POLYTECHNICAL UNIVERSITY
OF CARTAGENA

Department of Food and Agricultural Engineering

Ecophysiological and Agronomic Response of Horticultural Crops Grown under Screens in a Mediterranean Climate

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Cartagena, 2014

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This research work is presented by Evangelini KITTA, MSc, in order to obtain the Doctorate Degree of the Polytechnical University of Cartagena

PhD Advisor:

Dr. Alain BAILLE

Cartagena, 2014

This thesis belongs to the category "Compendium of Publications"
The references of the publications are the following:

- **Publication 1**: **Kitta, E.,** Katsoulas, N., Savvas, D., 2012. Shading effects on greenhouse microclimate and crop transpiration in a cucumber crop grown under Mediterranean conditions. *Applied Engineering in Agriculture*, 28(1): 129-140

- **Publication 2**: **Kitta, E.** Katsoulas, N. Kandila, A. González-Real M.M., Baille A., 2014. Photosynthetic acclimation of sweet pepper plants to screenhouse conditions. *HortScience*, 49(2): 166-172.

- **Publication 3**: **Kitta, E.**, Baille, A., Katsoulas, N., Rigakis, N., González-Real, M.M., 2014. Effects of cover optical properties on screenhouse radiative environment and sweet pepper productivity. *Biosystems Engineering*, 122: 115-126

- **Publication 4**: **Kitta, E.**, Baille, A., Katsoulas, N., Rigakis, N. 2014. Predicting reference evapotranspiration for screenhouse-grown crops. *Agricultural Water Management*. 143 : 122–130

CONFORMIDAD DE SOLICITUD DE AUTORIZACIÓN DE DEPÓSITO DE TESIS DOCTORAL POR EL/LA DIRECTOR/A DE LA TESIS

D. Alain BAILLE, Director de la Tesis doctoral: "Ecophysiological and Agronomic Response of Horticultural Crops Grown under Screens in a Mediterranean Climate"

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Que la referida Tesis Doctoral, ha sido realizada por Dª Evangelini KITTA, dentro del programa de doctorado TAIDA **(**Técnicas Avanzadas en Investigación y Desarrollo Agrario y Alimentario)**,** dando mi conformidad para que sea presentada ante la Comisión de Doctorado para ser autorizado su depósito.

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29 SEP 2014
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Vistos los informes favorables de los Directores de Tesis y el VºBº de la Comisión Académica para la presentación de la Tesis Doctoral titulada: ***"Ecophysiological and agronomic response of horticultural crops grown under screens in a mediterranean climate"*** en la modalidad de "compendio de publicaciones" solicitada por Dña. Kitta Evangelini, la Comisión de Doctorado de la Universidad Politécnica de Cartagena, en reunión celebrada el 24 de septiembre de 2014, considerando lo dispuesto en el artículo 33 del Reglamento de Estudios Oficiales de Máster y Doctorado de la UPCT, aprobado en Consejo de Gobierno el 13 de abril de 2011 y modificado el 11 de julio de 2012,

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ACKNOWLEDGEMENTS

I am very grateful to my PhD advisor, Professor Dr. Alain Baille, for his scientific guidance, support, help and assistance during my Doctoral Thesis preparation period. I would also like to thank by heart Assistant Professor Dr. Nikolaos Katsoulas for his scientific advice and knowledge, and many insightful discussions and suggestions but also for his friendship.

Finally, I would like to thank the personnel of my Research Institute (CERTH / IRETETH) for its assistance, especially my Director, Professor Elias Houstis, for his continuous countenance and the Head of the Agrotechnology sector, Dr. Thomas Bartzanas, for his support and friendship.

I dedicate this thesis to

my daughters Ariadni and Faidra and to my father

Costas for their constant support and

unconditional love.

CONTENTS

1. Objectives

The general scope of this work was to investigate the effect of crop covering-nets, like shade-nets or insect-proof screens, on the microclimate and crop response in protected cultivation. Protected horticulture can be defined as any agricultural activity taking place under a protective cover. A protective structure is defined as any structure designed to modify the environment in which plants are grown. Protective structures, such as greenhouses and screenhouses, are known worldwide as production systems for high-quality vegetable.

Protective structures are generally classified in two main groups; (i) greenhouses, which are non-porous structures and (ii) screenhouses or net-houses, which are porous structures (Santos *et al.*, 2013).

In some case, nets can be also used within greenhouses:

- as a barrier in vent openings against the penetration of insects, or
- as a shading device for cooling the enclosure.

The main difference between a greenhouse with internal screen and a screenhouse is that, in the former, the net is considered as part of the climate control equipment, while in the latter, the net is an element constitutive of the structure.

Insect-proof nets play an important role in preventing pest invasion through the ventilation openings in Mediterranean and South Eastern Europe climates (Tanny, 2013). These screens are necessary in summer since the targeted insects are most abundant during the warm and hot season, but they have the disadvantage to reduce the ventilation rate (Bethke *et al.*, 1994; Klose and Tantau, 2004), which is essential for avoiding stressful conditions for both crop plants and workers (Teitel, 2001). In recent years several methods have been developed to compensate the negative effect on ventilation due to insect screens, such as removal of insect screens from vents when the risk of pest invasion is low, or maximization of screened area (Montero *et al.*, 2013).

Shading screens represent one of the most common cooling device used by growers for improve environmental conditions during warm periods. Several studies concerning the influence of nets on greenhouse climate and crop production have been carried out. Until now, only scarce data exist concerning the influence of nets with different shade levels on crop behaviour, energy balance and transpiration of greenhouse crops.

On the other hand, the use of porous screens to cover crops is constantly increasing, mainly because they are less expensive than greenhouses. In screenhouses, the covering net acts as a passive means in controlling the internal climate of the enclosure and consequently is the main factor driving screenhouse productivity. The screenhouses as productive ecosystem present the following advantages:

- reduce high radiation loads and wind speed,
- modify positively the crop physiological response
- protect the crop from hail storms, and
- minimise the invasion of insects, thus, allowing a significant reduction in pesticide application.

Knowledge and modelling of the effects of screens on microclimate should lead to a better design of the screens and adapted crop techniques, in order to ultimately increase growers' profitability with minimum impact on the environment. It is therefore a prerequisite to characterize the microclimate modifications induced by different types of shading material and screenhouse structures. Comparative experiments with shading materials differing in shading intensity and porosity should be carried out to assess their effects on microclimate and crop behaviour. Up to now, only a few studies have dealt with these issues, which are of high relevance to the development of protected horticulture in the Mediterranean Countries.

Consequently, the main objective of the present PhD work is to investigate on general relationships that could relate agro-physiological plant attributes and crop performance to physical screen properties. This objective was divided into four specific sub-objectives:

1. *Assessing the impact of shading nets on greenhouse environment*

To this aim, we characterised the impact of different of shading nets as cooling device in a cucumber greenhouse. More specifically, the influence of shading intensity on energy balance, transpiration and productivity are investigated (Publication 1).

2. *Assessing the impact of the type of nets on the screenhouse environment*

We characterised the changes in aerial and radiative environment under different sweet pepper grown screenhouses of different transmittance and porosity. In the experiments, sweet pepper was chosen because it represents a horticultural species of great economic importance in the Mediterranean countries (Publications 2 and 3).

3. *Evaluating the agrophysiological response of sweet pepper under screenhouse*

The seasonal pattern of leaf photosynthetic attributes (gas exchange, water use efficiency, radiation use efficiency) was investigated. In a first step, the acclimation process of leaf photosynthetic to changes in light/temperature regime induced by the nets has been characterised and analysed in details (Publication 2). In a second step, the impact of screen optical properties on sweet pepper productivity was investigated through the relationships between plant attributes and screen properties (Publication 3)

4. *Estimating the water requirements of screenhouse crops*

To improve irrigation scheduling, a simple method to estimate the reference evapotranspiration of screenhouse-grown crops ($ET_{ref,in}$) from routine outside weather data and main screenhouse characteristics was proposed and validated (Publication 4).

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2. State-of-the-Art

2.1. Protected agriculture in Mediterranean regions

Protected agriculture is a high-investment and a high-risk business that demands professional expertise, based on the synthesis of proven technologies and market requirements along with economic objectives. Achieving high productivity in the greenhouse is possible by exerting a suitable control of both environmental parameters and crop status. The economic optimum, however, depends on the trade-off between the costs of improving environment control and the increase in return due to improved crop status, dictated by yield quantity, yield quality and production timing.

Additional constraints are those related to improving resource use efficiency (water, nutrients, energy and soil) and to decreasing environmental impact. Environmental sustainability, however, must be considered jointly with economic sustainability. In this respect, greenhouse crops are often the only form of economically sustainable agriculture that can be proposed in many marginal areas of the Mediterranean environment, where land abandonment is expanding considerably. Indeed, in contrast to what most may believe, the greenhouse system is in some respects quite a resource-efficient system compared to open field agriculture (de Pascale and Maggio, 2005, 2008).

In Europe, climatic differences have fostered the development of greenhouse systems based on simple structures and inexpensive climatic control devices in the warmer Southern regions compared to the Northern greenhouse systems. Hi-tech greenhouses are capable of providing the optimal conditions for year-round production; however, they constitute the most expensive option, in terms of capital, running costs and energy consumption. Growers' experience shows that in many situations high profits can also be achieved using low cost structures, as the ‘parral’ greenhouse (common in the Almeria region, Southern Spain), or the screenhouse (Möller and Assouline, 2007). These simplified systems present some limitations for an efficient use of the natural resources: poor ventilation, inefficient humidity control and reduced light transmission due to the covering material all pose serious constraints for timing production and guaranteeing high yields with high quality standards.

