-day albedo changes (Pinty et al., 2005).

Crop albedo can be calculated from albedo of plants and soils weighted by their respective ground covering fractions. Soil albedo typically ranges between 0.10 and 0.24 (Kaye and Quemada, 2017), although some sandy dry soils with low organic carbon concentrations may have higher albedos (Tarara, 2000). A mean soil albedo value of 0.17 was considered by Kaye and Quemada (2017). The soil albedo can be substantially modified by soil mulches, which present a wide range of reflectance values (Ham et al., 1993). Albedo of open field crops with a high LAI fully covering the soil surface typically ranges from 0.21 to 0.30, mostly as a function of solar elevation angles and crop characteristics (Breuer et al., 2003; Kaye and Quemada, 2017; Monteith and Szeicz, 1961). A mean albedo value of 0.26 was considered for crops such as wheat, alfalfa, soybean and cowpea (Kaye and Quemada, 2017), while Allen et al. (1998) proposed 0.23 for short green grass completely shading the ground.

Greenhouse production systems are expanding worldwide. One of the largest greenhouse areas in the world is located on the SE Spanish Mediterranean coast, where low-cost, unheated, plastic greenhouses with gravel-sand mulched soils (*enarenado*) predominate (Bonachela et al., 2020). In greenhouse systems, the solar radiation reaching the crop and that reflected outdoors are clearly influenced by both the cover (a_c) and the ground (a_g) albedo, which are not independent since changes in one surface might induce changes in the other (Baille, 1999). Measured albedo values of greenhouse crops are scarce (Al-Riahi et al., 1989; Hansson, 1990) and, compared to outdoor crops, they can be influenced by the greenhouse or by specific crop/soil management practices. Solar radiation incidence angles inside the greenhouse can be modified by diffuse covering materials (Li et al., 2014) and by the greenhouse geometry. In greenhouse crops cultivated with high-wire production systems, such tomato, cucumber and melon, plants are grow vertically up to 1.5-4 m height in rows separated 1 to 2 m, leaving a substantial part of the soil uncovered (Teitel et al., 2016; Van de Vooren et al., 1986). In these production systems, the crop canopy architecture and distribution, and the radiative properties of the uncovered ground (soil/mulch) might also affect the solar radiation reflection. Moreover, the multiple reflexions of the solar radiation in the greenhouse (part of the radiation reflected from the ground is, in turn, reflected by the greenhouse cover, and so on) may theoretically increase the a_g of greenhouse crops. Therefore, a deeper insight into the a_g of greenhouse crops is required to better compute the solar radiation available at greenhouse crop surfaces.

In single wall greenhouses with crops, the daily mean fraction of S_o reaching the crop-soil surface typically ranges between 0.55 and 0.70, while the daily mean reflectance to S_o ranges between 0.20 and 0.30 (Baille, 1999). The a_c of greenhouses depends on surface properties of the covering material, greenhouse geometry and orientation, and solar radiation incidence angles, but also on the a_g because part of the radiation reflected by the ground surface is transmitted back outside the greenhouse. Moreover, the a_c might be influenced by greenhouse management practices or processes that modify the reflectance properties of covering materials, such as material ageing, dust accumulation (Fan et al., 2015), surface water condensation (Pollet and Pieters, 1999), whitening (Baille et al., 2001), etc. Whitening, a common practice in Mediterranean greenhouse areas, consists of painting the external surface of the greenhouse cover with calcium carbonate solution around summer to increase the reflected radiation and contribute to the greenhouse air cooling (Baille et al., 2001).

The general objective of this work was to improve the understanding of the radiative interactions and feedbacks between ground and cover albedos in unheated greenhouses, particularly in winter when the radiation availability might limit crop production in Mediterranean greenhouses. Specific objectives were to: (i) quantify *in situ* the ground (a_g) and cover (a_c) albedos of a common Mediterranean greenhouse with different types of mulches, crops and management practices; (ii) analyse the effect of the ratio of outdoor solar diffuse-to-global radiation (D_o/S_o) and the sun angle on the cover and ground albedos; and (iii) simulate the greenhouse cover albedo.

2. Material and methods

2.1 Greenhouses and experiments

Experiments were conducted in identical three-span greenhouses (22.5 m × 28 m), oriented E−W and located at the "Cajamar Foundation" research station (2º43'W; 36º48'E; 155 m.a.s.l.), Almería, SE Spain. Greenhouses were arch-roofed (4.5 m high to the ridge and 3.2 m to the eave) with one roof vent per span and a sidewall rolling vent in the southern and northern sides. The plastic film covering the greenhouses, installed in January 2008, was a three-layer thermal film of 200 µm thickness (Sotrafa SA, Almería, Spain) with a transmission of 89% to shortwave and 25% to longwave radiation (manufacturer's data). This covering material was renovated twice, in early autumn 2011 and 2014, with a three-layer, anti-fog thermal film of 200 µm thickness (Sotrafa SA) with a transmission of 90 % to shortwave radiation and 10 % to longwave radiation and a haze factor of 0.55 (manufacturer's data). Greenhouses had similar *enarenado* soils, widely used in this region (Bonachela et al., 2020). They consisted of the naturally occurring, gravel sandy-loamy soil covered with a 0.3 m layer of imported loamy soil, and an upper 0.1 m mulch layer of mostly fine gravel and very coarse sand particles.

2.1.1 Soil mulches

One greenhouse was divided in two equal compartments of 22.5 m × 10 m for conducting the soil mulch experiments. Buffer zones of 4 m between compartments and 2 m at each end of the greenhouse minimised climate differences between compartments (Bonachela et al., 2012). Three experiments were carried out in this greenhouse around the winter period. At each experiment, two treatments (one per compartment) were compared, the greenhouse remained without crop and the top gravel-sand layer was maintained dry. These conditions can be representative of crop periods just after sowing/planting when seedlings have a low LAI and the soil area wetted by drippers is small. Greenhouse vents remained closed during the experiments and plastic mulches covered the whole compartment.

One experiment, conducted from 10 to 28 December 2008, compared the soil with the gravel-sand mulch layer (GM) to the same soil covered with a black plastic film (BGM) of 30 μm thickness (Sotrafilm NG, Sotrafa SA) with a shortwave transmission of 0.01, absorption of 0.95, and a reflection of 0.04, and a longwave transmission of 0.15 (manufacturer's data). Another experiment, conducted from 5 to 16 November 2008, compared a transparent plastic mulch (TGM) *versus* a black plastic mulch (BGM) in the soil with the top gravel-sand mulch layer. The transparent mulch was an anti-fog plastic film of 35 μm thickness (Sotrafilm NT, Sotrafa SA) with a shortwave transmission, reflection and absorption of 0.85, 0.10 and 0.05, respectively, and a longwave transmission of 0.74. A third experiment, conducted from 14 to 26 January 2009, compared a soil with (GM) and without (NM) the top gravel-sand mulch layer. One day before starting this experiment the top gravel-sand layer of the NM compartment was entirely removed.

2.1.2 Crop management

The following experiments were carried out in one, two or three of the above-mentioned greenhouses.

Cucumber 2009. A cucumber crop (*Cucumis sativus* L. cv. Mirlo) was grown in one greenhouse from 24 August to 24 November 2009 (early autumn cycle). It was cultivated in 40 L B12 perlite grow-bags (particle diameter 0.1 to 5.0 mm) laid on the *enarenado* soil. Plants were separated 1.6 m between rows (2.0 plants m^{-2}) and vertically guided with polypropylene cords supported by wires to a height of 2.25 m (high-wire production system). Before starting the experiment, the greenhouse cover was heavily whitened with calcium carbonate, which was completely removed (water cleaning) on the 22 of September.

Melon 2010. A melon crop (*Cucumis melo* L. cv. Yalo) was grown in one greenhouse from 14 January to 1 June 2010 (early spring cycle). It was cultivated in 40 L B12 perlite grow-bags laid on the *enarenado* soil. Plants were separated 1.6 m between rows (1.5 plants m^{-2}) and vertically guided to a height of 2.25 m (high-wire production system).

