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Research Paper

Adaptation of standardised (FAO and ASCE) procedures of estimating net longwave and shortwave radiation to Mediterranean greenhouse crops

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Daily net shortwave ($S_{n,g}$) and longwave ($L_{n,g}$) radiation were both measured in six representative Mediterranean greenhouse crop cycles. Daily $S_{n,g}$ and $L_{n,g}$ were firstly estimated with the standardised FAO and ASCE procedures for reference surfaces using meteorological data. Daily $S_{n,g}$ estimated with a seasonal albedo of 0.23 was generally lower than measured values for most crops (RMSE of 0.66 MJ m^{-2} d^{-1}). Accurate $S_{n,g}$ estimates were obtained using a seasonal albedo of 0.16 for all the studied crops (RMSE of 0.33 MJ m^{-2} d^{-1}). Most crops, sown/transplanted at low densities and grown with high-wire production systems over the cold winter period, presented limited vegetative growth. Consequently, in most cases a substantial soil part was uncovered throughout the whole cycle. Daily $L_{n,g}$ determined with the standardised procedure was substantially underestimated (RMSE of 4.12 MJ m^{-2} d^{-1}). The $L_{n,g}$ is affected by the transmission coefficient of the covering material to the longwave radiation (τ_{LR}), which varies mostly depending on its optical properties. Incorporating τ_{LR} as multiplicative factor into the standardised procedure led to accurate daily $L_{n,g}$ estimates for all crops, particularly when they reached effective full cover (RMSE of 0.75 MJ m^{-2} d^{-1}), although $L_{n,g}$ was still overestimated at the beginning of the cycles, particularly during hot periods. Daily total net radiation ($R_{n,g}$), estimated with standardised $S_{n,g}$ and $L_{n,g}$ procedures, was much lower than measured values for all cycles, with poor model performance indicators. Daily $R_{n,g}$ was correctly estimated when standardised $S_{n,g}$ and $L_{n,g}$ procedures were adapted to Mediterranean greenhouse crops: pooling all measured data the RMSE was 0.94 MJ m^{-2} d^{-1}, which improved further when data from the beginning of the cycles were excluded.

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Nomenclature

Abbreviations

e_a	daily actual vapour pressure (kPa)
ET_o	reference crop evapotranspiration (MJ m^{-2} d^{-1})
L_i	daily incoming longwave radiation (MJ m^{-2} d^{-1})
L_o	daily outgoing longwave radiation (MJ m^{-2} d^{-1})
L_n	daily net longwave radiation (MJ m^{-2} d^{-1})
MAE	mean absolute error (MJ m^{-2} d^{-1})
R_n	daily net radiation (MJ m^{-2} d^{-1})
RMSE	root mean square error (MJ m^{-2} d^{-1})
S_i	daily incoming shortwave radiation (MJ m^{-2} d^{-1})
S_{io}	daily clear-sky radiation (MJ m^{-2} d^{-1})
S_n	daily net shortwave radiation (MJ m^{-2} d^{-1})
S_o	daily outgoing shortwave radiation (MJ m^{-2} d^{-1})
SP	standardised procedure
SP-G	standardised procedure adapted to Mediterranean greenhouse crops
T_{max}	daily maximum absolute air temperature (K)
T_{min}	daily minimum absolute air temperature (K)
α	shortwave albedo
σ	Stefan–Boltzmann constant (4.903 10^{-9} MJ K^{-4} m^{-2} d^{-1})
τ_{LR}	greenhouse longwave radiation transmission
τ_{SR}	greenhouse shortwave radiation transmission

Subscripts

g	inside the greenhouse

1. Introduction

Net radiation (R_n) is used in many agricultural modelling applications (e.g. crop growth or irrigation requirement estimation), but it is not routinely measured at weather stations (Dong et al., 1992; Kessler & Jaeger, 1999) or its measurement may be of poor quality because net radiometers are problematic to maintain and calibrate (American Society of Civil Engineers, 2005). Daily R_n is commonly estimated based on other meteorological variables (Allen et al., 1998; American Society of Civil Engineers, 2005; Kjaersgaard et al., 2009; Monteith & Unsworth, 1990).

Denoting radiation flux directed towards the surface as positive, R_n is the sum of incoming and outgoing shortwave (0.2–3 μm) and longwave (3–100 μm) radiation (eq. 1).

$$R_n = S_n + L_n = S_i - S_o + L_i - L_o = (1-\alpha)S_i + L_n \tag{1}$$

where S_i and S_o are incoming and outgoing shortwave radiation, respectively; L_i and L_o are incoming and outgoing longwave radiation, respectively; α is shortwave albedo or canopy/soil reflection coefficient integrated over all shortwave bands; and S_n and L_n are net shortwave and longwave radiation, respectively.

The Penman–Monteith equation, adapted to a well irrigated reference crop with fixed canopy and aerodynamic characteristics, has been adopted as the standardised method for computing the reference crop evapotranspiration (ET_o) by the Food and Agriculture Organization, FAO, and the American Society of Civil Engineers, ASCE (Allen et al., 1998; American Society of Civil Engineers, 2005). This method is used worldwide for calculating irrigation requirements of open field crops (Pereira et al., 2015). Net radiation, the major input affecting ET_o, is usually estimated from meteorological data because it is difficult and expensive to measure accurately (Allen et al., 1998; American Society of Civil Engineers, 2005). Daily S_n is usually obtained from S_i measurements, readily obtainable from many weather stations, and crop albedo, which can be determined from surface properties and solar radiation incidence angles. The albedo of most green field crops with full vegetation cover generally ranges from 0.20 to 0.30 (Brutsaert, 1982; Fritschen, 1967; Kaye & Quemada, 2017). Soil albedo is usually lower than plant albedo and it typically ranges between 0.10 and 0.24 (Kaye & Quemada, 2017). Crop albedo can be determined from the albedo of plants and soils weighted by their respective ground covering fractions. The albedo of standardised short (clipped grass) and tall (full-cover alfalfa) reference surfaces for ET_o calculation (Allen et al., 1998; American Society of Civil Engineers, 2005) has been fixed at 0.23.

Daily L_n is usually computed from other meteorological variables. The standardised ASCE and FAO procedure (Allen et al., 1998; American Society of Civil Engineers, 2005) to calculate daily L_n (MJ m^{-2} d^{-1}) over reference surfaces (eq. (2)) is based on the Brunt approach (Brunt, 1932, 1952) for predicting net surface emissivity. Daily L_o is proportional to the absolute temperature of the surface raised to the fourth power (Stefan–Boltzmann law), but the net energy flux leaving the earth's surface is less than that emitted due to the absorption and downward radiation from the sky (L_i). Water vapour, clouds, carbon dioxide and dust are both absorbers and emitters of longwave radiation. In general, humidity and cloudiness are the main factors determining L_i, assuming that concentrations of the other absorbers are constant. Thus, the net outgoing flux of longwave radiation can be estimated by correcting L_o values by humidity and cloudiness factors.

$$L_n = L_o - L_i = \sigma\left[\frac{T_{max}^4 + T_{min}^4}{2}\right]\left(0.34 + 0.14\sqrt{e_a}\right)\left(1.35\frac{S_i}{S_{io}} + 0.35\right) \tag{2}$$

where σ is Stefan–Boltzmann constant (4.903 10^{-9} MJ K^{-4} m^{-2} d^{-1}); T_{max}, and T_{min} are daily maximum and minimum absolute air temperatures (K) at the standard height (normally 2 m aboveground), respectively; e_a is daily mean vapour pressure (kPa), calculated from daily maximum and minimum data of air temperature and humidity at the standard height (Allen et al., 1998; American Society of Civil Engineers, 2005); S_{io} is daily clear-sky radiation (MJ m^{-2} day^{-1}). The term

$(0.34 + 0.14\sqrt{e_a})$ expresses the correction factor for air humidity, calculated using the relationship developed by Brunt (1932). The cloudiness effect is expressed by the term (1.35 S_i/S_{io} + 0.35), an empirical relationship based on the ratio of S_i and S_{io} (Wright & Jensen, 1972), which is limited ($0.3 < S_i/S_{io} \leq 1.0$). Allen (1996) and American Society of Civil Engineers (2005) outlined methods to estimate theoretical S_{io} curves.