As a result, the majority of the Mediterranean greenhouses (i) currently under-use the potential energy in the fall/winter period, and (ii) are strongly limited during summer/spring (with two production peaks, in spring-early summer and in autumn and approximately 3-5 months of non-productive time) due to the lack of efficient control of high temperatures and vapour pressure deficit (González-Real and Baille, 2006). Therefore, greenhouse cooling is a matter of increasing interest for growers in Mediterranean countries.

2.2. Greenhouse cooling methods

Various methods can be used to cool the greenhouse. Natural ventilation is one of the most usual practices. However, currently the majority of greenhouses include some type of ventilation system (Boulard *et al*., 1997; Kittas *et al*., 1997). Natural ventilation is generally not sufficient for releasing the excess energy during sunny days in summer and, therefore, other cooling methods have to be used in combination with natural ventilation (Katsoulas *et al*., 2001).

The use of nets or screens is a typical practice in the whole Mediterranean basin. It is considered a low-cost method of decreasing radiation and the concomitant energy load during warm periods. The few studies (Baille *et al*., 1980; Baille *et al*., 2001; Mashonjowa *et al*., 2010) relevant to whitening suggest that white painting of the greenhouse cover material is not only a cheap but also an efficient crop shading method. Greenhouse whitening allows inside air temperature to be maintained close to or even lower than the outside level during summer periods due to an increase of crop transpiration rate under shading (Baille *et al*., 2001; Mashonjowa *et al*., 2010) while it reduces the solar infrared fraction that enters to the greenhouse, enhancing slightly the photosyntheticaly active radiation (PAR) proportion in the incoming solar irradiance (Kittas *et al*., 1999). The latter characteristic of whitening could represent an advantage with respect to other shading options, especially in warm countries with high radiation load during summer. On the other hand, the major disadvantage of whitening is the lack of flexibility, since neither the application of shading nor its level can be adapted to natural changes of solar radiation intensity during the cropping period. Additionally, it is easy to add more but difficult to remove the whitening material at the end of the warm season, when natural solar radiation intensity decreases and shading may restrict crop light perception to critical levels.

Mobile shading allows improvement of greenhouse climate, especially during the noon hour. It reduces canopy transpiration and water uptake, and increases remarkably water use efficiency (Lorenzo *et al*., 2006). The use of shading screens in greenhouses became a common practice during the last decade (Cohen *et al*., 2005; Castellano *et al*.,

2008) because it is a flexible and efficient method of reducing the energy load inside the greenhouse (Teitel and Segal, 1995), especially in climates characterized by high evaporative demand and limited water resources (Lorenzo *et al*., 2006).

The optical properties of the screens (type of fabric and shade factor) and the whitening of the cover (type of product and concentration) can modify the diffuse-to-direct radiation ratio (Baille *et al*., 2001; Raveh *et al*., 2003; Cohen *et al*., 2005) and cooling performance (Willits, 2001), while reducing air and crop temperature (Smith *et al*., 1984; Fernandez-Rodriguez *et al*., 2000). The modifications arising from the optical properties of the screens can affect radiation absorbed by the crop, stomatal conductance, and net CO_2 assimilation, and consequently crop growth and productivity. Furthermore, light quality modifications affect morphogenesis and photosynthesis, although their role in growth has not been yet completely clarified (Li *et al*., 2000). Nevertheless, adaptation of plants to light conditions depends also on the specific behavior of the plant species grown in greenhouses (Raveh *et al*., 2003; Barradas *et al*., 2005; Romacho *et al*., 2006). Shade can increase total and marketable yield of tomato grown in hot climates. Depression of crop yield is frequently observed under Mediterranean conditions when high solar radiation and low air humidity conditions prevail. Tomato plants grown in Egypt for the entire season with under 30% to 40% shade produced more fruit thereby rendering a higher yield than those grown without shade (El-Aidy, 1986; Abdel-Mawgoud *et al*., 1996). Increasing shade intensity to above 40% decreased flowering and yield. El-Gizawy *et al.* (1993) observed that increasing shading intensity up to 51% over a tomato crop resulted in fruit total production increase. The same authors mention that the highest tomato crop production was obtained under 35% shading, while increasing shading intensity decreased by up to 100% the incidence of sunscald on fruit. Concerning the effect of shading on cucumber crop, Naraghi and Lofti (2010) observed that increasing shading density up to 35% led to an increase in the number of fruits per plant. However, the number of fruits tended to decrease as shading density increased to 60%. Furthermore, the above authors mention that shading intensity greatly influenced the physiological disorders like sun-scald of cucumber fruits.

A better understanding of plant responses to shading is of great interest for greenhouse crops. With respect to the Mediterranean greenhouses, more information is needed mainly on plant responses to the time of application, including both commencement and termination of shading dates, degree of shading, and shading technique (whitening products, disposition and mobility of the screens in the greenhouse).

2.3. The screenhouse: a hybrid system between open-field and greenhouse

Reductions in photosynthetic activity and/or in assimilate partitioning to the fruits, negatively affecting crop yield, are frequently observed for open-field crops grown in Mediterranean regions where plants are subjected to high radiation load and low air relative humidity during a great part of the crop cycle (Aloni *et al.*, 1990; Dinar and Rudich, 1985; Erickson and Markhart, 2001). An alternative to alleviate the effects of radiation load is the use of reflection or shading (whitening, internal or external screens). Shading conditions, creating a light regime compatible with the requirements of leaf physiological functions (Barber and Anderson, 1992), have been proven to induce a positive impact on leaf gas exchange (Gonzalez-Real and Baille, 2006; Jaimez and Rada, 2011) and on plant growth and crop yield in several crops (Baille *et al.*, 2001; Gent, 2007; Lorenzo *et al.*, 2003) including sweet pepper (Jaimez and Rada, 2011; Rylski and Spigelman, 1986a, 1986b). The latter, like other species, is sensitive to high temperature (Erickson and Markhart, 2001, 2002; Rylski and Spigelman,1982) but appear to maintain their leaf netCO2assimilation rates at temperatures as high as 33ºC in detriment of developing fruits (Erickson and Markhart, 2001).

Screenhouses seem to be a valuable alternative to reduce radiation load, because they can simultaneously act as cover and shading devices. These low-cost structures have been progressively adopted by growers in the last decade (Castellano *et al.*, 2008) as shown by the increasing area of field-grown crops that shifted to screenhouse (Cohen *et al.*, 1997, 2005; Kittas *et al.*, 2012; Tanny and Cohen, 2003). In particular, the use of insect-proof nets raised much interest among growers, because they limit the use of pesticides and associated costs through implementation of Integrated Pest and Disease Management strategies favoring a production of quality (Raviv and Antignus, 2004; Reuveni *et al.*, 1989).

The reduction of solar radiation due to net-covering allows alleviating conditions of stress-induced limitations of the physiological fluxes (Stanhill G., Cohen S., 2001) which are a major constraint in the productivity and quality of greenhouse-grown crops. The positive impact of a net-covering on plant behaviour can be mostly explained by the more favourable microclimate under a screenhouse than outdoors. Screens modify in a positive way several microclimatic variables that drive plant physiological and morphological processes, i.e. incident light, air and soil temperature, air humidity and air speed, among the most relevant. Net-covering increased the relative fraction of diffuse radiation that positively affected the amount of radiation absorbed by crops (Goudriaan, 1977), the photosynthetic rate (Spitters, 1986; Monteith and Unsworth, 1990), crop radiation use efficiency (Cockshull *et al.*, 1992), crop yield (Healey *et al.*, 1998) and the spatial distribution inside the greenhouse of both solar radiation (Dayan *et al.*, 1986) and yield (Adams *et al.*, 2000). Several studies in semiarid areas have demonstrated that crops grown under nets experience a notable increase in production (El-Gizawy *et al.*, 1993; Abdel-Mawgoud *et al.*, 1996, Leonardi *et al.*, 2000; Kittas *et al.*, 2012; Kitta *et al*. 2012) and/or in quality (Rylski, 1986; Whaley-Emmons and Scott, 1997) with respect to open-field crops.

2.2.1. Effects on photosynthesis

Screenhouses substantially modify the radiation regime with respect to the outside conditions, both quantitatively, through reduction of photosynthetic photon flux density (PPFD) reaching the crop, and qualitatively, through changes in the ratio of diffuse-to direct radiation (Healey *et al.*, 1998) and the spectral distribution of solar radiation (Ehret *et al.*, 1989; Kittas and Baille, 1999). With regard to open-field crops, the radiative microclimate under a screenhouse can lead to modifications in leaf physiological attributes and carbon allocation patterns, which in turn affects crop yield and quality (Rylski and Spigelman, 1986a, 1986b). It has been observed that the midday depression of photosynthesis under harsh environmental conditions along with the reduction of transpiration rate can be compensated by higher values of stomatal conductance induced by net-screens (Raveh *et al.*, 2003). However, this behaviour was not observed in some species (Barradas *et al.*, 2005). The wide range of plant response to artificial or natural shading reported in the literature (Cockhull *et al.*, 1992; Jaimez and Rada, 2011; Li *et al.*, 2000; Raveh *et al.*, 2003; Stanhill and Cohen, 2001) can be related to (i) differences in screen physical properties (e.g., porosity) and shading duration and intensity (Gent, 2007); (ii) stage of plant development (Cohen *et al.*, 2005); (iii) plant density (Papadopoulos and Pararajasingham, 1997); and (iv) response of leaf structural and physiological attributes to changes in local light regime (e.g., Egea *et al.*, 2012).