Melon 2012. Three melon crops (*Cucumis melo* L. cv. Azafran) were grown in three greenhouses (one crop per greenhouse) from 8 February to 31 May 2012 (spring cycle). Plants (1.0 plant m^{-2}) were cultivated in 40 L coconut coir grow-bags (Pelemix Ltd. Murcia, Spain) laid on the *enarenado* soil. They were not vertically supported and fully covered the soil surface after crop flowering (horizontally-grown crops). Three treatments (one per greenhouse) were studied: crop grown in a greenhouse without plastic mulch (GM), with a white plastic mulch (WGM) of 25 μm thickness (Bicolor, or Acosol BN, Solplast SA, Murcia, Spain) and with a black plastic mulch (BGM) of 25 μm thickness (Natura BD o Acosol, Ng, Solplast SA). The white film had a shortwave transmission of 0.01, a reflection of 0.60 and absorption of 0.39, while the black film had a transmission of 0.01, a reflection of 0.04 and an absorption of 0.95 (manufacturer´s data).

Cucumber 2014/15. Two cucumber crops (*Cucumis sativus* L. cv. Valle) were grown in two greenhouses (one per greenhouse) from 16 October 2014 to 4 March 2015 (winter cycle). A low-cost, fixed, water-impermeable plastic screen was installed inside each greenhouse (Hernández et al., 2017). Plants were cultivated in 30 L coconut coir grow-bags (FICO, Ispemar SCA, Almería, Spain) laid on the *enarenado* soil. They were grown in rows, separated 1.6 m (1.0 plant m^{-2}), and vertically guided to a height of 2.25 m (high-wire production system). Two treatments were compared: a crop on a soil without plastic mulch (GM) *versus* a crop on the same soil with micro-perforated black plastic mulch (BGM) of 25 µm thickness (Sotrafilm NG, Sotrafa SA), which had a shortwave transmission of 0.01, a reflection of 0.04, an absorption of 0.95 and a longwave transmission of 0.15 (manufacturer's data).

2.2 Measurements

Incident and reflected shortwave radiation were measured by means of pairs of pyranometers, one in inverted position (CNR1, Kipp&Zonen, Delft, The Netherlands). In the experiments with soil mulches, these sensors were located 0.3 m above the ground and 0.3 m above the greenhouse cover in the middle of each greenhouse compartment. In the crop experiments, these sensors were located above the crop canopy (2.1 m aboveground) and 0.3 m above the greenhouse roof cover in the middle of the greenhouse. Greenhouse ground (a_g) and roof cover (a_c) albedos were obtained as the ratio between the corresponding daily integrals of the reflected and the incident shortwave radiation (Al-Riahi et al., 1989; Monteith and Szeicz, 1961). Diurnal a_g and a_c dynamics were obtained using 5-minute means of reflected and incident shortwave radiation. Moreover, the outdoor solar radiation was measured on a horizontal plane by two pyranometers located 1.5 m aboveground under open field conditions on bare land about 100 m away from the experimental greenhouses. One pyranometer (Model CM21, Kipp & Zonen) measured the outdoor shortwave radiation (S_o), while the other, equipped with a polar axis shadowband (model CM 121 B Shadow Ring, Kipp & Zonen) to prevent the solar beam from impinging on the pyranometer, supplied the uncorrected raw data of the outdoor diffuse shortwave radiation (D_u). The net shortwave radiation (S_n) at the ground (soil/mulch/crop) and cover surface was obtained as the difference between the incident and the reflected shortwave radiation. CNR1 and CM21 comply with the specifications for the firstclass WMO classification of this instrument (resolution better than ±5 Wm^{-2}). Measurements were taken every 2 seconds and averaged values were registered every 5 minutes by data loggers (DL 15, Thies GmbH & Co. KG, Göttingen, Germany; CR1000, Campbell Scientific Ltd., Leicestershire, UK). Greenhouse radiation measurements during the middle part of the three 2014/15 cucumber crop cycles are unavailable due to technical problems.

Volumetric soil water content (VWC) was measured with a TDR system (TRASE 6005X1, Soil Moisture Corp. Santa Barbara, CA, USA) in the imported soil layer of the greenhouse with GM and with NM. TDR probes of 0.3 m length were installed in 6 locations in the middle of each greenhouse compartment below the gravel-sand mulch layer. The crop leaf area index (LAI) was measured with an electronic planimeter (AM7626, Delta T Devices LTD, Cambridge, England) at different stages of the studied cucumber and melon cycles.

2.3 Diffuse radiation data processing

Outdoor diffuse shortwave radiation (D_o) was determined by applying an isotropic correction factor (F, equation 1) to the uncorrected raw data of diffuse radiation (D_u) (LeBaron et al., 1990):

$$F = \frac{1}{1 - \mathrm{f}_v} \tag{1}$$

where f_v is the view factor and represents the proportion of the sky obscured by the shadow ring under isotropic conditions. For f_v calculation under cloudy conditions, methods accounting for anisotropic conditions (e.g., LeBaron et al., 1990; Batlles et al., 1995) are preferably applied. In this study, the correction method proposed by Batlles et al. (1995) was used. A more detailed explanation can be found in Cabrera et al. (2009). The direct component of the outdoor solar radiation incident on a horizontal plane was deduced as S_o minus D_o.

2.4 Modelling greenhouse cover albedo

In greenhouse systems the multiple reflexions of the shortwave radiation penetrating into the greenhouse might increase the a_c, as part of this radiation is reflected from the ground, which, in turn, is partially transmitted outside the greenhouse and partially reflected by the greenhouse cover (Fig. 1), and so on (Baille, 1999). These processes can be described by equation 2, based on a previous work from Fan et al. (2015).

$$a_c = \rho + \tau \times a_g \times \tau + \tau \times a_g \times \rho \times a_g \times \tau + \cdots = \rho + a_g\tau^2 + a_g\tau^2 \sum_{n=1}^{\infty} (\rho a_g)^n \quad (2)$$

where τ is the daily mean transmission coefficient of the greenhouse and ρ is the daily mean reflectance coefficient of the greenhouse cover. Both parameters for a given greenhouse mostly depend on the surface properties of the covering material and the solar radiation incidence angles. By solving the geometrical series contained in equation 2, the a_c can be written as (equation 3).

$$a_c = \rho + \frac{a_g\tau^2}{1 - a_g\rho} \quad (3)$$

In each of the experiments where the a_c and a_g were measured, the daily mean ρ value was determined by minimising the root mean square error of measured and estimated a_c values for some days (model calibration). In the mulch experiments without crop, one mean daily ρ value was determined for the two studied treatments because greenhouse cover characteristics were the same for both treatments and the sun elevation angle was very similar during the relatively short experimental period, except for the experiment comparing GM *versus* NM (section 3.1.3). In the crop experiments, the daily mean ρ was determined in two periods of each crop cycle: the greenhouse with (W) and without whitening (NW) in the 2009 cucumber crop; and the early (EC) and the mid-late phase (MLC) of the 2010 melon cycle. Later on, the model was validated using measured mean daily a_c values different from those used for model calibration (Medrano et al., 2005). In the crop experiments, the daily mean ρ was determined in two periods of each crop cycle: the greenhouse with (W) and without whitening (NW) in the 2009 cucumber crop; and the early (EC) and the mid-late phase (MLC) of the 2010 melon cycle. Later on, the model was validated using measured mean daily a_c values different from those used for model calibration.

Comparisons of estimated and measured values of daily a_c were carried out by linear regressions. Moreover, the root mean square error (RMSE), the mean absolute error (MAE) and the efficiency factor of the model (EF) were calculated (Willmott, 1982).