Greenhouse crop systems are expanding in many parts of the world. Most of them are plastic greenhouses located in regions with mild winter climates (Zabeltitz, 1999), such as the Mediterranean coast of South-East Spain (the largest greenhouse concentration in Europe), where low-cost, unheated, naturally ventilated, plastic greenhouses predominate (Pardossi et al., 2004). In greenhouse crop systems, the daily greenhouse net radiation ($R_{n,g}$) is also used for modelling crop growth and water requirements, greenhouse climate, etc. (Baille, 1999; Fernández et al., 2010). Greenhouses modify the crop microclimate as compared to open field crops (Baille, 1999). Both the shortwave ($S_{n,g}$) and longwave ($L_{n,g}$) radiation components of $R_{n,g}$ might be substantially affected by the greenhouse, mostly by the covering material. The fraction of the external solar radiation that enters the greenhouse, or greenhouse transmission coefficient (τ_{SR}), usually ranges between 55 and 70% (Baille, 1999), but in Mediterranean greenhouses this fraction might be lower during some crop periods, particularly around the summer, when the external greenhouse cover is usually whitened to shade the crops (Baille et al., 2001). Albedo measurements of greenhouse crops are scarce and, compared to open field crops, they can be influenced by the greenhouse or crop/soil management practices (Bonachela, López, Hernández, et al., 2020). These authors found lower albedos in Mediterranean greenhouse crops cultivated with high-wire production systems (plants grown in separated rows with the canopy distributed vertically up to 1.5–2.25 m, leaving a substantial part of the soil uncovered) than those usually found for open field crops. No specific measurements of soil albedo have been carried out in Mediterranean greenhouse crops, but measurements carried out immediately after planting when plants cover only a small fraction of the ground of vegetables crops grown on enarenado soils ranged between 0.20 and 0.27 (Bonachela, López, Hernández, et al., 2020). Measurements of $L_{n,g}$ are also scarce (Hernández et al., 2017), and are likely affected by greenhouse covering materials, especially thermal ones, which reduce longwave radiation losses (Kitta, Baille, Katsoulas, & Rigakis, 2014; Papadakis et al., 2000). The transmission coefficient of the covering material to the longwave radiation (τ_{LR}), which varies mostly depending on material optical properties, affects $L_{n,g}$. The τ_{LR} is usually defined as the mean material transmission in the range of 7.5–13 μm, where bodies at ambient temperature have the maximum energy emission (Siegel & Howell, 1971). Values of τ_{LR} for horticultural glasses covering heated greenhouses are close to 0, while conventional plastic films covering unheated greenhouses (mostly polyethylene, PE) present τ_{LR} higher than 0.40 (PE) or between 0.10 and 0.25 (thermal PE).

The Penman–Monteith standardised ET_o equation is also used to calculate irrigation water requirements in low-cost, naturally-ventilated greenhouse crops (Fernández et al., 2010; Gavilán et al., 2015; Qiu et al., 2013). For these crops, a simple method of daily $R_{n,g}$ estimation is needed, since this variable is not commonly measured and the standardised ASCE and FAO calculation procedure has not been well evaluated. Daily $R_{n,g}$ can also be predicted using outside (S_i) or greenhouse ($S_{i,g}$) global radiation measurements (Katsoulas & Stanghellini, 2019; Saadon et al., 2021), but this approach, which neglects the net greenhouse exchange of thermal radiation, usually requires locally calibrated coefficients.

This work focussed on unheated, naturally ventilated, plastic greenhouses, the vast majority in the Mediterranean, where the external climate has a strong influence on the greenhouse microclimate. The main objectives were: i) to measure and analyse net shortwave and longwave radiation in Mediterranean greenhouse crops; and ii) to adapt and evaluate the standardised ASCE and FAO procedure of estimating daily net radiation (net longwave and shortwave components) to Mediterranean greenhouse crops using mainly meteorological data.

2. Materials and methods

2.1. *Experiments and greenhouses*

Experiments were carried out in two identical three-span greenhouses of 22.5 m × 28 m (630 m^2) at the research station of “Cajamar Foundation” (2°43′W; 36°48′E; 155 m.a.s.l.), Almería, SE Spain. The E–W oriented greenhouses were arch-roofed (4.5 m high to the ridges and 3.0 m to the eaves), with one roof vent per span and southern and northern sidewall rolling vents (Fig. 1). 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 τ_{SR} of 89% and a τ_{LR} of 25% (manufacturer's data). It was replaced in early autumn 2011 and 2014, and early summer 2019 with a three-layer, anti-fog thermal film of 200 μm thickness (Sotrafa SA) with a τ_{SR} of 90%, a τ_{LR} of 10%, and a haze factor of 55% (manufacturer's data). Crops were grown on enarenado soils, widely used in this region (Bonachela, López, Granados, et al., 2020): soils with a 0.3 m layer of imported loamy soil covered with a 0.1 m mulch layer mostly composed of fine gravel and very coarse sand particles. The following crop experiments were conducted applying local management practices (Table 1).

- Autumn cucumber 2009 cycle. A cucumber crop (*Cucumis sativus* L. cv. Mirlo) was grown from 24/08/2009 to 24/11/2009 in perlite grow-bags. Plant rows were separated 1.6 m (2.0 plants m^{-2}). The greenhouse external cover was moderately whitened with calcium carbonate before planting to avoid excessive temperatures (τ_{SR} was reduced to about 34%). The whitening was completely removed (water cleaning) on the 22 of September (Bonachela, López, Hernández, et al., 2020).
- Winter-spring melon 2010 cycle. A melon crop (*Cucumis melo* L. cv. Yalo) was cultivated from 14/01 to 1/06/2010 in perlite bags and plant rows were separated 1.6 m (1.5 plants m^{-2}). During the two first weeks of the cycle, crop rows were covered with floating row covers