A large body of studies, focusing on light acclimation of leaf physiological function, stressed the close relationship between the distribution of photosynthetic traits and the local light regime in species grown in the open field (Field and Mooney, 1986; Niinemets *et al*., 2004) and under greenhouses (Acock *et al*., 1978; Gonzalez-Real *et al*., 2007; Gonzalez-Real and Baille, 2000) including pepper crops (Dueck *et al*., 2006; Gonza´lez- Real *et al.*, 2009). Changes in the light environment may induce a wide range of structural and physiological changes such that the photosynthetic capacity of uppermost leaves can reach values more than 2-fold higher than that of the bottom leaves (Niinemets, 2007).

In sweet pepper, the impact of light may interfere with the internal control induced by either the presence or removal of fruits (Gucci and Flore, 1989; Hall, 1977), which are known to exhibit strong temporal changes in their demand for assimilates at different stages of growth (Gonzalez-Real *et al.*, 2009).

Therefore, knowledge about plasticity in leaf physiological function and its interaction with leaf ontogeny in response to light distribution within the crop is determinant not only for assessing crop carbon uptake, but also for characterizing the impact of greenhouse agronomic practices (e.g., pruning and defoliation strategies) on crop yield (Adams *et al*., 2002; Heuvelink *et al*., 2005).

To our knowledge, an important issue not yet fully investigated in screenhouses concerns plant acclimation to the light regime imposed by the screen.

2.2.2. Screen optical properties

The solar radiation broad-bands generally considered in agricultural applications are (i) UV radiation (300-400 nm), Photosynthetically Active Radiation (PAR: 400-700 nm; and Near Infrared (700-3000 nm). PAR is the most important wave band because it is needed for photosynthesis, and its absorption by the leaves is an essential process in the elaboration of crop biomass. The optical properties of the screen modify the light spectrum with respect to the outside radiation, and therefore modify substantially the amount of radiation incoming on screenhouse crop.

The most important quantitative effect of a screen is that it transmits only part of the solar radiation. As the literature shows, the screen transmissivity is different for the different broad-bands. Another effect of screens is the conversion of part of the radiation from direct to diffuse. This change in light quality has significant effects on whole crop photosynthesis, because diffuse light penetrates deeper in the canopy than direct light, making that shaded leaves at lower levels could benefit from more radiation. It is documented that one of the reasons for increased water use efficiency under shade is the larger proportion of diffuse radiation (Healey *et al*., 1998).

To account for the effects of screens on radiation properly, a sound radiation balance analysis is required. This was first presented by Waggoner *et al*. (1959) in a full- scale field study and later studied by Cohen and Fuchs (1999) and Moller *et al.* (2010), who investigated the radiation balance of screen samples in a semi-laboratory apparatus situated on the roof of a building. In the following we will only discuss radiation measurements in full scale screenhouses or screen covers under field conditions. This is because such measurements reproduce more realistically the effects of the screen on radiation and other microclimate variables than laboratory measurements.

Net-covering may has positive effects on plant physiology, as referred above, by preventing a down-regulation of photosynthesis during periods of high radiation (Medina *et al*., 2002; Kato *et al*., 2003) but as counterpart, nets reduce the amount of light during periods of low radiation, therefore limiting the potential for plant light capture and biomass production. There is therefore a compromise to find between the requirements of protecting the plants from excessive radiation load and high temperature, and the objective of maximising light capture and standing biomass of the plant canopy. This compromise is not straightforward to find. Manipulation of light environment by artificial shading requires the knowledge of (i) the characteristics and parameters of the modified light regime, on both the quantitative and qualitative aspects and (ii) the response of the crop to the modified regime.

Some previous studies have dealt with the quality of screenhouse light environment (Castellano *et al.*, 2008; Schettini *et al.*, 2011; Schettini and Vox, 2012, Shahak, 2008), but most of studies on the agronomic impact of nets consider only the quantitative aspects, that is, the amount of light reduction due to the nets. The parameter that is currently used by manufacturers to characterise the impact on light is the shading factor (SF, %), which corresponds to the relative amount of radiation that is absorbed and reflected in the visible range (380-760 nm) of solar radiation (Castellano *et al*., 2008), or in the photosynthetically active radiation (PAR: 400-700 nm). As such, SF represents a quantitative estimate of the light loss due to the net, but does not inform on the qualitative (spectral) changes.

Furthermore, screen transmissivity does not depend on screen properties only. The effect of solar elevation angle on screen transmissivity to short wave radiation was reported by Möller *et al.* (2003) in an insect-proof screenhouse in which pepper was grown. Transmissivity depended on solar elevation with a 58% maximum at noon, as expected, and an average of 52% of the external radiation. This was due to the thickness of the screen material itself which blocked the direct beam radiation at low elevation angles.

The effect of screen hole size, screen colour and roof configuration on transmissivity was explored by Desmarais *et al.* (1999) who investigated the thermal properties of four empty small insect-proof screenhouses. Transmissivity was calculated as the ratio between simultaneous data for inside and outside global radiation. Transmissivity depended on the roof type: It was largest for the Teflon roof, which was highly transparent, and lowest for a screenhouse with a double roof consisting in Teflon and screen.

Moller and Assouline (2007) investigated a flat-roof screenhouse made of a black 30%-shading screen, in which sweet pepper was grown. On a seasonal basis global radiation inside was 0.56 of outside. Moller and Assouline (2007) also demonstrated how screen transmissivity decreased with decreasing solar elevation angle, in a similar manner as in the insect-proof screenhouse (Moller *et al.*, 2003).

Screen transmissivity may decrease with time due to dust accumulation. For a full-scale shading screenhouse covering a banana plantation Moller *et al.* (2010) reported that screen transmission decreased linearly with time by about 0.1% per day during a rainless summer due to dust accumulation on the screen, but recovered after rain. The initial transmissivity was about 90% and it was reduced to about 75% by the end of the summer. Kittas *et al.* (2012) measured radiation below four different shading screens covering tomato plants, with shading intensities between 34 and 49%. Transmissivity for PAR ranged between 0.51 and 0.63, and for NIR between 0.53 and 0.71. The transmissivity was roughly correlated with the initial shading intensity: screens with 34 and 49% shading had the largest and lowest transmissivity, respectively, for both PAR and NIR. In contrast with Moller *et al.* (2010), screen transmissivity to PAR did not change with time and was close to the nominal shading level given by the screen manufacturer.

2.2.3. Crop evapotranspiration under screenhouse

Knowledge of whole canopy evapotranspiration (ET) is a key parameter in adequate irrigation management. Changes in canopy ET under shade depend on both microclimatic factors and physiological status of the crop. Microclimate-based models predicting crop evapotranspiration are important components of optimised irrigation scheduling (Allen *et al*., 1998). Numerous authors give account of the application of the Penman–Monteith model (PM) in the open field (e.g. Fuchs *et al*., 1987; Petersen *et al*., 1992; Ventura *et al*., 1999). In screenhouses, the reduction in both radiation load (net radiation) and wind speed due to the presence of the cover material, results in a concomitant reduction of the climatic demand with respect to the open field. This reduction of the climatic demand – generally expressed in terms of the evapotranspiration of a reference crop, E_{ref}, as proposed by the FAO (Allen *et al*., 1998, hereafter FAO-56-PM method), leads to a concomitant reduction of the actual evapotranspiration rate of screenhouse crops with respect to the open field. This was demonstrated by several studies performed in the last decade (Moller *et al*., 2004; Tanny *et al*., 2006; Siqueira *et al*., 2012).

However, whereas irrigation scheduling of open field crop by means of the calculation of the FAO-56-PM method and subsequent application of a crop coefficient (K_c) is used worldwide, it is not possible to apply this method to screenhouse crops, because the calculation of the crop net radiation, R_n, is based on formulae that are valid only for open field conditions. In particular, R_n of a screenhouse crop differs substantially from that of an open field crop, due to the presence of the cover, which changes both the net short-wave and net long wave radiation budget.

Nevertheless, in spite of the increasing area of screenhouses around the world, no measurements or predictive estimates of evapotranspiration in screenhouses have been reported. Irrigation scheduling in these structures is mainly done on a trial-and-error basis. Möller *et al*. (2004) performed a comparison between measured (by the eddy covariance method) and estimated external evapotranspiration, using the classic Penman-Monteith equation for outside conditions. They showed that inside ET was about 40% of the outside, reflecting the strong effect of the dense insect-proof screen on exchange processes between the crop and the outside atmosphere. They also showed that the main factors contributing to the reduced ET in the screenhouse were, first, radiation and then temperature, VPD and wind. This could be explained by the finding that the evaporative climate in the screenhouse was strongly decoupled, with a decoupling factor of about 0.8 during most daytime hours. This decoupling was attributed by Möller *et al*. (2004) to the insect proof screen which inhibited the contribution of VPD and wind to the evapotranspiration.