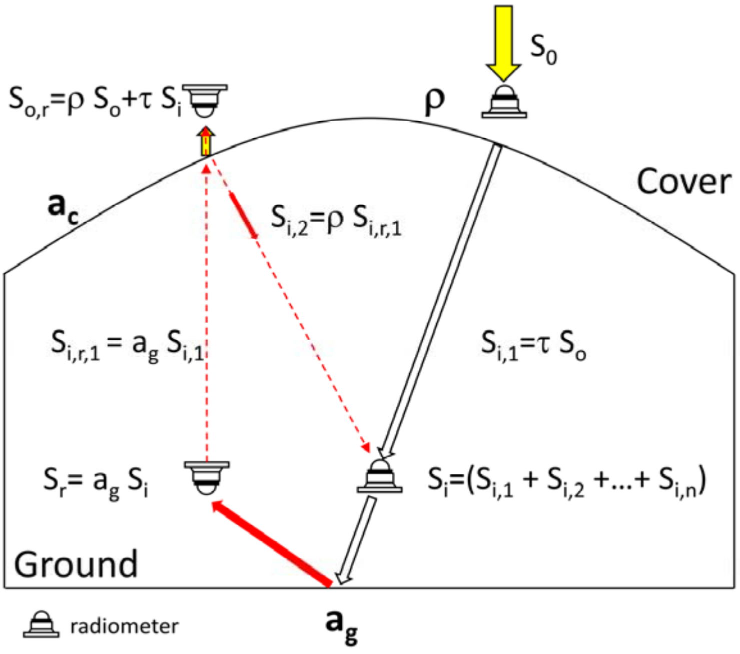

Figure 1. Schematic representation of the multiple reflexions of the shortwave radiation in a greenhouse. The outdoor shortwave radiation (S_o) transmitted into the greenhouse ($S_{i,1}=\tau\ S_o$) is partially reflected from the ground ($S_{i,r,1}=a_g\ S_{i,1}$), which, in turn, is partially transmitted outside the greenhouse ($\tau\ S_{i,r,1}$) and partially reflected by the greenhouse cover ($S_{i,2}=\rho\ S_{i,r,1}$), and so on. τ is the mean greenhouse transmission coefficient, ρ is the mean reflection coefficient of the greenhouse covering and a_g is the ground albedo.

3. Results

3.1 Soil mulches

3.1.1 BGM *versus* GM

Daily mean a_g and a_c values in the greenhouse with BGM and without it (GM) are shown by Figures 2a and 2b. Under the same outdoor climate, the daily mean a_g and a_c were higher in the GM than in the BGM greenhouse, although the differences were smaller at the cover surface. Averaged over the experimental period, the mean a_g and a_c, was 0.33 ± 0.03 and 0.38 ± 0.04, respectively, in the greenhouse with GM, and 0.10 ± 0.02 and 0.29 ± 0.03, respectively, in the greenhouse with BGM (Table 1). The daily mean a_g or a_c values varied slightly throughout the experimental period in both greenhouse compartments and this variation was mostly associated with the variation in the daily ratio of the outdoor diffuse to outdoor shortwave radiation (D_o/S_o), since the daily mean a_g or a_c decreased linearly as the daily D_o/S_o ratio increased (Figs. 2a and 2b). Narrow linear relationships were found between a_g or a_c and D_o/S_o values (Table 2).

The shortwave radiation available at the ground and cover surfaces in both greenhouse compartments increased with the daily D_o/S_o ratio. The daily ratio of net to incident shortwave radiation inside ($S_{n,i}/S_i$) and outside ($S_{n,o}/S_o$) the greenhouse increased linearly as the daily D_o/S_o ratio rose (Table 2). On the other hand, no clear relationships were found between mean daily ratios of net longwave to incident shortwave radiation inside or outside the greenhouse and the D_o/G_o ratio (data not shown).

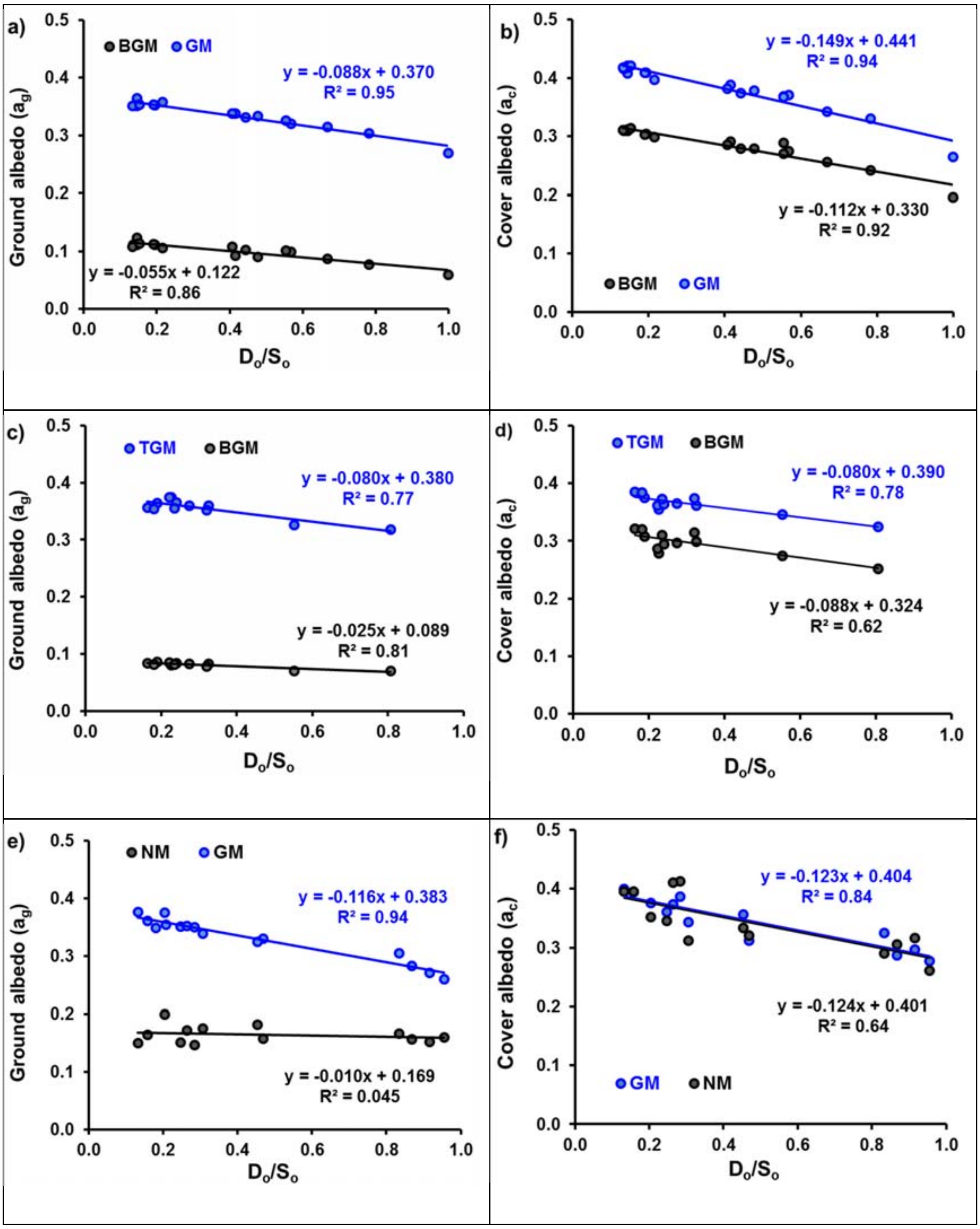

Figure 2. Relationships between the daily mean ground (a_g) or cover (a_c) albedo and the outdoor daily diffuse to incident shortwave radiation ratio (D_o/S_o) in greenhouse compartments with: (a and b) a gravel-sand mulch layer with (BGM) and without (GM) a black plastic mulch; (c and d) a gravel-sand mulch layer with a black (BGM) and? transparent (TGM) plastic mulch; (e and f) a soil with (GM) and without (NM) a top gravel-sand mulch layer.