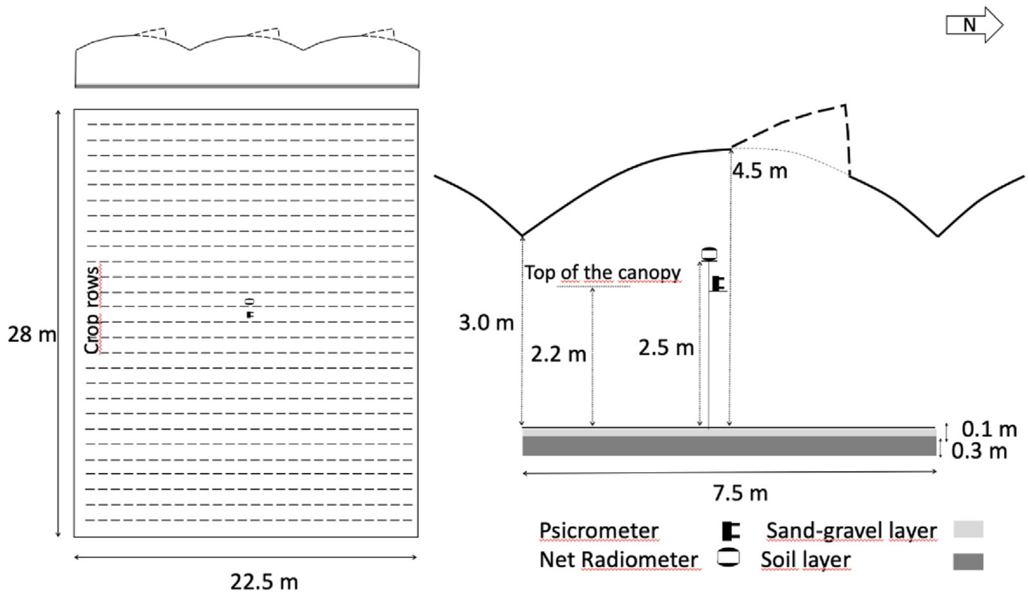

Fig. 1 – Schematic views of the experimental greenhouse including soil layers, orientation of crop rows and top of the crop canopy, greenhouse structure and covering materials, and type and location of climate sensors. El Ejido, Almería, Spain.

(17 g m^{-2} density) to improve the microclimate around the plants.

- Autumn-winter cucumber 2010/11 cycle. A cucumber crop (cv. Dylan) was grown from 28/10/2010 to 4/03/2011 in perlite grow-bags and plant rows were separated 1.6 m (1.33 plants m^{-2}). The greenhouse had a low-cost, internal, fixed plastic screen between the crop and the cover (Hernández et al., 2017).
- Autumn-winter cucumber 2014/15 cycle. A cucumber crop (cv. Valle) was grown from 16/10/2014 to 4/03/2015 in coconut coir grow-bags and plant rows were separated 1.6 m (1.0 plant m^{-2}). The greenhouse had a low-cost, internal, fixed plastic screen.
- Summer-winter sweet pepper 2019/20 cycle. A sweet pepper crop (*Capsicum annuum* L., cv. Sibelius) was grown on an enarenado soil from 11/07/2019 to 5/02/2020. Plant rows were separated 1 m (2.0 plant m^{-2}). The cover was heavily whitened with calcium carbonate before planting (τ_{SR} was reduced to about 27%), which was progressively removed throughout September and October.
- Summer-autumn cucumber 2020 cycle. A cucumber (cv. Pradera) crop was grown on the enarenado soil from 5/08 to 15/11/2020. Plants were separated 1.4 and 0.6 m between rows (1.33 plants m^{-2}). The cover was moderately whitened with calcium carbonate before planting (τ_{SR} was reduced to 42%), which was progressively removed throughout October.

Crops were North-South oriented and guided vertically (high-wire production system) to a height of about 2–2.25 m (1.5 m in the case of sweet pepper). These are common practices in Mediterranean greenhouse crops in SE Spain.

2.2. *Measurements*

During each experiment, greenhouse air temperature and relative humidity were measured around the upper part of the crop canopy (2.0–2.2 m aboveground) in the middle of the greenhouse (Fig. 1) with ventilated capacitance psychrometers. The HMP45C probe (Vaisala, Campbell Scientific Inc., Logan, UT, USA) was used for the cucumber 2009, melon 2010

Table 1 – Crop experiments carried out in two identical three-span greenhouses (1 and 2), crop cycles and main radiometric properties of greenhouse covering material [plastic transmission coefficient (%) to shortwave (τ_{SR}) and longwave (τ_{LR}) radiation].

Crop experiments	Greenhouses and crop cycles	Covering	
		τ_{SW}	τ_{LW}
Cucumber 2009	1 (24/08–24/11/2009)	89	25
Melon 2010	1 (14/01–1/06/2010)	89	25
Cucumber 2010/11	1 (28/10/2010–4/03/2011)	89	25
Cucumber 2014/15	2 (16/10/2014–4/03/2015)	90	10
Pepper 2019/20	1 (11/07/2019–5/02/2020)	90	10
Cucumber 2020	1 (5/08–15/11/2020)	90	10

and cucumber 2010/11 cycles, while the HMP155 probe (Vaisala, Campbell Scientific) for the remainder. Outdoor air temperature and relative humidity, and solar radiation were measured with a ventilated psychrometer (mod. 1.1130, Thies Clima, Göttingen, Germany) and a pyranometer (model CM21, Kipp & Zonen), respectively, mounted at 1.5 m height on bare land 100 m away from experimental greenhouses.

Net radiation inside the greenhouse ($R_{n,g}$) was measured with a net radiometer (CNR1, Kipp & Zonen, Delft, The Netherlands) located above the crop canopy in the middle of the greenhouse (Fig. 1). This sensor, equipped with two pyranometers and two pyrgeometers, measures separately the total upward and downward shortwave and longwave radiation fluxes. Daily net shortwave radiation at the crop surface ($S_{n,g}$) was obtained from the difference between incident and reflected solar radiation. Daily net longwave radiation ($L_{n,g}$) was calculated as the difference between incident longwave radiation and that emitted by the crop/ground surface. Data were averaged and registered every 5 min by data logging devices (CR1000 and CR3000, Campbell Scientific Inc.).

A set of statistical goodness-of-fit indicators (Willmott, 1982) was used: regressions (intercept and slope) and determination (R^2) coefficients of the linear regression relating estimates with observed data; root mean square error (RMSE, MJ m^{-2} d^{-1}); and mean absolute error (MAE, MJ m^{-2} d^{-1}).

3. Results and discussion

3.1. Measurement and estimation of greenhouse net shortwave radiation

Daily $S_{n,g}$, measured above the crop surface of six representative Mediterranean greenhouse crop cycles (autumn cucumber 2009, winter-spring melon 2010, autumn-winter cucumber 2010/11, autumn-winter cucumber 2014/15, summer-winter sweet pepper 2019/20 and summer-autumn cucumber 2020), ranged between 0.4 and 16.6 MJ m^{-2} d^{-1} (Fig. 2). It was generally lower in winter when solar radiation is usually lowest, but it was also relatively low at the beginning of the cucumber 2009, sweet pepper 2019/20 and cucumber 2020 crop cycles when the greenhouse cover was whitened.