Intents of predicting the evapotranspiration of screenhouse crops by adapting the Penman-Monteith formula to the internal conditions specific to each screenhouse were carried out (Dicken *et al*., 2010; Pirkner *et al.*, 2013). Other option is to use the PM-screen model (PM_{sc}) developed by Möller *et al*. (2004), which incorporates a screenhouse specific resistance that accounts for the effect of the additional boundary layer occupying the air gap between the horizontal screen and the underlying canopy. For practical applications in growers' screenhouses, such approaches present the great inconvenience to require continuous measurements of net radiation, temperature and humidity inside the screenhouse, which does not appear feasible on a practical and economical point of view for most screenhouse growers.

The conclusion of this section is that there is an urgent need to develop and validate an operational and robust method for predicting ET under screenhouses. This is one of the objectives of this PhD.

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3. Publications

3.1. Publication 1

Kitta, E., Katsoulas, N., Savvas, D., 2012. Shading effects on greenhouse microclimate and crop transpiration in a cucumber crop grown under Mediterranean conditions. *Applied Engineering in Agriculture*, 28(1): 129-140

Extended summary

The aim of this article was to investigate the effects of greenhouse shading on greenhouse microclimate and energy balance, and on crop production. Experiments were carried out in the experimental farm of the University of Thessaly at Velestino, in three similar, plastic-covered greenhouses using hydroponically-grown cucumbers as a test crop. One of the greenhouses was used as a control ($Gr_{0\%}$, without shading); the other two were shaded using two different shade nets ($Gr_{35\%}$, and $Gr_{50\%}$, shading intensity of approximately 35% and 50%, respectively), applied in the external side of the greenhouse cover.

The difference between the values of incoming solar radiation observed in the control greenhouse ($Gr_{0\%}$) and the greenhouse with the highest shading intensity ($Gr_{50\%}$) was 270, 220, and 200 W m^{-2} on sunny (1 June) and cloudy days (2 and 3 June), respectively, and the measured differences in air temperature between $Gr_{0\%}$ and $Gr_{50\%}$ during the sunny (1 June) and cloudy (2 and 3 June) days were 3.9°C, 2.5°C, and 2.2°C, respectively. Willits (2001) note that when screens are used, the reduction in solar radiation does not always result in a notable temperature decrease, especially when ventilation rate is low. A high radiation absorption by the screen can contribute to an increase in the amount of energy transferred by convection into the greenhouse.

The high values of air temperature and vapour pressure deficit observed during the sunny day under no shading conditions [air temperature ≈41°C (fig. 4b) and vapour pressure deficit ≈6 kPa] were reduced under shading, the maximum air temperature and vapor pressure deficit values observed during the same day under shading were 38°C and 36°C and 4.5 and 4.3 kPa for the $Gr_{35\%}$ and $Gr_{50\%}$ treatments, respectively. However, shading was not able to maintain the greenhouse air temperature and humidity at optimal level (25°C and 70%, respectively, Bulder *et al*., 1987), or at least at temperature level below 30ºC (Growers Books, 1980; Olympios and Hanan, 1992) and VPD_i below 1.5 kPa (Bakker *et al*., 1987).

The canopy transpiration rate (λE_c) was affected to a lesser extent than the solar radiation intensity by shading. During the summer period, the difference in λE_c between the non-shaded greenhouse and that shaded by 35% was approximately 25% when integrated over the whole diurnal period, which is considered moderate. The same type of feedback was reported when a mist system was used for cooling, which decreased the vapour pressure deficit in the greenhouse air (Baille *et al*., 2001).

It was found that shading increased the leaf area index, the number of harvested fruit and the total crop production. The higher leaf area index and crop production observed under 35% shading compared to no shading conditions could probably be due to better water status and higher photosynthetic rates of plants under shading. Reducing crop temperature and vapour pressure deficit could greatly affect plant growth through different processes: (a) by improving the leaf water status (Stirzaker et al., 1997) which increases leaf conductance and hence CO_2-assimilation (Bakker, 1990) and (b) by decreasing fruit transpiration (Leonardi et al., 2000). Ogren and Evans (1992) mention that exposure of leaves to excessive light causes photoinhibition that is associated with photosynthesis decrease. The above, along with the fact that diffuse fraction of solar radiation is higher under shading (Abdel-Ghany and Al-Helal, 2010), favouring radiation penetration in the lower parts of the canopy and increasing canopy interception, could explain the increase in crop production observed under 35% shading compared to no shading conditions. Thus, it appears that a physiologically-based optimal value of shading intensity exists, and that this value depends on several factors: the outside climate conditions (solar radiation, air temperature, and humidity), the greenhouse characteristics (ventilation rate, radiation transmission coefficient, cooling system), which affect the thermal and hydrological negative feedback effects, namely the impact of stomatal opening variation on crop transpiration rate (Jarvis and McNaughton, 1986; Aubinet et al., 1989), crop water status (transpiration and stomatal conductance), and production and quality characteristics (Abdel-Mawgoud *et al*., 1996). From the crop production data it was found that shading intensity should not exceed 35%.

From the growers' point of view, one of the main problems when using shading for alleviating the greenhouse heat load is the right decision on the intensity of shading and the correct timing of shading application. The analysis of crop production data showed that under Mediterranean conditions, shading is necessary with intensity not higher than 35% to 40 from the middle of spring. However, shading of approximately 50% was not sufficient to cool the greenhouse during noon time of summer days in Central Greece. Accordingly, it is necessary either to expand the crop leaf area by increasing plant density, thereby increasing evaporative cooling by crop transpiration, or to introduce an evaporative cooling system to further reduce the energy load caused by excess solar radiation, with the first option being costless.

SHADING EFFECTS ON GREENHOUSE MICROCLIMATE AND CROP TRANSPIRATION IN A CUCUMBER CROP GROWN UNDER MEDITERRANEAN CONDITIONS

E. Kitta, N. Katsoulas, D. Savvas

ABSTRACT. *The aim of this study was to investigate the effects of greenhouse shading on greenhouse microclimate and energy balance, and on crop production. Experiments were carried out in the experimental farm of the University of Thessaly at Velestino, in three similar, plastic-covered greenhouses using hydroponically-grown cucumbers as a test crop. One of the greenhouses was used as a control (without shading); the other two were shaded using two different shade nets (shading intensity of approximately 35% and 50%, respectively). Climatic parameters were measured during two growing seasons from April to June and from September to November 2008 and seven selected days of the above periods are presented. The results showed that shading could not keep greenhouse air temperature and vapor pressure deficit below 30 °C and 1.5 kPa, respectively, values that are considered acceptable for cucumber crop growth (Growers Books, 1980; Bakker et al., 1987; Olympios and Hanan, 1992). From the crop production data it was found that shading intensity should not exceed 35%. The analysis of greenhouse microclimate and energy balance showed that shading is necessary from the middle of spring, while even shading of approximately 50% was not sufficient to cool the greenhouse during noon time of summer days in Central Greece and that an additional cooling system was required.*

Keywords. *Air temperature, Solar radiation, Shade net, Energy balance.*

Greenhouse cooling is a matter of increasing interest for growers in Mediterranean countries, due to excessively high air temperature and vapor pressure deficit levels during summer. These conditions negatively affect crop physiological activities, crop growth, and quality (Jarvis and McNaughton, 1986; Aubinet et al., 1989), crop water status (transpiration and stomatal conductance) and production, and quality characteristics (Abdel-Mawgoud et al., 1996). Various methods can be used to cool the greenhouse. Natural ventilation is one of the most usual practices. However, currently the majority of greenhouses include some type of ventilation system (Boulard et al., 1997; Kittas et al., 1997). Natural ventilation is generally not sufficient for releasing the excess energy during sunny days in summer and, therefore, other cooling methods have to be used in combination with natural ventilation (Katsoulas et al., 2001).

The use of screens, especially the white wash of the cover, is a typical practice in the whole Mediterranean basin. It is considered a low-cost method of decreasing radiation and the concomitant energy load during warm periods. The few studies (Baille et al., 1980; Baille et al., 2001; Mashonjowa et al., 2010) relevant to whitening suggest that white painting of the greenhouse cover material is not only a cheap but also an efficient crop shading method. Greenhouse whitening allows inside air temperature to be maintained close to or even lower than the outside level during summer periods due to an increase of crop transpiration rate under shading (Baille et al., 2001; Mashonjowa et al., 2010) while it reduces the solar infrared fraction that enters to the greenhouse, enhancing slightly the photosyntheticaly active radiation (PAR) proportion in the incoming solar irradiance (Kittas et al., 1999). The latter characteristic of whitening could represent an advantage with respect to other shading options, especially in warm countries with high radiation load during summer. On the other hand, the major disadvantage of whitening is the lack of flexibility, since neither the application of shading nor its level can be adapted to natural changes of solar radiation intensity during the cropping period. Additionally, it is easy to add more but difficult to remove the whitening material at the end of the warm season, when natural solar radiation intensity decreases and shading may restrict crop light perception to critical levels.

Mobile shading allows improvement of greenhouse climate, especially during the noon hour. It reduces canopy transpiration and water uptake, and increases remarkably water use efficiency (Lorenzo et al., 2006). The use of shading screens in greenhouses became a common practice during the last decade (Cohen et al., 2005; Castellano et al., 2008) because it is a flexible and efficient method of reducing the energy load inside the greenhouse (Teitel and Segal, 1995), especially in climates characterized by high evaporative demand and limited water resources (Lorenzo et al., 2006).

Submitted for review in April 2011 as manuscript number SE 9151; approved for publication by the Structures & Environment Division of ASABE in October 2011.