Treatments	**BGM *vs.* GM**		**TGM *vs.* BGM**		**NM *vs.* GM**	
	BGM	**GM**	**TGM**	**BGM**	**NM**	**GM**
a_g	0.10±0.02	0.33±0.03	0.35±0.02	0.08±0.01	0.17±0.01	0.33±0.04
a_c	0.29±0.03	0.38±0.04	0.36±0.02	0.30±0.02	0.34±0.05	0.35±0.04
ρ	0.26	0.26	0.28	0.28	0.30	0.24

Table 1. Daily mean values, averaged over the experimental period, of greenhouse ground (a_g) and cover (a_c) albedo, and daily mean reflection coefficient of the greenhouse cover (ρ) in three experiments carried out around the winter period: i) soil with a top gravel-sand mulch layer with (BGM) and without (GM) a black plastic mulch; ii) soil with a top gravel-sand mulch layer and a transparent plastic mulch (TGM) *versus* soil with a top gravel-sand mulch layer and a black plastic mulch (BGM); and iii) soil with (GM) and without (NM) a top gravel-sand mulch layer. El Ejido, Almería. Spain.

Experiments and treatments	a_g or a_c *vs.* D_o/S_o			$S_{n,i}/S_i$ or $S_{n,o}/S_o$ *vs.* D_o/S_o			N
	Slope	Intercept	R^2	Slope	Intercept	R^2	
BGM and GM							
Ground							
BGM	-0.055	0.122	0.86	0.053	0.878	0.78	19
GM	-0.088	0.370	0.95	0.094	0.630	0.86	19
Cover							
BGM	-0.112	0.330	0.92	0.112	0.670	0.92	19
GM	-0.149	0.441	0.94	0.149	0.559	0.94	19
TGM and BGM							
Ground							
TGM	-0.080	0.380	0.77	0.080	0.620	0.77	12
BGM	-0.025	0.089	0.81	0.025	0.089	0.81	12
Cover							
TGM	-0.080	0.390	0.78	0.080	0.611	0.78	12
BGM	-0.088	0.324	0.62	0.088	0.676	0.62	12
NM and GM							
Ground							
NM	-0.010	0.169	0.05	0.102	0.830	0.04	13
GM	-0.116	0.383	0.94	0.121	0.614	0.95	13
Cover							
NM	-0.124	0.401	0.64	0.124	0.560	0.64	13
GM	-0.123	0.404	0.84	0.123	0.596	0.84	13

Table 2. Summary of statistics. Linear relationships between daily mean values of ground (a_g) and cover (a_c) albedos *versus* the outdoor diffuse to incident shortwave radiation ratio (D_o/S_o), and between daily mean values of the ratio of net to incident shortwave radiation inside ($S_{n,i}/S_i$) and outdoor ($S_{n,o}/S_o$) the greenhouse *versus* the D_o/S_o ratio in three greenhouse experiments: i) soil with a top gravel-sand mulch layer with (BGM) and without (GM) a black plastic mulch; ii) soil with a top gravel-sand mulch layer and a transparent plastic mulch (TGM) versus a soil with a top gravel-sand mulch layer and a black plastic mulch (BGM); and iii) soil with (GM) and without (NM) a top gravel-sand mulch layer. R^2: coefficient of determination of the linear regression; N: total number of observations.

3.1.2 TGM *versus* BGM

The daily mean a_g or a_c was higher in the greenhouse with TGM than with BGM, although the differences were lower at the cover surface (Figs. 2c and 2d). Averaged over the experimental period, the mean a_g and a_c were 0.35 ± 0.02 and 0.36 ± 0.02, respectively, in the greenhouse with TGM, and 0.08 ± 0.01 and 0.30 ± 0.02, respectively, in the greenhouse with BGM (Table 1). The variation in the daily mean albedo values observed at both surfaces and greenhouse treatments was mostly associated with the variation in the daily D_o/S_o ratio (Figs. 2c and 2b). Narrow negative linear relationships were found between the daily mean a_g or a_c and the daily D_o/S_o ratio (Table 2).

A higher daily D_o/S_o ratio induced a lower albedo, which enhanced the shortwave radiation available at the ground and cover surfaces of both greenhouse treatments. The daily ratio of net to incident shortwave radiation inside ($S_{n,i}/S_i$) and outside ($S_{n,o}/S_o$) the greenhouse increased linearly as the daily D_o/S_o ratio rose (Table 2).

3.1.3 GM *versus* NM

The daily mean a_g was higher in the greenhouse with GM than with NM, while the daily mean a_c was similar for both treatments (Figs. 2e and 2f). Averaged over the experimental period, the mean a_g and a_c were 0.17 ± 0.01 and 0.34 ± 0.05, respectively, in the greenhouse with NM, and 0.33 ± 0.04 and 0.35 ± 0.04, respectively, in the greenhouse with GM (Table 1). The variation observed in the daily mean values of a_g in the greenhouse with GM and of a_c in both greenhouse treatments was mostly associated with the variation in the daily D_o/S_o ratio (Figs. 2e and 2f). Negative linear relationships were found between the daily mean a_c and the daily D_o/S_o ratio for both treatments, and between the daily mean a_g and the daily D_o/S_o ratio in the greenhouse with GM (Table 2).

Dropwise condensation was observed during daytime, especially in the morning, on the inner roof surface of the greenhouse with NM, but not in the greenhouse with GM, and this condensation was more intense at the beginning of the experimental period. The effect of roof condensation on cover albedo can be observed in the daytime a_c dynamics on 14 January (sunny day, Fig. 3). During the first half of the daytime, when roof condensation usually occurred and/or was more intense (Granados et al., 2011), a_c values were slightly higher in the greenhouse with NM than in the greenhouse with GM, while the opposite occurred during the second half of daytime, when roof condensation was small or null. The volumetric soil water content in the greenhouse with NM decreased during the observation period (from 25.7 m^3 m^{-3} ± 2.0 to 22.7 m^3 m^{-3} ± 1.2), but it hardly changed in the greenhouse with GM (from 22.8 m^3 m^{-3} ± 2.1 to 23.0 m^3 m^{-3} ± 1.4). This reduction was mostly due to soil water evaporation, since there was no crop in this greenhouse and the volumetric soil water content values were below field soil capacity for this soil type (Bonachela et al., 2006).

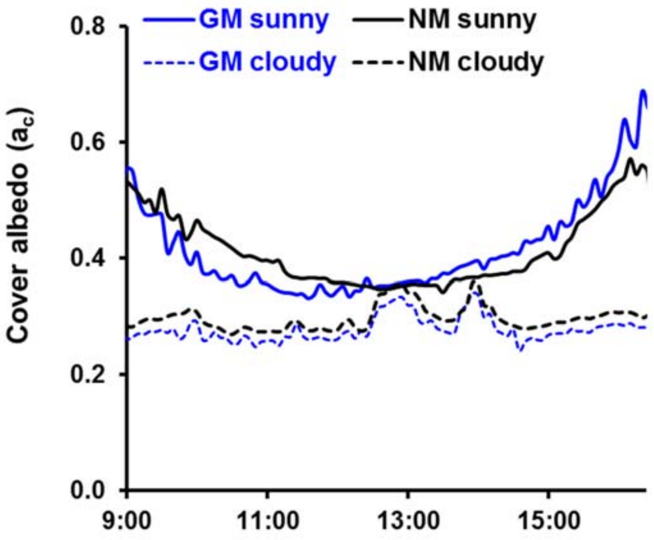

Figure 3. Diurnal dynamics of the cover (a_c) albedo in a sunny (14/01/2009) and an overcast (16/01/2009) day in greenhouse compartments with a soil with (GM) and without (NM) a top gravel-sand mulch layer.

A higher daily D_o/S_o ratio decreased the albedo and increased relatively the shortwave radiation available at the ground of the greenhouse with GM and at the cover of the greenhouses with GM and NM. In these cases, the daily ratio of net to incident shortwave radiation inside ($S_{n,i}/S_i$) and outside ($S_{n,o}/S_o$) the greenhouse increased linearly as the daily D_o/S_o ratio rose, but not at the ground of the greenhouse with NM (Table 2).