For each crop cycle, the daily $S_{n,g}$ was estimated as the daily incoming solar radiation reaching the crop ($S_{i,g}$) multiplied by the mean seasonal crop albedo. Considering the statistical indicators, the best fit between estimated and measured $S_{n,g}$ values was obtained with a mean seasonal albedo value that ranged from 0.13 for the autumn-winter cucumber 2010/11 and 2014/15 cycles to 0.23 for the autumn cucumber 2009 cycle (Fig. 3, Table 2). The latter crop developed a high vegetative growth (leaf area index values close to 5 m^2 m^{-2} at the end of the cycle) since it mostly grew over an autumn period with quasi optimal greenhouse climate conditions (Bonachela, López, Hernández, et al., 2020). The RMSE was low and ranged from 0.14 MJ m^{-2} d^{-1} for the cucumber 2020 to 0.30 MJ m^{-2} d^{-1} for the cucumber 2014/15 cycle. For all studied crop cycles, except for the cucumber 2009, the daily $S_{n,g}$ estimated with a mean seasonal albedo of 0.23, commonly used for open field crops (Allen et al., 1998; American Society of Civil Engineers, 2005), was clearly lower than measured values (Fig. 3). Pooling data from the six crop cycles (Fig. 4), a narrow linear relationship was found between daily $S_{n,g}$ estimates using a mean seasonal albedo of 0.16 and measured $S_{n,g}$ values (N = 671; R^2 = 0.99; RMSE = 0.33 MJ m^{-2} d^{-1}; MAE = 0.25 MJ m^{-2} d^{-1}). These crops, usually grown at relatively low plant densities for preventing fungal diseases, presented a relatively low vegetative growth, particularly those growing over the winter period when air temperature and radiation values are usually suboptimal (Bartzanas et al., 2005; Lorenzo et al., 2005), leaving substantial parts of the soil uncovered throughout most of their cycles. The lower albedos of these greenhouse crops, compared to those usually found for open field crops with effective full cover (Kaye & Quemada, 2017; Tarara, 2000) or for greenhouse crops grown horizontally and covering most or all the soil surface (Bonachela, López, Hernández, et al., 2020), can be mainly attributed to their canopy architecture (leaf area density and distribution), which allows greater trapping of reflected solar radiation than crops grown horizontally fully covering the soil surface (Bonachela, López, Hernández, et al., 2020), although other factors (sun elevation angle, crop layout, soil albedo, whitening, etc.) might also have contributed. Nevertheless, when greenhouse crops with high-wire production systems present a high vegetative growth and cover most of the soil surface, higher albedo values, close to 0.23, might provide better $S_{n,g}$ estimates. Overall, a mean seasonal albedo of 0.16 might provide correct estimates of daily $S_{n,g}$ for most Mediterranean greenhouse crops grown with high-wire production systems.

3.2. Measurement and estimation of greenhouse net longwave radiation

The daily $L_{n,g}$, measured above the crop surface of six representative Mediterranean greenhouse crop cycles, ranged between −4.0 and 0.5 MJ m^{-2} d^{-1} (Fig. 5). It was negative throughout all the studied crop cycles, with the exception of a few days, since the downward is usually lower than the upward longwave radiation (Bonachela et al., 2012; Hernández et al., 2017). Daily $L_{n,g}$ values were generally lower (more negative) at the beginning of each crop cycle (Fig. 5), when the crop leaf area index was small and most of the soil surface was uncovered, after which the daily $L_{n,g}$ remained relatively steadier. This occurred particularly when the beginning of the cycle occurred during hot crop periods (Fig. 5). The high soil surface temperatures of enarenado soils during hot crop periods may substantially increase the upward longwave radiation, and consequently reduce the daily $L_{n,g}$ (Bonachela et al., 2012; Bonachela, López, Granados, et al., 2020). However, at the beginning of the 2010 melon cycle, which took place during a cold crop period (January and February 2010), the daily $L_{n,g}$ was not usually lower than during the remaining cycle (Fig. 5), which could be associated to relatively lower soil surface temperatures and/or the use of floating row covers.

The daily $L_{n,g}$ was firstly estimated with the standardised ASCE and FAO procedure (eq. (2); Allen et al., 1998; American

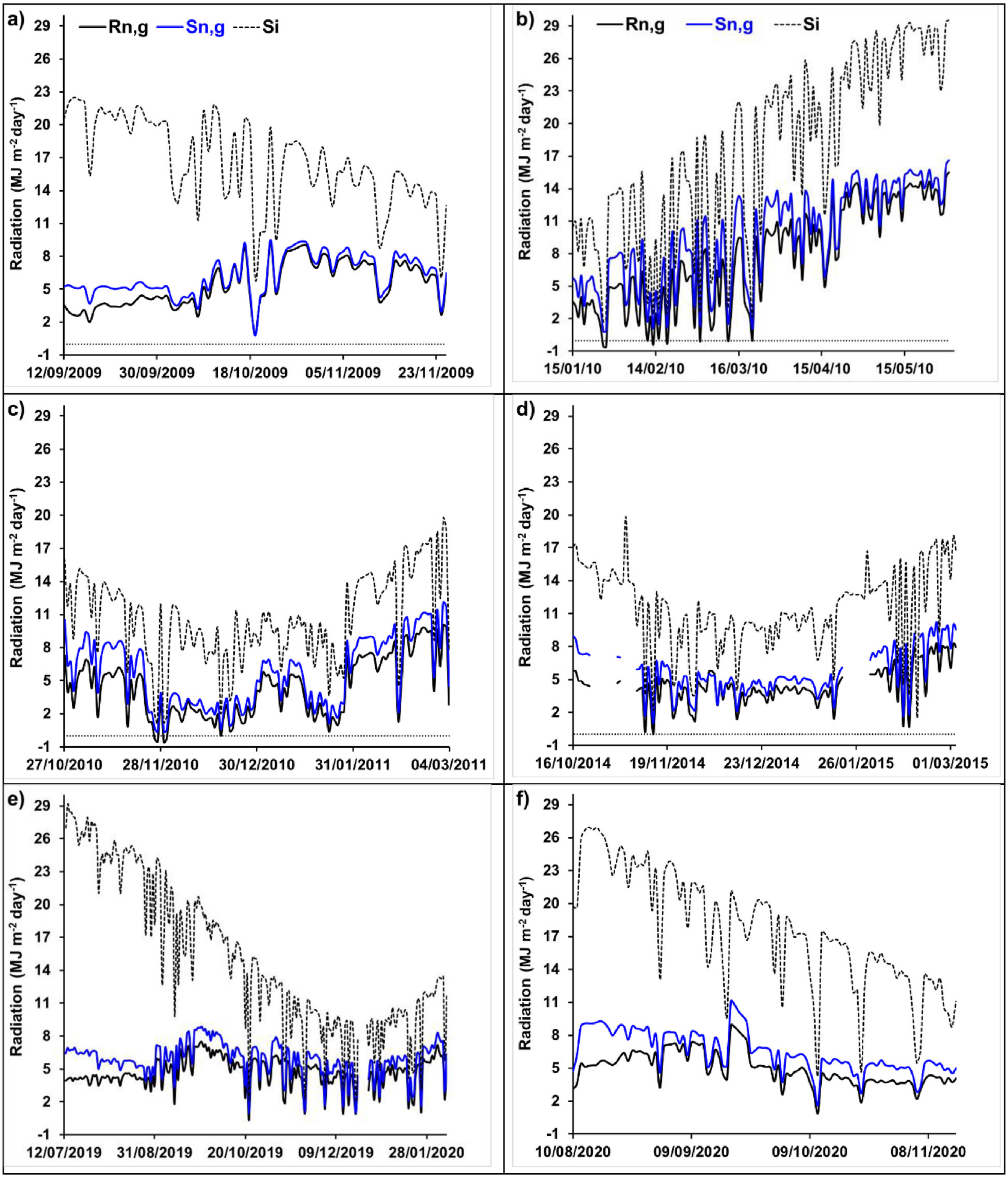

Fig. 2 – Daily values of net shortwave ($S_{n,g}$) and total radiation ($R_{n,g}$), and outdoor incoming shortware radiation (S_i), measured in six representative Mediterranean greenhouse crop cycles: a) autumn-cucumber 2009; b) winter-spring melon 2010; c) autumn-winter cucumber 2010/11; d) autumn-winter cucumber 2014/15; e) summer-winter sweet pepper 2019/20; and f) summer-autumn cucumber 2020. El Ejido, Almería, Spain.