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ISSN 0883-8542

The optical properties of the screens (type of fabric and shade factor) and the whitening of the cover (type of product and concentration) can modify the diffuse-to-direct radiation ratio (Baille et al., 2001; Raveh et al., 2003; Cohen et al., 2005) and cooling performance (Willits, 2001), while reducing air and crop temperature (Smith et al., 1984; Fernandez-Rodriguez et al., 2000). The modifications arising from the optical properties of the screens can affect radiation absorbed by the crop, stomatal conductance, and net assimilation of CO_2, and consequently crop growth and productivity. Furthermore, light quality modifications affect morphogenesis and photosynthesis, although their role in growth has not been yet completely clarified (Li et al., 2000). Nevertheless, adaptation of plants to light conditions depends also on the specific behavior of the plant species grown in greenhouses (Raveh et al., 2003; Barradas et al., 2005; Romacho et al., 2006). Shade can increase total and marketable yield of tomato grown in hot climates. Depression of crop yield is frequently observed under Mediterranean conditions when high solar radiation and low air humidity conditions prevail. Tomato plants grown in Egypt for the entire season with under 30% to 40% shade produced more fruit thereby rendering a higher yield than those grown without shade (El-Aidy, 1986; Abdel-Mawgoud et al., 1996). Increasing shade intensity to above 40% decreased flowering and yield. El-Gizawy et al. (1993) observed that increasing shading intensity up to 51% over a tomato crop resulted in fruit total production increase. The same authors mention that the highest tomato crop production was obtained under 35% shading, while increasing shading intensity decreased by up to 100% the incidence of sunscald on fruit. Concerning the effect of shading on cucumber crop, Naraghi and Lofti (2010) observed that increasing shading density up to 35% led to an increase in the number of fruits per plant. However, the number of fruits tended to decrease as shading density increased to 60%. Furthermore, the above authors mention that shading intensity greatly influenced the physiological disorders like sun-scald of cucumber fruits.

A better understanding of plant responses to shading is of great interest for greenhouse crops. With respect to the Mediterranean greenhouses, more information is needed mainly on plant responses to the time of application, including both commencement and termination of shading dates, degree of shading, and shading technique (whitening products, disposition, and mobility of the screens in the greenhouse).

To our knowledge there is little information in the literature regarding the responses of cucumber crops to greenhouse shading under Mediterranean climatic conditions. Thus, the present work aimed at studying the effect of different shading levels achieved by means of agricultural shade nets, on greenhouse microclimate, energy balance, and crop transpiration under Mediterranean climate conditions.

Materials and Methods

Greenhouse Facilities and Plant Material

The experimental work was carried out in three similar, single-span, arched roof, greenhouses covered by a single polyethylene film (type PE-EVA-film TUV 3945, film thickness of 180 µm, Plastika Kritis S.A., Heraklion-Crete, Greece), N-S oriented, located at the experimental farm of the University of Thessaly near Volos (Velestino: Latitude 39° 22′, longitude 22° 44′, altitude 85 m) during spring, summer, and autumn in 2008 (fig. 1). The geometrical characteristics of each greenhouse were as follows: eaves height of 2.4 m, ridge height of 4.1 m, total width of 8 m, total length of 20 m, ground area of 160 m^2, and volume of 572 m^3. The greenhouses were equipped with two continuous side roll-up windows located at a height of 0.6 m above the ground with a maximum opening area A_T of 27 m^2 (two vents of 15 m length × 0.9 m opening height) for both vents (ratio of opening to greenhouse ground area of about 17%). The vents were controlled automatically via a controller (Macqu, Geometions SA, Athens, Greece) and opened in steps; they began to open when greenhouse air temperature exceeded 23°C, and reached their maximum aperture when temperature reached 28°C. The prevailing wind of the region had a N-S direction. The greenhouse soil was totally covered by a double-side (black downwards - white upwards) plastic film 200 µm thick (Plastika Kritis S.A., Heraklion-Crete, Greece).

During the experimental period, two cucumber crops (*Cucumis sativus* cv. Stamina) were grown, specifically a spring crop planted on 10 April and terminated on 28 June and an autumn crop planted on 1 September and terminated on 12 November. The plants were grown hydroponically in bags (1 m long, 0.3 m wide, 0.2 m high) filled with perlite. The plant density was 2.4 plants·m^{-2}. Plants were laid out in four double rows, with an in-row spacing of 0.33 m, and a row spacing of 0.80 m. The supply of a standard nutrition solution for cucumber was automatically controlled by a fertigation computer and pH set point was at 5.6 with small fluctuations

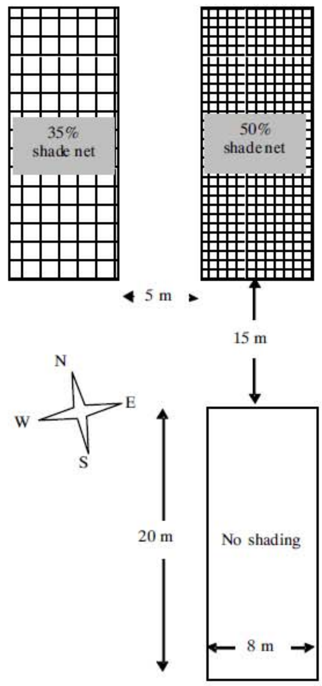


Figure 1. Layout of the experimental greenhouses with indication of the shade nest used for greenhouse shading.

aimed to maintain the pH between 5.5 and 6.5 in the drainage solution. The plants were pruned according to the umbrella training system (Klieber et al., 1993) and all other cultural practices not related to the energy balance inside the greenhouse (plant protection, harvesting, etc.) were similar to those practiced commonly by local greenhouse cucumber producers.

Three levels of greenhouse shading were tested, obtained using no net in one of the greenhouses and shade nets made by polypropylene strips (C. Vellis S.A., Piraeus, Greece) differing in hole size. The fixed nets were installed over the external surface of the cover in the two shaded greenhouses. In particular, the three shading treatments were as follows:

- 0% shading ($Gr_{0\%}$), greenhouse transmission to solar radiation of approximately 79%,
- 35% shading ($Gr_{35\%}$) (net hole size 2 × 8 mm), greenhouse transmission to solar radiation of approximately 50%, and
- 50% shading ($Gr_{50\%}$) (net hole size 1 × 8 mm), greenhouse transmission to solar radiation of approximately 38%.

The values of greenhouse transmission to solar radiation are the mean values calculated using the ratio of inside to outside solar radiation during the experimental period.

In the spring-summer crop, the three different shading treatments were commenced 46 days after transplanting (DAT), specifically on 27 May 2008, and maintained up to crop termination. In the autumn crop, shading was installed immediately after transplanting and maintained up to the end of the experiment.

Measurements

Climate Measurements

The following climatic data were recorded inside and outside the three experimental greenhouses:

- air temperature (T, °C) and water vapor pressure (e, kPa), by means of ventilated psychrometers (wet and dry bulb) (model VP1, Delta-T Devices, Cambridge, England), placed 1.5 m above the ground (that was 0.5 m bellow the top of the cucumber plants during spring-summer days presented and at the same level with the top of the crop during autumn days presented) and at the center of each greenhouse and outside 15 m away from the greenhouse on a mast 3.5 m above ground;
- solar radiation (W m^{-2}), by means of pyranometers (model Middleton EP08-E, Brunswick Victoria, Australia), placed 2 m above the ground (that corresponded to a position above plant canopy) at the center of each greenhouse ($R_{s,i}$) and outside ($R_{s,o}$) 15 m away from the greenhouse on a mast 3.5 m above ground.
- crop transpiration rate E_c (kg m^{-2} s^{-1}) was measured every ten minutes by means of weighing lysimeters, located at a central plant row in two of the three greenhouses, particularly in those with 0% and 35% shading. E_c of the 50% shading greenhouse was not measured. The device used for crop transpiration measurements included an electronic balance (model 60000 G SCS, capacity of 62 kg, accuracy of ±1 g, Precisa, Zurich, Switzerland) equipped with a tray carrying three plants, and an independent system of water supply and drainage. Considering that perlite was completely covered by bags and thus evaporation losses from the substrate were negligible, the weight loss measured by the electronic balance was assumed to be equal to crop transpiration.
- Additionally, measurements of wind speed (m s^{-1}), with a cup anemometer (model AN1-UM-3, Delta-T Devices, Cambridge, UK) and wind direction, with a wind vane (model WD1-UM-3, Delta-T Devices, Cambridge, UK) were carried out on a mast 4 m above the ground and 15 m away from the greenhouse.

Air temperature and relative humidity and solar radiation sensors were calibrated before their use in the experimental period. All of the above-mentioned measurements were recorded in four data logger systems (ZENO®-3200, Coastal Environmental Systems, Inc., Seattle, Wash.). Sensors were scanned every 30 s and the data was averaged and stored every 10-min time intervals except for the lysimeter data where the real-time vales were recorded every 10 minutes.

Crop Measurements

A series of non-destructive measurements was made in 16 randomly selected plants per greenhouse, eight times during the experimental period and plant stem length, leaf number and length (*L*), and width (*W*) of each leaf were measured. A scanner (GT 9500, Epson, Nagano, Japan) was used to measure leaf area (*LA*) in sample plants during the experimental period. These measurements allowed correlating *LA* to leaf *L* and *W* and the correlation was used afterwards to estimate *LA* as a relationship of *L* and *W* measurement in each plant. Fruits were harvested twice a week, starting on 20 May and finishing on 10 July. The harvested fruits from the abovementioned 16 randomly selected plants were weighted and the total production per greenhouse m^2 was calculated. The statistical package SPSS (SPSS-14.0 for Windows standard version, 2005, SPSS BI Greece S.A.) was used for statistical analysis of the data. Data were analyzed using ANOVA ($P \le 0.05$) and Duncan's multirange post hoc tests.