3.2 Combined effect of mulch and canopy architecture

3.2.1 Autumn 2009 cucumber cycle

The daily mean a_g at the surface of this crop, grown in an *enarenado* soil with a gravel-sand mulch layer, averaged over the cycle, was 0.20 ± 0.02 (Table 3). It was slightly higher at the beginning of the cycle (Fig. 4a) when the crop LAI was lower than 0.5 m^2 m^{-2}. Hereafter, it decreased slightly or remained relatively steady. The daily mean a_g was 0.21 ± 0.03 for the whitening period and 0.19 ± 0.02 for the period without whitening (Table 3). Averaged over the cycle, the daily mean a_c was 0.36 ± 0.14, but values were much higher from the beginning of the cycle up to mid-September because the external greenhouse cover was heavily whitened during this period (Fig. 4a). The daily mean a_c was 0.57 ± 0.03 for the whitening period and 0.27 ± 0.03 for the period without whitening (Table 3). No relationships were found between the daily mean a_g or a_c and the daily D_o/S_o ratio for the whole cucumber cycle, or for shorter and more homogeneous crop periods, such as the onset of the cycle when the greenhouse was whitened, or later on when the crop covered most of the soil surface and the greenhouse cover was not whitened (data not shown).

Treatments	**2009 cucumber crop**		
	W	**NW**	**Cycle**
a_g	0.21±0.03	0.19±0.02	0.20±0.02
a_c	0.57±0.03	0.27±0.03	0.36±0.14
ρ	0.56	0.21	-
	2010 melon crop		
	EC	**MLC**	**Cycle**
a_g	0.24±0.02	0.16±0.01	0.18±0.03
a_c	0.33±0.03	0.27±0.02	0.29±0.03
ρ	0.23	0.20	-
	2012 melon crops		
	EC	**LC**	
a_g **(GM)**	0.18±0.02	0.22±0.02	
a_g **(BGM)**	0.04±0.02	0.22±0.01	
a_g **(WGM)**	0.38±0.03	0.23±0.01	
	2014/15 cucumber crops		
	EC	**MLC**	**Cycle**
a_g **(GM)**	0.22±0.04	0.12±0.01	0.13±0.03
a_g **(BGM)**	0.11±0.03	0.08±0.01	0.08±0.02
a_c **(BGM)**	0.27±0.01	0.36±0.05	0.35±0.06

Table 3. Daily mean values, averaged over the experimental period, of greenhouse ground (a_g) and roof cover (a_c) albedos, and daily mean reflection coefficient of the greenhouse cover (ρ) in four crop experiments: i) 2009 cucumber in a soil with a top gravel-sand mulch layer in two crop periods [greenhouse with (W) and without (NW) whitening]; ii) 2010 melon in a soil with a top gravel-sand mulch layer in two crop periods [early (EC) and mid-late (MLC) phases of the cycle]; iii) 2012 melons in a soil with a top gravel-sand mulch layer (GM), in a soil with GM and white plastic mulch (WGM), and in a soil with GM and black plastic mulch (BGM) in two crop periods [early (EC) and late (LC) phases of the cycle]; iv) 2014/15 cucumbers in a soil with a top gravel-sand mulch layer without (GM) and with a black plastic mulch (BGM) in two crop periods [early (EC) and middle-late (MLC) phases of the cycle].

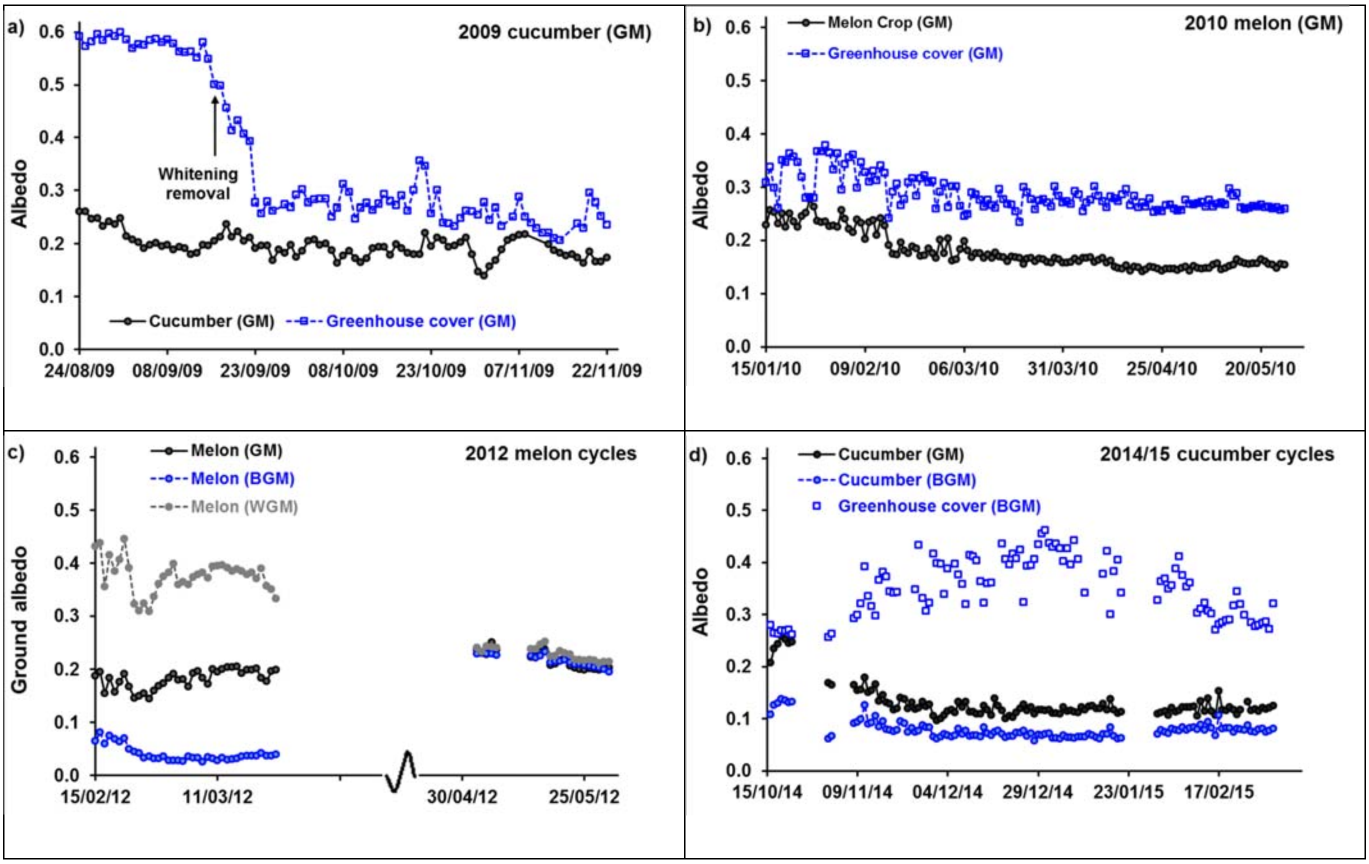

Figure 4. Daily mean ground (a_g) and cover (a_c) albedos in a greenhouse with a gravel-sand mulch layer (GM) throughout the 2009 cucumber **(a)** and the 2010 melon **(b)** cycles. Daily mean a_g values in three greenhouses with a gravel-sand mulch layer, with a black (BGM), a white (WGM) or without (GM) plastic mulch, respectively, at the early and late part of the 2012 melon cycle **(c)**. Daily mean a_g and a_c values in a greenhouse with a gravel-sand mulch layer and a black plastic mulch (BGM), and daily mean a_g values in a greenhouse with a gravel-sand mulch layer (GM) throughout the 2014/15 cucumber cycle **(d)**.

3.2.2 Early 2010 melon cycle

The average over the cycle of the daily mean a_g at the surface of this crop, grown in an *enarenado* with a gravel-sand layer, and of the a_c was 0.18 ± 0.03 and 0.29 ± 0.03, respectively (Table 3). Daily mean a_g and a_c values were higher and more variable at the beginning of the cycle (Fig. 4b). Later on, they decreased slightly and then they remained relatively steady. Daily mean a_g and a_c values averaged over the early part of the cycle when the LAI of the crop was low (< 0.5 m^2 m^{-2}) were 0.24 ± 0.02 and 0.33 ± 0.03, respectively, while over the middle and late of the cycle they were 0.16 ± 0.01 and 0.27 ± 0.02 (Table 3). No relationships were found between daily mean a_g or a_c values and the daily D_o/G_o ratio for this melon cycle (data not shown).