Society of Civil Engineers, 2005). In this equation, daily maximum and minimum absolute greenhouse air temperatures ($T_{max,g}$ and $T_{min,g}$) were used, the humidity factor was calculated with the daily mean outdoor vapour pressure (e_a), and the cloudiness factor was calculated with daily values of outdoor incoming solar radiation and clear-sky radiation (S_{io}) data. Daily $L_{n,g}$ estimates were substantially lower than measured values for all crop cycles (Fig. 5) with poor model performance indicators (Table 2): the RMSE ranged from 3.38 MJ m^{-2} d^{-1} for the cucumber 2020 cycle to 5.48 MJ m^{-2} d^{-1}

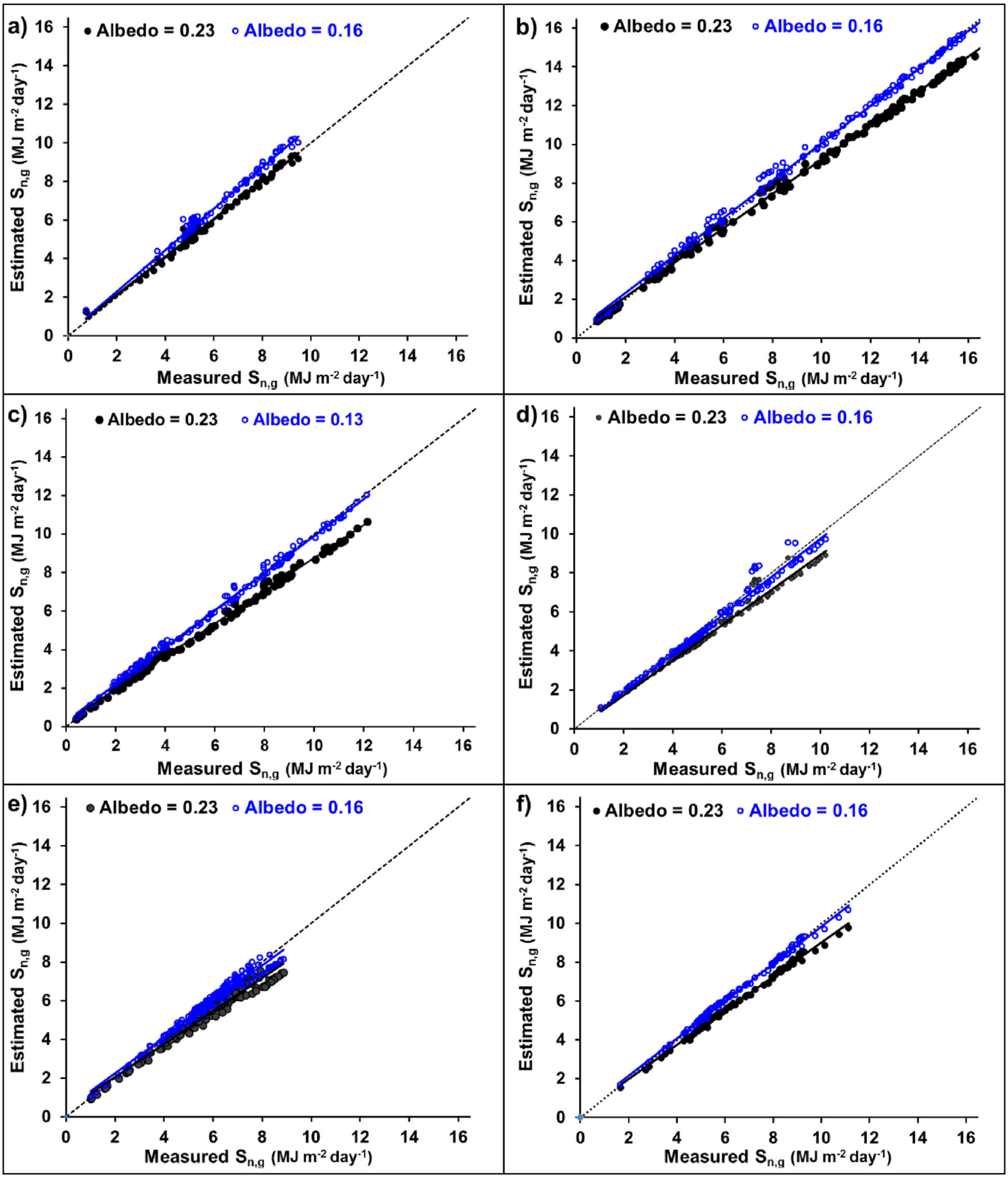

Fig. 3 – Comparisons and linear regression lines of estimated versus measured values of the daily net shortwave radiation ($S_{n,g}$) throughout six representative Mediterranean greenhouse crop cycles: a) autumn-cucumber 2009 [N = 75; (albedo = 0.23: y = 0.98x + 0.15, R^2 = 0.99); (albedo = 0.16: y = 1.07x + 0.16, R^2 = 0.99)]; b) winter-spring melon 2010 [N = 137; (albedo = 0.23: y = 0.89x + 0.38, R^2 = 0.99); (albedo = 0.16: y = 0.97x + 0.41, R^2 = 0.99)]; c) autumn-winter cucumber 2010/11 [N = 130; (albedo = 0.23: y = 0.85x + 0.25, R^2 = 0.99); (albedo = 0.13: y = 0.96x + 0.28, R^2 = 0.99)]; d) autumn-winter cucumber 2014/15 [N = 115; (albedo = 0.23: y = 0.90x − 0.08, R^2 = 0.98); (albedo = 0.16: y = 0.98x − 0.09, R^2 = 0.98)]; e) summer-winter sweet pepper 2019/20 [N = 206; (albedo = 0.23: y = 0.85x − 0.36, R^2 = 0.97); (albedo = 0.16: y = 0.93x − 0.39, R^2 = 0.97)]; and f) summer-autumn cucumber 2020 [N = 99; (albedo = 0.23: y = 0.88x + 0.21, R^2 = 0.99); (albedo = 0.16: y = 0.96x + 0.23; R^2 = 0.99)].

Table 2 – Summary of statistics from the comparison between estimated and measured values (MJ m^{-2} d^{-1}) of daily net shortwave ($S_{n,g}$), longwave ($L_{n,g}$) and total radiation ($R_{n,g}$) in six representative Mediterranean greenhouse crops. Crop albedo (α). Standardised ASCE and FAO procedures of $L_{n,g}$ and $R_{n,g}$ estimation (SP), and the SP adapted to Mediterranean greenhouses (SP-G).

	$S_{n,g}$			$L_{n,g}$		$R_{n,g}$	
	α=0.13	α=0.16	α=0.23	SP	SP-G	SP	SP-G
Cucumber 2009							
RMSE (MJ–m^{-2}–d^{-1})	0.89	0.65	0.20	5.48	0.77	5.46	0.77
MAE (MJ–m^{-2}–d^{-1})	0.84	0.60	0.15	5.19	0.68	5.16	0.48
Melon 2010							
RMSE	0.49	0.28	0.90	3.04	1.12	3.86	1.13
MAE	0.43	0.20	0.73	2.69	0.93	3.36	0.99
Cucumber 2010/11							
RMSE	0.22	0.31	0.78	4.15	0.60	4.82	0.64
MAE	0.18	0.26	0.61	3.79	0.47	4.38	0.51
Cucumber 2014/15							
RMSE	0.30	0.34	0.72	5.23	0.58	5.90	0.79
MAE	0.16	0.29	0.66	4.79	0.44	5.41	0.63
Pepper 2019/20							
RMSE	0.32	0.27	0.60	3.38	0.84	3.89	0.81
MAE	0.28	0.19	0.51	3.15	0.71	3.66	0.68
Cucumber 2020							
RMSE	0.25	0.14	0.61	4.18	0.78	4.73	0.77
MAE	0.23	0.10	0.56	3.97	0.56	4.52	0.57
All crops							
RMSE		0.33	0.66	4.12	0.91	4.67	0.94
MAE		0.25	0.50	3.72	0.74	4.24	0.72

RMSE: root mean square error; MAE: mean absolute error.

for the cucumber 2009 cycle. Moreover, $L_{n,g}$ estimates did not improve when outdoor air temperatures instead of greenhouse air temperatures were used in equation (2) (data not shown).