Calculations

Greenhouse Energy Balance

The energy balance in the greenhouse, according to the *ASAE Standards* (2003) can be written in the following simplified form:

$$(1-\varepsilon)\,R_{s,i} = U\,(T_i - T_o) + \rho\,C_p\,Q(T_e - T_o) \qquad (1)$$

where ε is the 'evaporation' coefficient, which represents the ratio of the latent energy released by the canopy and the floor to the heat load. The latter is usually taken equal to the inside global radiation $R_{s,i}$ because the net radiation, which is a better estimate of the actual heat load, is not frequently available. The heat transfer coefficient through the cover is depicted by U in W m^{-2} K^{-1}, and T_e is the exhaust air temperature considered equal to greenhouse air temperature T_i (Seginer, 1997). In order to calculate ε, equation 1 and U = 6.2 W m^{-2} $°C^{-1}$ (*ASAE Standards,* 2003) were used.

Q is the greenhouse ventilation rate as calculated using the simplified relationship suggested by Kittas et al. (1996):

$$Q = \frac{A_T}{2} C_d \sqrt{C_w}\, u_o + Q_0 \qquad (2)$$

where u_o is the outside air speed, A_T (m^2) the actual vent opening area, Q_0 (m^3 s^{-1}) the leakage ventilation, and C_d $C_w^{0.5}$ the wind and vent related coefficient, where C_d is the discharge coefficient and C_w is the overall wind effect coefficient (Roy et al., 2002). The parameters Q_0 and C_d $C_w^{0.5}$ were determined by Katsoulas et al. (2006) for the same experimental greenhouses; and found equal to 0.135± 0.149 m^3 s^{-1} and 0.078±0.0057, respectively.

The evaporation from the soil and the substrate were considered negligible, and thus the evaporation coefficient can be also calculated as:

$$\varepsilon = \lambda E_c / R_{s,i} \tag{3}$$

where λ is the latent heat of vaporization (J kg^{-1}).

Results

The data selected for analysis are for three consecutive days (15, 16, and 17 May) before shade nets application and three consecutive days after shade nets application (1, 2, and 3 June) during the spring experiment, which differed slightly in the outside radiation and temperature conditions, and one representative day during the autumn experimental period, particularly 19 September 2008. The selected days before shading are presented in order to show that the greenhouse microclimate before shading was similar in all three greenhouses and, accordingly, any changes in greenhouse microclimate were due to the different shading treatments. The installation of shade nets during the spring experiment was made on the 46th day after transplanting, namely on 27 May 2008. Thus, on 1, 2, and 3 June, the crop was only a few days under shading and, therefore, no differences in crop development were anticipated. Furthermore, during 19 September, plants had been grown for only 19 days in the greenhouse and, consequently, their leaf area index was relatively low. Accordingly, it is reasonable to attribute any differences in greenhouse microclimate during the selected days to greenhouse shading only and not to differences in crop development between the three greenhouses. The daily mean values (averaged over 09:00 h-18:00 h local time) of the outside climate variables for the days selected are given in table 1. The 1st of June 2008 was a sunny summer day while 2 and 3 June were relatively cloudy days. The presentation of data for days differing in cloudiness is intentional, aiming to allow for greenhouse microclimate comparisons under different outside radiation conditions.

Greenhouse Microclimate

Effect on Radiation

The diurnal variation of solar radiation inside the three greenhouses and outside, during the selected days before or after shading, is shown in figure 2.

It can bee seen that before shading, all three greenhouses had similar levels of incoming solar radiation. After shade net application, the solar radiation intensity at mid-day reached very high levels (720 W m^{-2}) in the greenhouse without shading, but did not exceed 450 W m^{-2} in the shaded greenhouses. In the spring experiment, the daily averages (09:00 – 18:00) of the incoming solar radiation intensity during the three selected days were 455 (±198) W m^{-2}, 290 (±128) W m^{-2}, and 220 (±107) W m^{-2} in the greenhouses corresponding to $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$, respectively. During the same days, the daily average of the outside solar radiation intensity was 562 (±226) W m^{-2}. The values in parenthesis represent standard deviation of mean. The maximum values of solar radiation observed in $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$, during the 1st of June were 730 W m^{-2}, 445 W m^{-2}, and 365 W m^{-2}, respectively. The respective mean values during 19 September were 353 (±160) W m^{-2}, 210 (±110) W m^{-2}, and 160 (±90) W m^{-2} in the $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$, respectively, while the mean value of the outside solar radiation during the same day was 420 (±200) W m^{-2}.

Table 1. Average (and standard deviation in parenthesis) and maximum values of climatic variables outside the greenhouse over the period 09:00 h-18:00 h local time during seven selected days.

Day	$R_{s,o}$[a] ($MJ\ m^{-2}$)	T_o[b] (°C)	RH_o[c] (%)	VPD_o[d] (kPa)	u_o[e] ($m\ s^{-1}$)
15 May	20.7	21.7 (±2.9)	41.4 (±11.9)	1.59 (±0.52)	2.1 (±0.6)
16 May	20.5	23.4 (±3.1)	37.5 (±5.4)	1.85 (±0.45)	2.0 (±0.9)
17 May	20.4	24.5 (±3.2)	37.6 (±6.7)	1.98 (±0.50)	2.3 (±1.2)
1 June	21.8	27.3 (±2.9)	37.3 (±8.3)	2.35 (±0.63)	2.0 (±0.7)
2 June	19.4	25.7 (±1.1)	45.3 (±5.1)	1.82 (±0.28)	4.3 (±1.1)
3 June	16.5	22.0 (±1.1)	47.4 (±4.7)	1.4 (±0.21)	3.6 (±1.1)
19 Sept	14.3	18.6 (±2.1)	44.0 (±6.0)	1.23 (±0.27)	1.9 (±0.5)

[a] $R_{s,o}$ = global radiation ($MJ\ m^{-2}$).
[b] T_o = air temperature (°C).
[c] RH_o =air relative humidity (%, kPa).
[d] VPD_o = vapor pressure deficit (kPa).
[e] u_o = wind speed ($m\ s^{-1}$).

The greenhouse radiation transmission coefficient, τ, was calculated from the ratio of inside to outside solar irradiance ($\tau = R_{s,i} / R_{s,o}$). The diurnal variation of τ during the selected days is shown in figure 3.

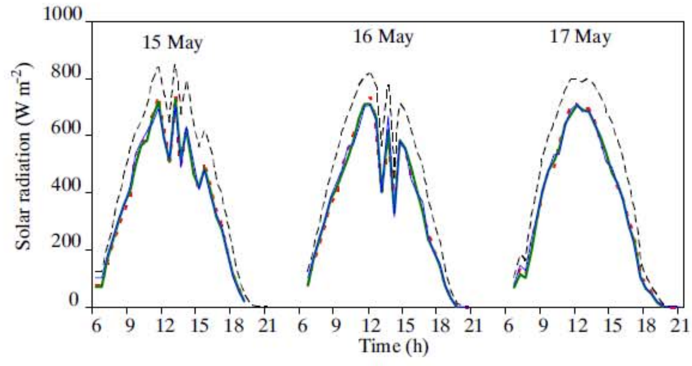
The average values of τ in the three greenhouses during the period between 09:00-18:00 were about 0.78±0.07 before shading, and 0.79±0.06, 0.50±0.07, and 0.38±0.05, for $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$, respectively, during the selected days after shading application. The observed fluctuations around the mean values were due to the interception of direct solar irradiance by the greenhouse structure and internal equipment located above the radiation sensors and the change of solar incidence angle (Wang and Boulard, 2000). The maximum transmission coefficients observed by noon during the selected days were 0.91, 0.64, and 0.49 for the $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$, respectively, when no internal obstacle was interfering.

Effect on Temperature and Air Vapor Pressure Deficit

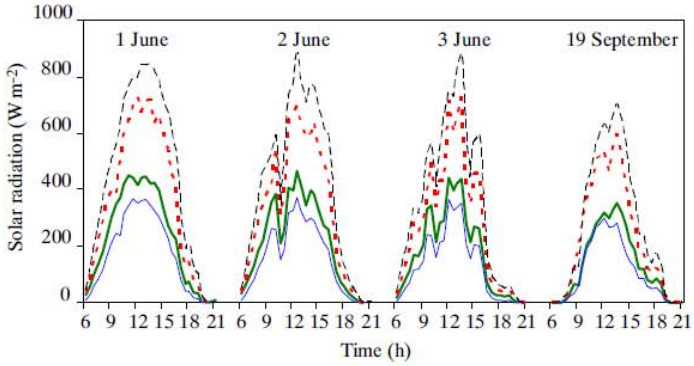
The diurnal variation of the air temperature in the three greenhouses before shading (fig. 4a) shows that the air temperature was similar in the three greenhouses before shading. The diurnal variation of air temperature during the selected days of June (fig. 4b) indicates that shading reduced greenhouse air temperature. Similar reduction was observed for the air vapor pressure deficit (data not shown).