3.2.3 Spring 2012 melon cycle

At the beginning of this cycle, when most of the soil was uncovered, the daily mean a_g was much higher in the greenhouse with WGM than in the greenhouse with BGM, while the greenhouse with GM presented intermediate values (Fig. 4c). The daily mean a_g at the beginning of this cycle, averaged from 14/02 to 23/03/2012, was 0.38 ± 0.03, 0.04 ± 0.02 and 0.18 ± 0.02 in the greenhouses with WGB, BGM and GM, respectively (Table 3). At the end of the cycle, when crops fully covered the soil (they were grown horizontally), the daily mean a_g converged to a value close to 0.23, independently of the mulch type (Fig. 4c). The daily mean a_g averaged from 03/05 to 31/05/2012 was 0.23 ± 0.01, 0.22 ± 0.01 and 0.22 ± 0.02 for the greenhouses with WGB, BGM and GM, respectively. No relationships were found between daily mean a_g values and the daily D_o/G_o ratio at the beginning of the cycle, or at the end of the cycle for any greenhouse treatment (data not shown).

3.2.4 Winter 2014/15 cucumber cycle

The daily mean a_g at the surface of this crop, grown in an *enarenado* with a gravel-sand layer, was lower in the greenhouse with BGM than without it (GM) throughout the whole cycle (Fig. 4d). Averaged over the cycle, the daily mean a_g was 0.08 ± 0.02 in the greenhouse with BGM and 0.13 ± 0.03 in the greenhouse with GM (Table 3). The daily mean a_g was slightly higher at the beginning of the cycle, when the LAI of the crop was lower than 0.5 $m^2\ m^{-2}$, particularly in the greenhouse with GM. Daily mean a_g values were generally lower in this cucumber cycle than in the above-mentioned 2009 cucumber cycle. The daily mean

a_c, averaged over the cycle, was 0.35 ± 0.06 with slightly higher values around the winter solstice when sun elevation angles are lowest (Fig. 4b). A relatively high dispersion of a_c data was found for this cucumber cycle (Fig. 4 d), which might be mostly attributed to: i) the occurrence of overcast and clear days; no relationship was found between daily mean a_g and a_c values and the daily D_o/G_o ratio for the whole cycle, but when the analysis was restricted to shorter and more homogeneous crop periods these relationships, although still weak, improved; and ii) the occurrence of dropwise water condensation on the inner surface of the roof covering material, which frequently occurs during the winter period in Mediterranean greenhouse crops (Hernández et al., 2017).

3.3 Modelling the greenhouse cover albedo

The daily mean reflection coefficient of the greenhouse (ρ) was determined for each experimental period by minimising the RMSE between measured and calculated (eq. 3) a_c values (Tables 1 and 3). In the greenhouses without whitening the value of ρ ranged between 0.24 and 0.30 (Table 1). The highest ρ value corresponded to the greenhouse compartment with NM because the dropwise condensation observed especially in the morning must have increased the greenhouse reflection (Geoola et al., 1998). At the beginning of the 2009 cucumber cycle, the ρ value was much higher (Table 3) because the external surface of the greenhouse cover was heavily whitened. However, the other ρ values determined in the 2009 cucumber and 2010 melon cycles were slightly lower than those found in the experiments without crop, which must be mostly attributed to differences in the sun elevation angle. All the ρ values were logically lower than the corresponding measured a_c values and the difference between a_c and ρ values in each experiment generally increased as the a_g rose (Tables 1 and 3).

Measured daily mean a_c values were compared by linear regression to those estimated with equation 3 using the calibrated ρ value for each experiment or crop period (Tables 1 and 3). In general, most estimated a_c values were close to the measured ones ($a_{c,estimated} = 0.93a_{c,measured} + 0.02$; $R^2 = 0.89$; N = 138), except for data from overcast days ($D_o/S_o > 0.75$) and from the greenhouse with NM. Excluding these data, the goodness of the fit improved (Fig. 5a). The R^2 was 0.94, the MAE 0.017, the RMSE 0.022 and the EF 0.94. Then, the equation 3 was used to quantify the influence of a_g on a_c under a wide range of representative conditions in Mediterranean greenhouses (Fig. 5b). Increasing the a_g value [e.g. from 0.05 (highly absorptive mulch) to 0.60 (highly reflectance mulch)] considerably raised the value of a_c when the greenhouse was not whitened ($\rho < 0.30$), but this effect progressively decreased as the mean daily ρ increased (whitened greenhouse).

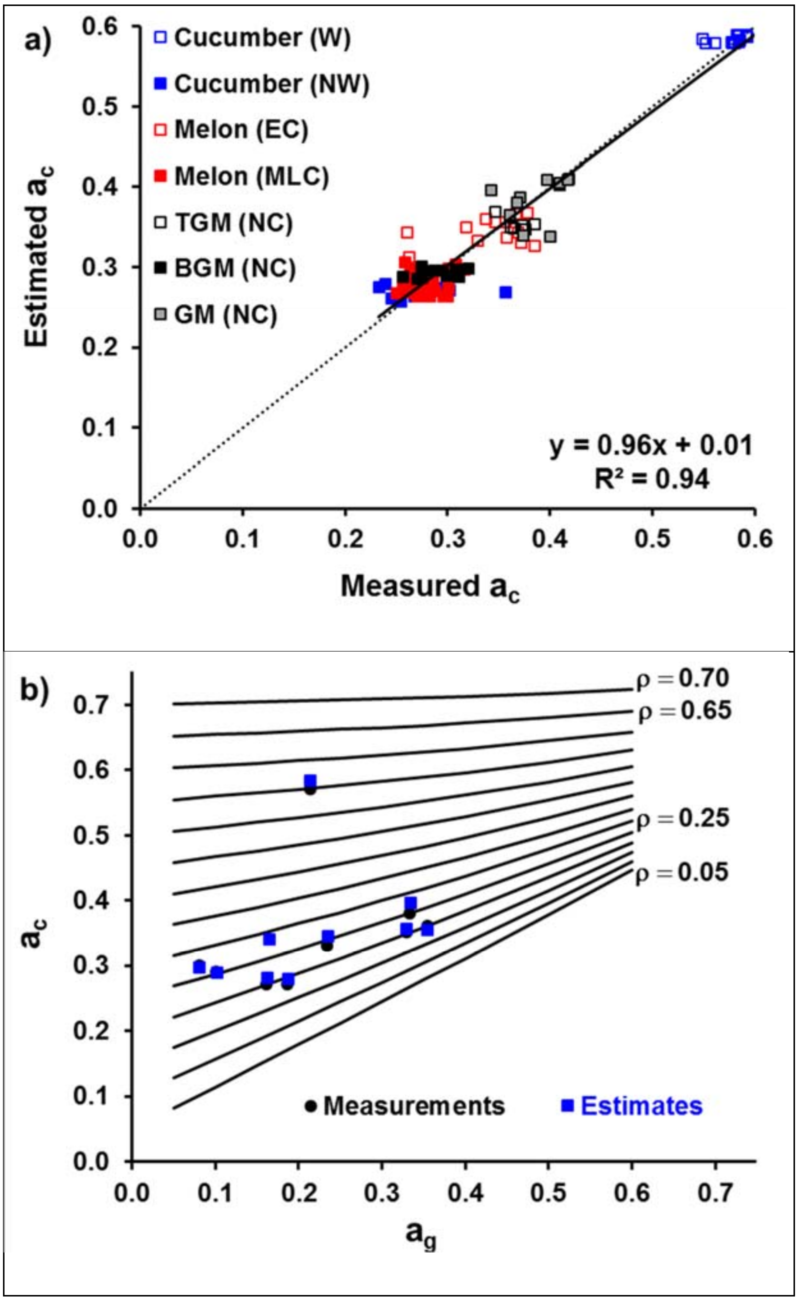

Figure 5. **a)** Estimated versus measured greenhouse cover albedo (a_c) values in a greenhouse without crop (NC) and with several mulch types [transparent (TGM) and black (BGM) plastic film, and gravel-sand layer (GM)], throughout the 2009 cucumber cycle with the greenhouse with (W) and without whitening (NW), and throughout the early (EC) and mid-late (MLC) part of the 2010 melon cycle. **b)** Lines represent daily mean estimated a_c as a function of daily mean ground albedo (a_g) for representative daily mean greenhouse reflectance values (ρ), and measured and estimates mean a_c values for the experiments without crop and for two crop periods throughout the 2009 cucumber and 2010 melon cycles.