The standardised ASCE and FAO procedure (Allen et al., 1998; American Society of Civil Engineers, 2005) for daily $L_{n,g}$ estimation was adapted to greenhouse crop systems by multiplying equation (2) by a covering factor, the τ_{LR} characteristic of the covering material (eq. (3)). This parameter, usually provided by the manufacturer, represents the covering material property primarily affecting the longwave radiation exchanges inside unheated greenhouses (Papadakis et al., 2000). The reflectivity and emissivity of the covering material might also affect daily $L_{n,g}$, but given the relatively narrow range of reflectivity and emissivity of longwave radiation values found in commercial materials covering unheated greenhouses and, particularly, the scarce and incomplete information about how these covering properties affect daily $L_{n,g}$, they have not been considered. Moreover, the effects of whitening, a common practice in Mediterranean greenhouse crops (Baille et al., 2001), on daily $L_{n,g}$ are not well-documented to our knowledge, and, consequently, have not been considered.

$$L_{n,g} = \sigma \left[\frac{(T_{max,g})^4 + (T_{min,g})^4}{2} \right] (0.34 + 0.14\sqrt{e_a}) \left(1.35 \frac{S_i}{S_{io}} + 0.35 \right) (\tau_{LR}) \tag{3}$$

The incorporation of this covering factor in equation (3) substantially improved daily $L_{n,g}$ estimates (Fig. 5) and all the studied statistical performance indicators (Table 2), particularly the RMSE and the MAE, which were much lower for all the studied crop cycles. Pooling data of the six studied crop cycles, the RMSE decreased to 0.91 MJ m^{-2} d^{-1} and the MAE to 0.74 MJ m^{-2} d^{-1}. The performance of this formula (eq. (3)) appears to improve when crops reached effective full cover (Fig. 5), since the daily $L_{n,g}$ was frequently overestimated at the beginning of the crop cycles, particularly during hot cropping periods, such as the sweet pepper 2019/20, the cucumber 2020 and 2014/15 cycles. When data from the beginning of the six studied crop cycles were excluded (first 30 days of each cycle), the RMSE and the MAE decreased to 0.75 and 0.61 MJ m^{-2} d^{-1}, respectively. At the beginning of the cycles, the soil/ground surface, which is mostly uncovered, might reach very high temperatures, particularly during hot crop periods in enarenado soils (Bonachela, López, Granados, et al., 2020). This may substantially increase the upward longwave radiation, and consequently reduce the daily $L_{n,g}$. The use of greenhouse soil/ground surface temperatures instead of greenhouse air temperatures in equation (3) at the beginning of the crop cycles, when the soil is mostly uncovered, appears to be more representative of greenhouse net longwave radiation exchanges and might provide better daily $L_{n,g}$ estimates, but soil temperatures were not measured in the studied

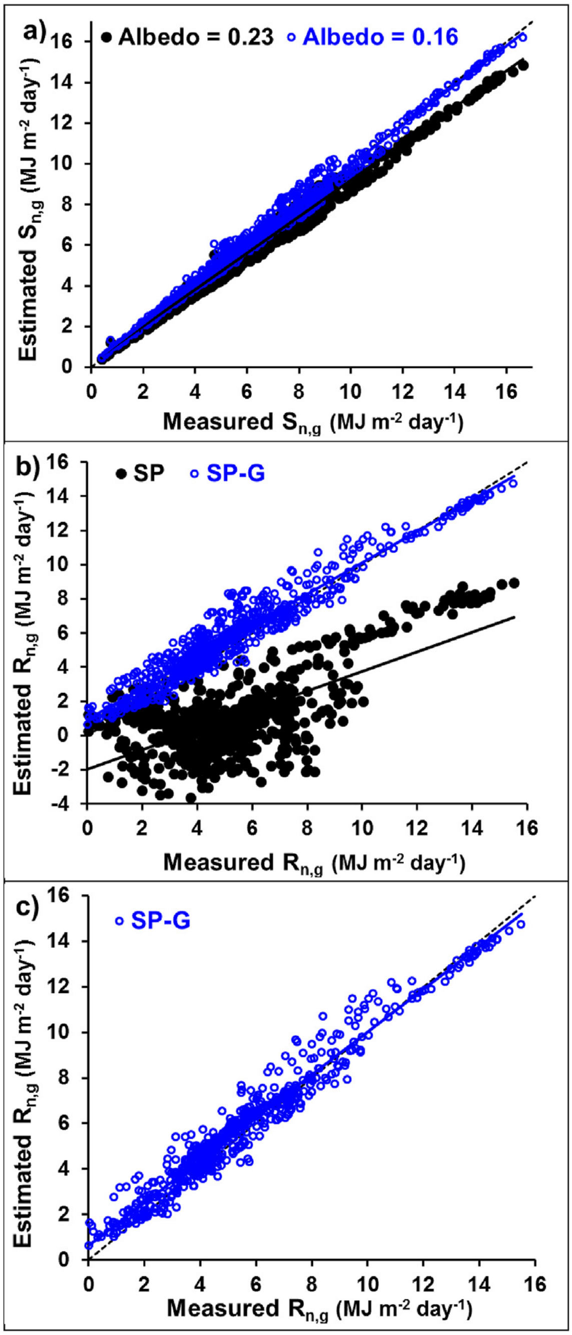

Fig. 4 – Comparisons and linear regression lines of estimated versus measured values of: a) daily net shortwave radiation ($S_{n,g}$) estimated using mean seasonal albedos of 0.23 (N = 761, y = 0.90x + 0.20, R^2 = 0.98) and 0.16 (y = 0.98x + 0.17, R^2 = 0.99); b) daily net radiation ($R_{n,g}$) estimated with the standardised ASCE and FAO procedure (SP: N = 761, y = 0.57x − 1.95, R^2 = 0.49) and with the standardised ASCE and FAO procedure adapted to Mediterranean greenhouses (SP-G: y = 0.92x + 0.97, R^2 = 0.93); c) daily $R_{n,g}$ estimated with the SP-G, but excluding data from the beginning of each crop cycle (N = 612, y = 0.94x + 0.65, R^2 = 0.96, MAE = 0.55 MJ m^{-2} day^{-1}, RMSE = 0.70 MJ m^{-2} day^{-1}). Pooled data of six representative Mediterranean greenhouse crops.

experiments and they are not normally available in commercial greenhouses.

3.3. Measurement and estimation of greenhouse net radiation

The daily measured $R_{n,g}$ ranged between −0.6 and 15.5 MJ m^{-2} day^{-1} (Fig. 2). It was generally lower in winter, when solar radiation is usually lowest, and was clearly reduced by the greenhouse whitening at the beginning of the cucumber 2009, sweet pepper 2019/20 and cucumber 2020 crop cycles.