The diurnal variation of air temperature difference between $Gr_{0\%}$ and $Gr_{50\%}$ and between $Gr_{0\%}$ and $Gr_{35\%}$ (fig. 5), shows that $Gr_{50\%}$ and $Gr_{35\%}$ had clearly lower temperature conditions than those observed in $Gr_{0\%}$. Similar trend, as obtained with air temperature, was observed for the air vapor pressure deficit differences between the non shaded and shaded greenhouses with no significant differences between the two shaded greenhouses (data not shown).

The mean values (average 09:00 h-18:00 h) of air temperature and air vapor pressure deficit (VPD) during the selected days before and after shading are presented in table 2. During the clear sunny day (1 June), the mean



(a)



(b)

Figure 2. Daily course of solar radiation during (a) three selected days without shading and (b) four selected days with shading. Discontinuous thick line: outside; discontinuous thin line: $Gr_{0\%}$; continuous thick line: $Gr_{35\%}$; continuous thin line: $Gr_{50\%}$.

greenhouse air temperature reduction due to shading was about 1.8°C in the greenhouse with moderate shading and 3.9°C in the greenhouse with high shading. The maximum air temperature values observed during the clear sunny day in Gr0%, Gr35% and Gr50% were 41.7.8°C, 38.8°C, and 36.8°C, respectively, which clearly indicate the beneficial effect of shading on greenhouse air temperature conditions.

On daily average, compared to the 1 June, *VPD* values were reduced by 30% on the two cloudy days (2 and 3 June), while they were even more strongly reduced during the autumn experimental period. The maximum air *VPD* values that were observed during the sunny day (1 June) in $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$ were 6.0, 4.6, and 4.3 kPa, respectively.

Effect of Shading on Crop Transpiration Rate

Figure 6 presents the diurnal variation of crop transpiration rate in two of the three greenhouses ($Gr_{0\%}$ and $Gr_{35\%}$) during the selected days.

The major differences were observed during the period between 10:00 and 17:00. The mean daily values of λE_c observed in $Gr_{0\%}$ and $Gr_{35\%}$ were 65 (±18) W m^{-2} and 48 (±18) W m^{-2}, and 44 (±16) W m^{-2} and 35 (±11) W m^{-2}, during the selected days in spring and autumn, respectively. The average decrease of crop transpiration rate due to shading over the 4-day period was 24%; the higher decrease (38%) was observed during the sunny day (1 June), whereas

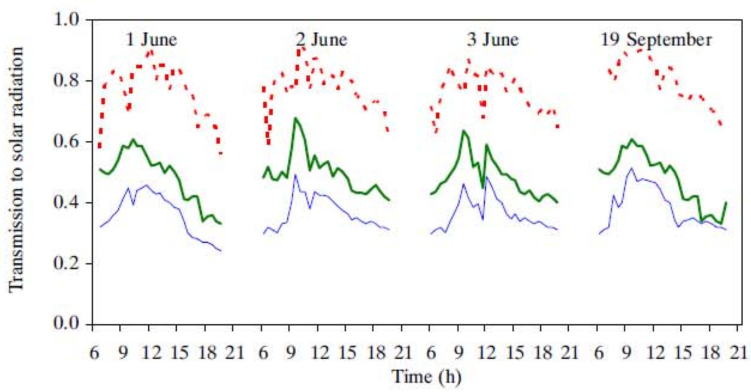
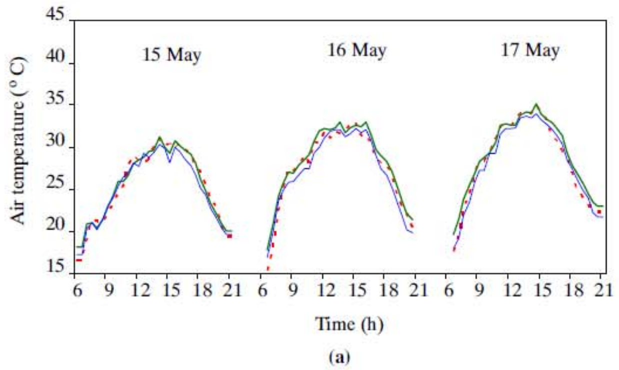


Figure 3. Daily course of greenhouse solar radiation transmission during the four selected days. Discontinuous line: $Gr_{0\%}$; continuous thick line: $Gr_{35\%}$; continuous thin line: $Gr_{50\%}$.



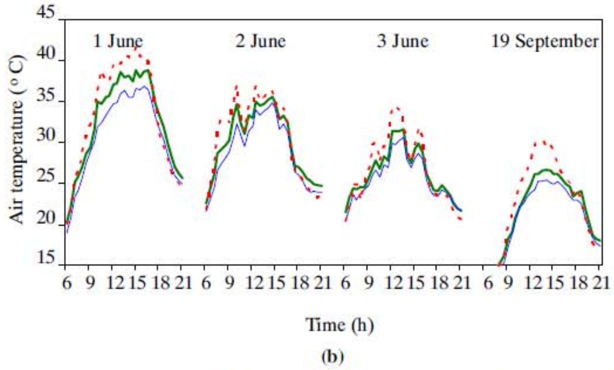


Figure 4. Diurnal variation of air temperature in the three greenhouses during (a) three selected days without shading, and (b) four selected days with shading. Discontinuous line: $Gr_{0\%}$; continuous thick line: $Gr_{35\%}$; continuous thin line: $Gr_{50\%}$.

the lowest decrease (15% and 18%) occurred during the cloudy days (2 and 3 June, respectively).

Greenhouse Energy Balance

The values of ε calculated by applying the greenhouse energy balance method (eq. 1) did not differ significantly between the three greenhouses. The average values of ε in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during the three selected days were 0.32 (±0.20), 0.28 (±0.18), and 0.30 (±0.12), respectively. The mean values of ε during the sunny day (1 June) were about 50% higher than those observed during the two cloudy days (2 and 3 June). The average values of ε observed in $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$ on 19 September were 0.39 (±0.20), 0.38 (±0.08), and 0.42 (±0.11), respectively. The average values of ε that were calculated for the three selected days using equation 2 were 0.26 (±0.08) and 0.27 (±0.05), for $Gr_{0\%}$ and $Gr_{35\%}$, respectively. These values of ε were lower than those observed using equation 1 with the maximum difference being about 19%.

Crop Production

Measurements of leaf length (L, cm), width (W, cm), and area (LA, cm^2) on randomly selected plants during the period of measurements were used for the development and calibration of a formula for LA calculation as a function of leaf L and W characteristics. A good correlation was obtained between the LA and L and between LA and the product $L \times W$. The relations obtained were:

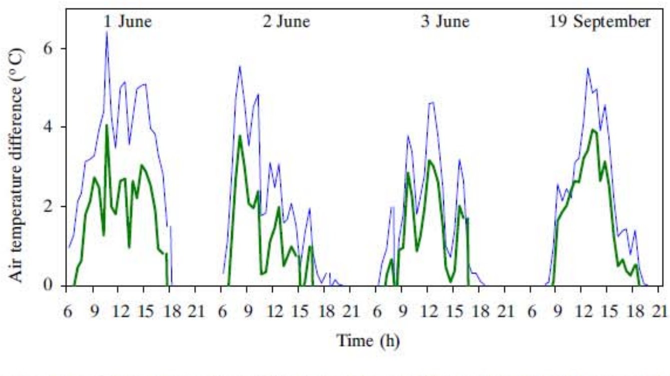


Figure 5. Diurnal variation of air temperature difference between the greenhouse with no shading and the greenhouses with 35% and 50% shading during four selected days. Continuous thick line: $T_{i,Gr0\%}-T_{i,Gr35\%}$; continuous thin line: $T_{i,Gr0\%}-T_{i,Gr50\%}$.

Table 2. Average values (and standard deviation in parenthesis) of greenhouse air temperature *Ti* and vapor pressure deficit *VPD$_i$* over the period 09:00 h-18:00 h local time during seven selected days in three greenhouses differing in shading level.

	Ti (°C)[a]			*VPD$_i$* (kPa)		
Day	$Gr_{0\%}$	$Gr_{35\%}$	$Gr_{50\%}$	$Gr_{0\%}$	$Gr_{35\%}$	$Gr_{50\%}$
15 May	28.0 (±2.5)	28.1 (±2.2)	27.6 (±2.1)	2.7 (±0.5)	2.8 (±0.7)	2.6 (±0.5)
16 May	30.2 (±1.9)	30.8 (±2.0)	29.8 (±2.2)	2.9 (±0.4)	3.0 (±0.5)	2.8 (±0.4)
17 May	31.5 (±2.4)	31.9 (±2.2)	31.1 (±2.3)	3.2 (±0.9)	3.3 (±0.9)	3.0 (±0.8)
1 June	38.0 (±3.1)	36.2 (±2.6)	34.1 (±2.3)	4.6 (±1.0)	3.6 (±1.0)	3.4 (±0.9)
2 June	33.3 (±3.2)	32.3 (±2.5)	30.8 (±2.4)	3.2 (±0.6)	2.8 (±0.5)	2.7 (±0.6)
3 June	29.2 (±3.4)	28.0 (±2.4)	27.0 (±2.2)	2.4 (±0.7)	2.1 (±0.6)	2.0 (±0.5)
19 September	26.2 (±3.1)	24.1 (±2.5)	23.6 (±2.3)	1.7 (±0.4)	1.8 (±0.4)	1.5 (±0.3)

[a] $Gr_{0\%}$; 0% shading, greenhouse transmission to solar radiation of about 79%;
$Gr_{35\%}$: 35% shading, greenhouse transmission to solar radiation of about 50%;
$Gr_{50\%}$: 50% shading, greenhouse transmission to solar radiation of about 38%.