4. Discussion

4.1 Ground albedos

4.1.1 Combined effect of mulch and canopy architecture

Gravel-sand mulches, extensively used for greenhouse vegetable production in SE Spain (Bonachela et al., 2020), and plastic mulches substantially affected the daily mean ground albedos (a_g) of unheated plastic greenhouses with and without crops. Substantial a_g differences were found between greenhouse treatments during periods without crop (Fig. 2), at the beginning of the crop cycles (Fig. 4), and also during the middle and late stages of crops grown with high-wire systems (Fig. 4). These differences were mostly attributable to the shortwave reflectance of soil mulches (Ham et al., 1993). The a_g, averaged over the beginning of the crop cycles or the period without crop, ranged from 0.04 to 0.38, and was logically lowest in the greenhouses with BGM and greatest in the greenhouse with WGM (Tables 1 and 3). Greenhouses without crop, or at the beginning of the crop cycle, with BGM and WGM generally presented a_g values close to the shortwave reflectance of these materials (Ham et al., 1993; Tarara, 2000). The a_g in greenhouses with GM was around or higher than 0.30 in periods without crop when the mulch was maintained dry (Table 1), which corresponds to the albedo of dry sandy soils without organic carbon content (Kaye and Quemada, 2017; Tarara, 2000). However, lower a_g were found at the beginning of crop cycles grown in greenhouses with GM (Fig. 4), which was probably due to the lower shortwave reflectance of the ground fraction covered by grow-bags and plants, and the soil partially wetted by drip irrigation (Kaye and Quemada, 2017).

The a_g of greenhouse crops was also influenced by the crop canopy architecture. All the 2012 melon crops, which fully covered the greenhouse soil surface during the second half of their cycles (they grew mostly horizontally since plants were not vertically trained), presented a_g of about 0.23 during most of the last part of their cycles (Fig. 4, Table 3). These values are similar to those usually found for outdoor crops covering most or all the soil surface (Allen et al., 1998; Kaye and Quemada, 2017; Tarara, 2000). On the other hand, greenhouse crops grown with high-wire production systems presented lower a_g values when they reached effective full cover (0.08 to 0.19; Table 3) than those found for crops grown outdoors covering most or all the soil surface (Allen et al., 1998; Kaye and Quemada, 2017; Tarara, 2000) and for greenhouse crops grown horizontally (Table 3). This occurred in spite of the fact that part of the solar radiation reflected from the ground in greenhouse crops is, in turn, reflected by the greenhouse cover, and so on (Fig. 1), which should theoretically increase the a_g of greenhouse crops, compared to those grown outdoors. To our knowledge, no albedo measurements of greenhouse crops grown with high-wire production systems, compared to those grown horizontally, have been reported in the literature. In high-wire production systems, plants are grown in well-separated rows and the canopy is distributed vertically up to 1.5–4 m high, leaving substantial parts of the soil uncovered. This canopy architecture allows greater trapping of reflected solar radiation than in crops grown horizontally fully covering the soil surface (Ling and Roberts, 1982). Therefore, the canopy architecture of greenhouse crops with high-wire production systems reduced the a_g, compared to crops grown outdoors or greenhouse crops grown horizontally (not vertically trained). Moreover, the a_g of greenhouse crops with high-wire production systems was influenced by the mulch type during the whole cycle (0.08 *versus* 0.012 for the 2014/15 cucumber crop with BGM and GM, respectively, Fig. 4 and Table 3) and it also appears to be affected by the sun elevation angle and, the leaf area density and distribution. The a_g of the 2009 cucumber cycle was generally higher than that of the 2014/15 cycle, both grown with high-wire production systems: the 2009 cucumber cycle was mostly grown at autumn under greenhouse climate conditions close to the optimal, leading to a high leaf area development (LAI close to 5 m^2 m^{-2} at the end of the cycle), while the 2014/15 cycle, mostly grown at winter when air temperature and radiation levels in Mediterranean greenhouses are usually suboptimal (Bartzanas et al., 2005; Bonachela et al., 2012; Lorenzo et al., 2005), presented a lower leaf area development (LAI of 3.3 m^2 m^{-2} at the end of the cycle). However, a more detailed study of canopy architecture and shortwave radiation incidence angles is required to elucidate the main factors influencing the a_g of greenhouse crops with high-wire production systems. The relatively lower a_g of greenhouse crops with high-wire production systems, which increases the net shortwave (S_n) radiation at their surface (Table 2), may affect the greenhouse climate, crop production and water use of greenhouse systems, but, to our knowledge, related quantitative information is scarce or lacking. Thus, the relatively higher S_n in greenhouse crops grown with high-wire production systems might explain, at least partially, the higher crop coefficients frequently found in these crops, compared to greenhouse crops grown horizontally (Orgaz et al., 2005).

The use of mulches in greenhouse crops with high-wire production systems modifies the a_g (Tables 1 and 3, and Fig. 4) throughout the whole crop cycles and, therefore, the S_n, but their effects on greenhouse microclimate, energy and water requirements, and crop growth and productivity are complex depending on greenhouse type, characteristics and location, crop cycle, characteristics and season, radiative mulch properties, etc. (Bonachela et al., 2012 and 2020; Decoteau, 2007; Karhu et al., 2007; Lorenzo et al., 2005; Mehlizt et al., 2008; Streck et al., 1995). In crops with high-wire production systems in unheated Mediterranean greenhouses, the use of low-medium reflectance mulches, like black plastic film or gravel-sand layer, appears to be recommendable in cycles centered or starting at winter because they increase usually soil and air temperatures (Bonachela et al., 2012 and 2020) when they are suboptimal (Bartzanas et al., 2005; Lorenzo et al., 2005). However, the use of high reflectance mulches, like white mulch, in these crop cycles does not appear to advisable. These mulches modify the plant light environment (Decoteau, 2007), e.g. increasing the available photosynthetically-active radiation (Lorenzo et al., 2005), but they also decrease greenhouse air and soil temperatures affecting negatively growth, and early or total yields of horticultural crops (Lorenzo et al., 2005). On the other hand, the use of high reflectance mulches, like white mulch, when greenhouse air temperatures are excessive in Mediterranean greenhouse crops with high-wire production systems and cycles centered or starting at summer is questionable and requires further research. These mulches can reduce greenhouse soil and air temperatures (Streck et al., 1995) and improve the photosynthetic active radiation absorbed by the crop (Lorenzo et al., 2005), but they might also increase excessively the radiation reaching the crop rising its temperature, particularly at early crop stages (López, 2020, personal communication).

4.1.2 Effects of diffuse radiation on the ground and cover albedos

The variation in the daily mean a_g or greenhouse cover albedo (a_c), observed in most of the experiments comparing soil mulches in a greenhouse without crop around winter, appears to be mainly attributable to the variation in the daily D_o/G_o ratio (Fig. 2). The daily mean a_g or a_c generally decreased as the daily D_o/G_o ratio rose, as narrow negative linear relationships were found between the daily mean a_g or a_c and the daily D_o/G_o ratio for different ground surfaces, except at the ground of the greenhouse with NM (Table 2). This albedo variation was not associated with changes in the main factors that typically influence the albedo of a given agricultural surface, such as sun elevation angles or soil moisture content (Pinty et al., 2005; Wang et al., 2005; Yang, 2006). For each measured period (two to four weeks) the daily sun elevation angle hardly changed and no relationships were found between daily mean a_g or a_c values and daily sun elevation angles (data not shown). Moreover, the soil water content hardly changed at any greenhouse soil surface, since the plastic or gravel-sand mulches avoided or minimised soil evaporation losses, except for the surface of the greenhouse with NM. We hypothesized that in the experiments without crop conducted near the winter solstice the albedo variation observed at each studied ground surface (GM, BGM or TGM) might be mainly associated with changes in solar radiation incidence angles caused by changes in the daily D_o/G_o ratio. Around the winter solstice, sun elevation angles in SE Spain are low (< 35º at noon) and, therefore, most solar radiation incidence angles on sunny days are relatively low. Overcast days with higher daily D_o/G_o ratios may present higher solar radiation incidence angles, which, in turn, may have slightly decreased the daily mean a_g or a_c. This albedo variation, which was small, was observed in the experiments without crop conducted around winter (Table 2), but not in the experiments with crops carried out for longer time periods from autumn to spring. The small albedo reduction induced by higher D_o/G_o ratios might not occur in the spring and autumn when sun elevation angles are higher than in winter. In the crop experiments (Fig. 4) , the albedo was influenced, besides of mulch type, crop training system and greenhouse whitening, by the sun elevation angle, which changed throughout the cycles, and the occurrence of dropwise water condensation on the inner surface of the covering material, which frequently occurs around winter in Mediterranean greenhouse crops (Hernández et al., 2017).