The daily $R_{n,g}$ was firstly estimated with the standardised ASCE and FAO procedures (SP) as the sum of daily greenhouse net shortwave radiation ($S_{n,g}$, determined as daily incoming greenhouse shortwave radiation multiplied by standardised crop albedo, 0.23) and daily greenhouse net longwave radiation ($L_{n,g}$, determined with equation (2), but using greenhouse air temperatures instead of outdoor air temperatures). These daily $R_{n,g}$ estimates were relatively low and even negative for some crops and periods (Fig. 6). They were much lower than the measured daily $R_{n,g}$ throughout all the studied crop cycles with poor model performance statistical indicators (Table 2): e.g. the RMSE ranged from 3.86 MJ m^{-2} d^{-1} for the melon 2010 cycle to 5.90 MJ m^{-2} d^{-1} for the cucumber 2014/15 cycle. This result was expected, because the use of a mean seasonal albedo of 0.23 (Allen et al., 1998; American Society of Civil Engineers, 2005) for fruit-vegetable crops grown with high-wire production systems in Mediterranean greenhouses might usually underestimate the measured daily $S_{n,g}$ (section 3.1) and, above all, because the standardised ASCE and FAO procedure to calculate daily $L_{n,g}$ (equation (2) but using greenhouse air temperatures instead of outdoor air temperatures) substantially underestimated measured values (section 3.2).

The daily $R_{n,g}$ was also estimated by calculating the daily $L_{n,g}$ with equation (3) and the daily $S_{n,g}$ as the incoming greenhouse shortwave radiation multiplied by a mean seasonal albedo of 0.16 (SP-G). In general, the measured daily $R_{n,g}$ was accurately estimated using these SP-G procedures (Fig. 6). All the statistical indicators of model performance improved substantially for each of the studied greenhouse crops (Table 2): the RMSE ranged from 0.6 to 0.8 MJ m^{-2} d^{-1} for most crop cycles, except for melon. Pooling all measured data, the RMSE and MAE decreased to 0.94 and 0.72 MJ m^{-2} d^{-1}, respectively (Table 2). The model performance further improved when data from the beginning of six studied crop cycles were excluded (Fig. 4; RMSE = 0.75 MJ m^{-2} d^{-1}, MAE = 0.50 MJ m^{-2} d^{-1}) because the daily $L_{n,g}$ was frequently overestimated at the beginning of the crop cycles, particularly during hot crop periods. Overall, this work provides simple procedures for estimating daily net greenhouse longwave and shortwave radiation by adapting the standardised FAO and ASCE procedures to Mediterranean greenhouse crops. Thus, greenhouse longwave radiation can be estimated by incorporating standard radiometric properties of the covering material, such as the transmission coefficient to the longwave radiation, into the standardised formula (eq. (3)). These adapted procedures, despite the diversity of greenhouses, crops and management practices, provide relatively accurate $R_{n,g}$ estimates and require only readily available

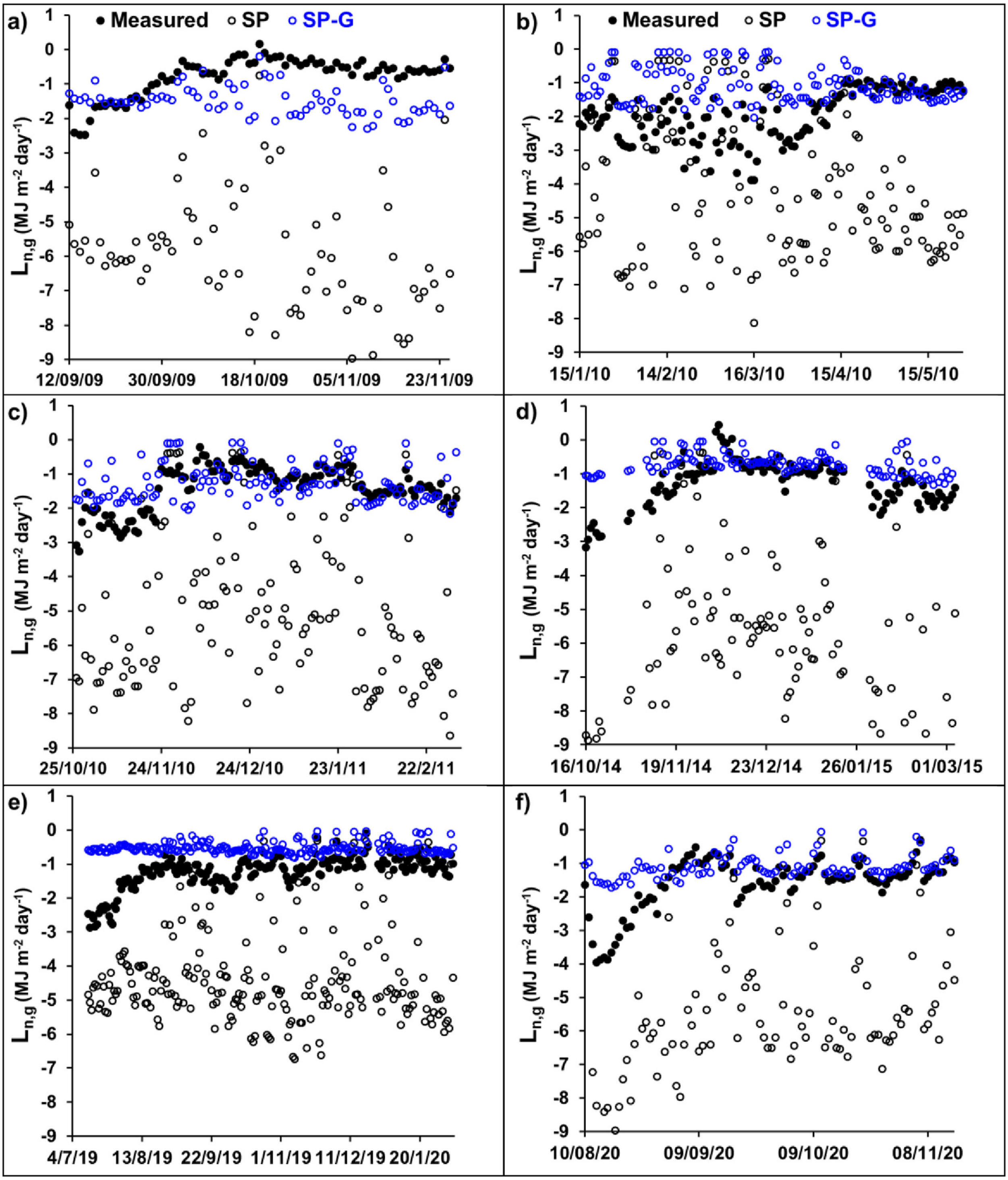

Fig. 5 — Time course of measured and estimated daily net longwave radiation ($L_{n,g}$) throughout six Mediterranean greenhouse crop cycles: a) autumn-cucumber 2009; b) winter-spring melon 2010; c) autumn-winter cucumber 2010/11; d) autumn-winter cucumber 2014/15; e) summer-winter sweet pepper 2019/20; and f) summer-autumn cucumber 2020. The $L_{n,g}$ was estimated with the standardised ASCE and FAO procedure (SP) and with the standardised ASCE and FAO procedure adapted to Mediterranean greenhouses (SP-G).

meteorological data from weather stations and greenhouse air temperature and shortwave radiation data. However, further research is needed to better ascertain: i) whether the τ_{LR}, defined as the mean material transmission in the range of 7.5–13 μm, is fully representative of how the plastic cover affects the greenhouse longwave radiation balance, or reflectivity and emissivity of greenhouse covering materials, which can be modified by applying reflective coatings with low

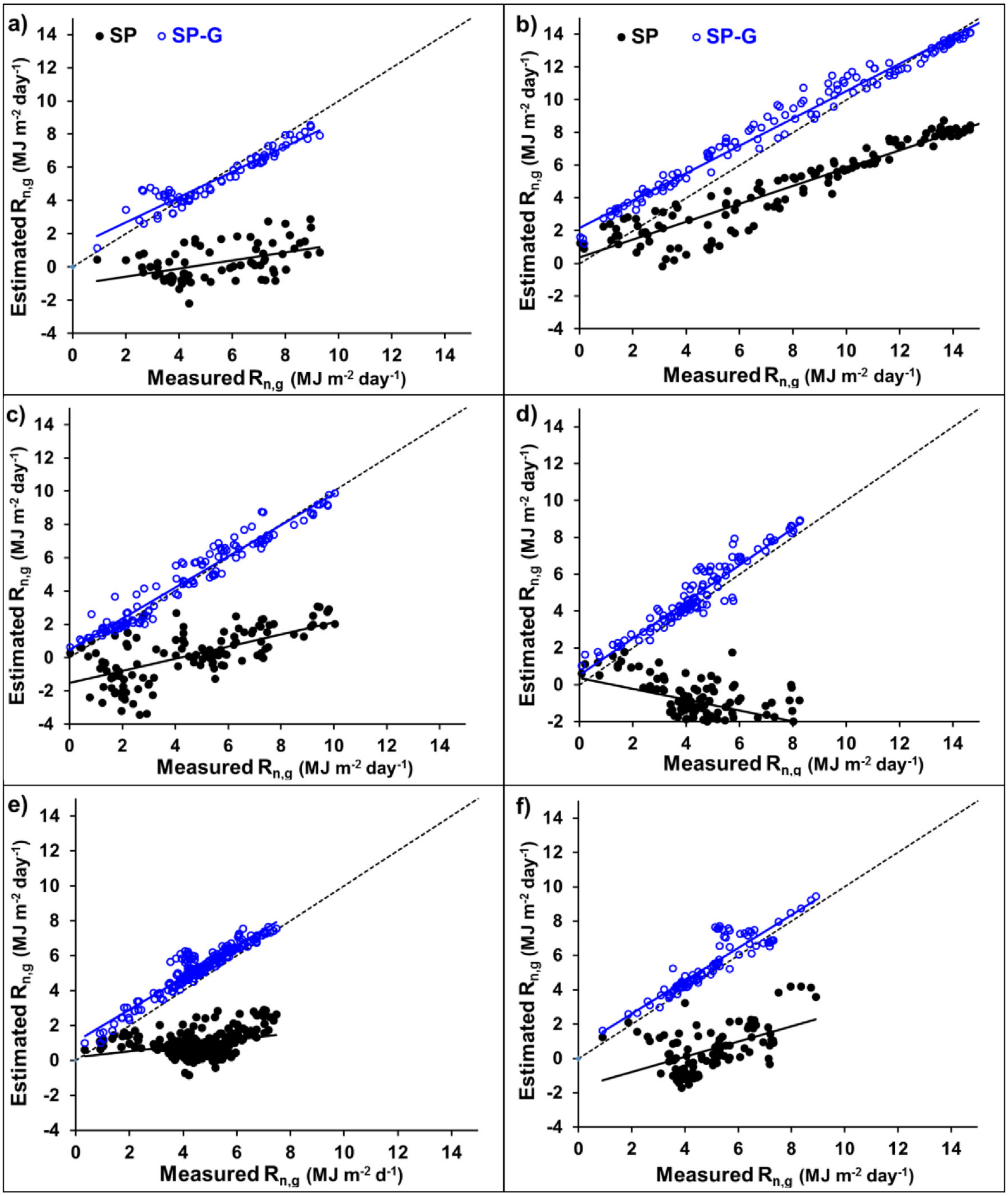

Fig. 6 – Comparisons and linear regression lines of estimated versus measured values of the daily net radiation ($R_{n,g}$) estimated with the standardised ASCE and FAO procedure (SP), and with the standardised ASCE and FAO procedure adapted to Mediterranean greenhouses (SP-G) throughout six Mediterranean greenhouse crops: a) autumn-cucumber 2009 [(SP: $y = 0.24x - 1.07$, $R^2 = 0.22$); (SP-G: $y = 0.76x + 1.17$, $R^2 = 0.90$)]; b) winter-spring melon 2010 [(SP: $y = 0.54x + 0.37$, $R^2 = 0.90$); (SP-G: $y = 0.84x + 2.17$; $R^2 = 0.98$)]; c) autumn-winter cucumber 2010/11 [(SP: $y = 0.36x - 1.52$, $R^2 = 0.36$); (SP-G: $y = 0.93x + 0.49$; $R^2 = 0.95$)]; d) autumn-winter cucumber 2014/15 [(SP: $y = -0.30x + 0.38$, $R^2 = 0.20$); (SP-G: $y = 0.99x + 0.54$; $R^2 = 0.90$)]; e) summer-winter sweet pepper 2019/20 [(SP: $y = 0.17x + 0.19$, $R^2 = 0.11$); (SP-G: $y = 0.92x + 1.07$; $R^2 = 0.90$)]; and f) summer-autumn cucumber 2020 [(SP: $y = 0.44x - 1.69$, $R^2 = 0.26$); (SP-G: $y = 0.96x + 0.68$; $R^2 = 0.84$)].

emission coefficients (Solovyev et al., 2015), should also be considered in equation (3); ii) how crop management practices that modify the greenhouse radiation balance, such as whitening, influence the daily $L_{n,g}$; and iii) how high greenhouse soil/ground surface temperatures that usually occur at the beginning of the crop cycles (when most of the soil surface is uncovered) during hot crop periods, affect the greenhouse net longwave radiation balance.

4. Conclusions

The standardised ASCE and FAO formulae for estimating the shortwave ($S_{n,g}$) and longwave ($L_{n,g}$) components of the daily net radiation ($R_{n,g}$) have been adapted to Mediterranean greenhouse crops. The mean seasonal albedo of these crops (six representative cycles), which were grown with high-wire production systems, ranged between 0.13 and 0.23, mostly depending on their vegetative growth. For these greenhouse crops, a mean seasonal crop albedo of 0.16 led to accurate $S_{n,g}$ estimates from greenhouse shortware radiation measurements.

Daily $L_{n,g}$ estimates using the standardised ASCE and FAO formula were substantially lower than measured values for all the crop cycles since this formula does not consider the effects of the greenhouse covering material on the greenhouse longwave radiation exchange. The incorporation of the transmission coefficient of the covering material to the longwave radiation as a multiplicative factor into the standardised formula led to more accurate daily $L_{n,g}$ estimates, particularly when crops reached effective full cover.

Daily $R_{n,g}$ estimates using the standardised ASCE and FAO $S_{n,g}$ and $L_{n,g}$ procedures was much lower than measured values for all crop cycles, but they were correctly estimated when these standardised procedures were adapted to Mediterranean greenhouse crops, particularly when crops reached effective full cover. Nevertheless, further research is also needed to assess how the greenhouse soil temperature, the reflectivity and emissivity of greenhouse covering materials and common crop management practices that substantially modify the greenhouse radiation balance, such as whitening, influence the daily $L_{n,g}$ and $R_{n,g}$.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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