The lower albedos induced by higher D_o/G_o ratios, in turn, increased the shortwave radiation available at the ground and cover surfaces of greenhouses without crop in the measurements carried out near the winter solstice. The ratio of net to incoming shortwave radiation increased linearly with the daily D_o/G_o ratio, except for the ground surface of the greenhouse without gravel-sand mulch, NM (Table 2). The relative greater shortwave radiation inside the greenhouse on overcast days might be of interest in unheated greenhouses located in mild winter climates, where air temperature is usually suboptimal for winter vegetable production (Bartzanas et al., 2005; López et al., 2008), particularly at early stages of crop cycles starting in winter, when canopy leaf area is small and most of the soil is uncovered. This effect might be enhanced by using more diffuse covering materials that increase the fraction of diffuse radiation inside the greenhouse. Diffuse plastic films are normally used for covering commercial greenhouses at SE Spain, with haze factors of 0.5 to 0.6. Diffuse covering materials, although reduce slightly the solar radiation transmission (Hemming et al., 2008), might increase the greenhouse crop production by inducing a more uniform spatial distribution of solar radiation, a more efficient crop light use and a higher crop photosynthesis (Li et al., 2014). The potential benefits of diffuse covering materials in greenhouse areas of low latitudes, such as the Spanish Mediterranean coast, appear to be high given the large number of clear days (Cabrera et al., 2009; Hemming et al., 2008), but, to our knowledge, experimental data confirming and quantifying these benefits are lacking.

In the greenhouse with NM the inner surface of the plastic cover (without anti-drop agents) presented dropwise condensates in daytime, especially in the morning, which frequently occurs at winter in commercial low-cost plastic greenhouses in SE Spain (Granados et al., 2011; Hernández et al., 2017). This reduced the incoming shortwave radiation reaching the ground surface by an average of 13 %, compared to the greenhouse with GM where no cover condensation was observed. Shortwave radiation transmission of greenhouses might be reduced (due to multiple reflection of solar radiation) or slightly increased, depending on the nature and amount of condensates formed on the covering material (Geoola et al., 1998; Pollet and Pieters, 1999). The water condensed in the greenhouse with NM must arise mostly from soil water evaporation losses, since the volumetric soil water content progressively decreased during the observation period (section 3.1.3), while the volumetric soil water content of the greenhouse with GM hardly changed during the observation period (Yuan et al., 2009). Condensates on the inner cover surface might have increased the diffuse radiation inside the greenhouse with NM, particularly on sunny days, which could explain why the a_g was not related to the daily D_o/G_o ratio (Fig. 2, Table 2), as occurred at the cover surface.

4.2 Greenhouse cover albedo

The simple model (eq. 3) to simulate the daily mean a_c requires prior determination of the daily mean reflectance of the greenhouse, ρ (Table 3). This parameter is not the shortwave reflectance of the greenhouse covering film measured in the laboratory and supplied by the manufacturer, as considered by Fan et al. (2015). The ρ value has to be determined *in-situ*, which requires some daily a_g and a_c measurements, because it mostly depends on, besides the reflectance of the covering film, the incidence angles of the incident shortwave radiation, which, in turn, depend on the solar elevation angle, the D_o/S_o ratio and the greenhouse dimension, geometry and orientation. In general, the calibrated model provided correct estimates of measured daily mean a_c values under a wide and representative range of soil, mulch, crop and greenhouse conditions (Fig. 5), but not on overcast days or in the greenhouse with NM. Both the occurrence of dropwise condensates on the inner surface of the plastic cover and overcast days must modify the calibrated ρ of the greenhouse, reducing the accuracy of the model. Equation 3 is a simple model but it could be useful to: i) determine the ρ value of representative greenhouses and covering materials in different climatic areas; ii) determine the range of ρ values for a representative greenhouse system and covering material; iii) to analyse and quantify how covering materials, crop and greenhouse managements affect the greenhouse cover albedo, and, consequently the greenhouse transmissivity. Thus, equation 3 was used to quantify the influence of a_g on a_c under a wide range of greenhouse conditions (Fig. 5b): e.g. increasing the a_g at the beginning of sweet pepper and tomato crops in Spanish Mediterranean greenhouses, when the greenhouse cover is heavily whitened, hardly affects the a_c (Fig. 5b); on the contrary, increasing the a_g in winter in Spanish Mediterranean greenhouses covered with normal transmission materials leads to substantial a_c decrements (Fig. 5b).

The daily mean a_c averaged over the crop cycle ranged from 0.29 ± 0.03 for the 2010 melon to 0.36 ± 0.14 for the 2009 cucumber crop (Table 3). The greater a_c for the 2009 cucumber crop was mostly due to greenhouse whitening at the beginning of the cycle (Table 3), a common practice in Mediterranean greenhouse areas (Baille et al., 2001). The daily mean measured a_c averaged over the studied greenhouse crop cycles was higher than the typical daily mean a_g of crops grown outdoors (0.23 to 0.26; Allen et al., 1998; Kaye & Quemada, 2017). This means that greenhouses can be an effective system of increasing the global albedo in a Mediterranean region (Campra et al., 2008), particularly from March to October, when greenhouses are usually whitened increasing substantially the greenhouse ρ (Fig. 5b). Using S_o data for the typical meteorological year on the SE Spanish coast (Fernández et al., 2015) and considering mean a_c values of 0.30 for winter, 0.40 for spring and autumn, and 0.50 for summer, the additional amount of daily S_o reflected away from the Earth's surface due to the greater cover albedo of Mediterranean greenhouses, compared to the typical albedo of outdoor crops (0.23 to 0.26), ranged between 34 and 40 W m^{-2}. Hence, extensive Mediterranean greenhouse areas might increase the global albedo, which could contribute to regionally mitigate global warming effects (Campra et al., 2008; Lenton and Vaughan, 2009).

5. Conclusions

Plastic and gravel-sand mulches, extensively used for Mediterranean greenhouse vegetable production, substantially influenced the a_g, which in turn affected the greenhouse a_c. In experiments without crop carried out near the winter solstice, a relatively greater shortwave radiation availability (ratio of net to incoming shortwave radiation) was generally found inside the greenhouse when the ratio of the outside diffuse-to-solar radiation rose, which was associated to lower measured a_g values.

Greenhouse crops grown with high-wire production systems presented lower a_g when they reached effective full cover than crops grown outdoors or greenhouse crops managed in a similar fashion to outdoor crops. The canopy architecture of crops grown with high-wire systems allows greater trapping of reflected solar radiation than in crops fully covering the soil surface. This lower a_g increases the net shortwave radiation at the crop surface, which has be considered when calculating greenhouse radiation components and balances, as well as crop water requirements. The a_g of greenhouse crops with high-wire production systems was influenced by the mulch type and also appears to be affected by the sun elevation angle and the canopy architecture.

A simple model to calculate a_c was developed, calibrated and assessed to quantify the influence of a_g on a_c under a wide range of greenhouse conditions. Greenhouses appear to be an effective system for increasing the global albedo of a Mediterranean region, particularly from March to October when greenhouses are usually whitened.

6. Acknowledgements

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