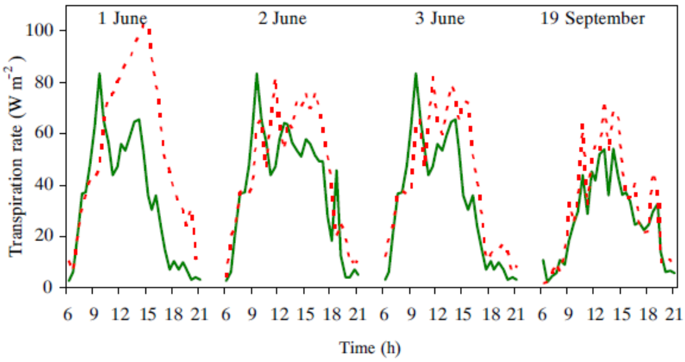


Figure 6. Diurnal variation of crop transpiration in the non-shaded greenhouse and in the 35% shaded greenhouse during the four selected days. Discontinuous line: $Gr_{0\%}$; continuous line: $Gr_{35\%}$.

$$LA = 26\ L - 182 \quad (4a)$$

$$LA = 0.77\ L\ W + 6.5 \quad (4b)$$

with R^2 values of 0.94 and 0.95, respectively. When equations 4a and 4b calibrated using the data of each greenhouse separately, no significant differences were found between their constant parameters for the different greenhouses. The leaf area index values found in $Gr_{35\%}$ and $Gr_{50\%}$ where significantly higher than those observed in $Gr_{0\%}$ after 15 June but no statistical differences were found in the number of leaves-nodes of cucumber plants between the three treatments (data not shown). The crop leaf area index I_{LA} [m^2 (leaf) m^{-2} (ground)] was about 1.5 during the fist days of June and about 0.7 during the 19 of September.

It was found that shading increased the number of harvested fruit and the total crop production (fig. 7). It can be seen that the values of cumulative fruit weight and number were higher for the $Gr_{35\%}$ than for the $Gr_{0\%}$ and $Gr_{50\%}$. The values of fruit production and fruit number observed at the end of experimental period were 9.8 kg m^{-2}, 15.1 kg m^{-2}, and 11.2 kg m^{-2} and 25.6 fruit m^{-2}, 39.4 fruit m^{-2}, and 29.4 fruit m^{-2} for $Gr_{0\%}$, $Gr_{35\%}$, and $Gr_{50\%}$, respectively. The mean value of fruit weight was about 0.38 kg $fruit^{-1}$ for all three greenhouses.

Discussion

Changes in Microclimate

When nets were applied in the two greenhouses, the incoming solar radiation was reduced by about 35% and 50% (figs. 2 and 3). This reduction of incoming solar radiation lead to greenhouse air temperature and vapor pressure deficit modifications. The high values of air temperature and vapor pressure deficit observed during the sunny day under no shading conditions [air temperature ≈41°C (fig. 4b) and vapor pressure deficit ≈6 kPa] were reduced under shading, the maximum air temperature and vapor pressure deficit values observed during the same day under shading were 38°C and 36°C and 4.5 and 4.3 kPa for the $Gr_{35\%}$ and $Gr_{50\%}$ treatments, respectively. However, shading was incapable of maintaining the greenhouse air temperature and humidity to optimal levels (25°C and 70%, respectively, Bulder et al., 1987), or at least at temperature levels below 30°C (Growers Books, 1980; Olympios and Hanan, 1992) and VPD_i below 1.5 kPa (Bakker et al., 1987).

The difference between the values of incoming solar radiation observed in the control greenhouse ($Gr_{0\%}$) and the greenhouse with the highest shading intensity ($Gr_{50\%}$) was 270, 220, and 200 W m^{-2} on the sunny (1 June) and cloudy days (2 and 3 June), respectively, and the measured differences in air temperature between $Gr_{0\%}$ and $Gr_{50\%}$ during the sunny (1 June) and cloudy (2 and 3 June) days were 3.9°C, 2.5°C, and 2.2°C, respectively. Willits (2001) note that when screens are used, the solar radiation decrease does not always involve a notable temperature decrease,

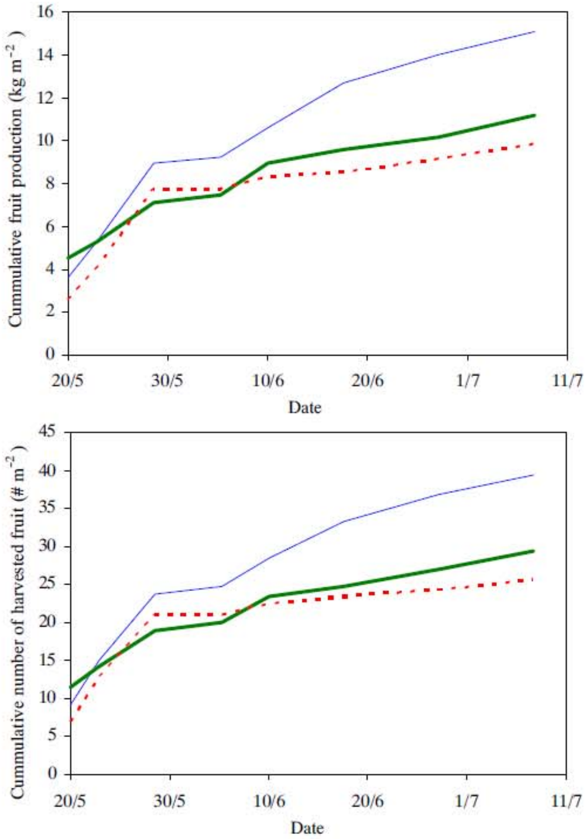


Figure 7. Development of (a) cumulative harvested fruit production and (b) cumulative harvested fruit number per m^{-2} of greenhouse ground area. Discontinuous line: $Gr_{0\%}$; continuous thick line: $Gr_{35\%}$; continuous thin line: $Gr_{50\%}$.

especially when the ventilation rates are low. A high radiation absorption by the screen can contribute to an increase in the amount of energy transferred by convection into the greenhouse.

To quantify the effect of shading intensity on greenhouse air temperature, a linear regression analysis was carried out between the air temperature measured inside the three greenhouses T_i and the outside air temperature T_o and solar radiation $R_{s,o}$ in order to calibrate the following equation:

$$T_i = a\, T_o + b\, \tau\, R_{s,o} + c \quad (5)$$

The coefficients a, b, and c, as calculated by replacing the values of T_o, τ, and $R_{s,o}$ that were measured on 1, 2, and 3 June in equation 5 amounted to 1.013 (with a standard error of ±0.040), 0.014 (with a standard error of ± 0.001), and 2.370 (with a standard error of ± 1.010), respectively, with a correlation coefficient R^2 of 0.88. Consequently, the calibrated equation 5 explains an 88% of the variability of T_i. Moreover, the small standard errors of a, b and c indicate that the results of the calibration are satisfactory. Equation 5 shows that greenhouse air temperature increase of about 1°C for every 100 W m^{-2} of increase of incoming solar radiation. Similar results were found by Kittas et al. (1987) for a plastic tunnel in the South of France.

Using equation 5, it is easy to calculate the difference between the inside and outside air temperature as a function of solar radiation and the level of greenhouse shading. Although equation 5 and the standard ASABE ventilation formula (eq. 1) both refer to the greenhouse air temperature, the proper temperature criterion is canopy temperature T_c (Seginer, 2002). Hence, it would be interesting to estimate the effect of shading on canopy to greenhouse air temperature difference than on greenhouse to outside air temperature difference. On this purpose, the following simple model for crop temperature estimation was used (Boulard and Baille, 1993):

$$Tc - Ti = \frac{\zeta Rs,i - \lambda Ec}{ga \rho Cp ILA} \quad (6)$$

where ζ is the canopy absorption coefficient for solar radiation, g_a (m s^{-1}) is the crop aerodynamic conductance, and ρ (kg m^{-3}) and C_p (j kg^{-1} °C^{-1}) the air density and specific heat of air, respectively. The crop aerodynamic conductance can be calculated using the equation suggested by Monteith (1973):

$$g_a = 2I_{LA} 6.62 * 10^{-3} \left(\frac{ui}{d}\right)^{0.5} \quad (7)$$

where u_i (m s^{-1}) is the mean air velocity inside the greenhouse and d (m) is the characteristic leaf length of cucumber crop [usually taken as 0.7 times the maximum leaf dimension in the direction of air flow (Campbell, 1986)]. The d value used was equal to 0.35 m, as calculated using leaf length measurements taken during both experimental periods.

Mean greenhouse air velocity can be calculated using the equation:

$$ui = \frac{Q}{Av} \quad (8)$$

where A_v is the area of a vertical cross-section of the greenhouse. Using equation 7, the mean value of g_a calculated was 60 m s^{-1}.

Taking into account the above considerations, a ζ value equal to 0.82 (Heuvelink, 1996; Rosati et al., 2001) and that λE_c is equal to 0.42 $R_{s,i}$ (Yang et al., 1990), the crop to greenhouse air temperature difference was calculated (fig. 8).

As shown in figure 8, a greenhouse transmission coefficient of 0.4 could result in crop temperature values lower than the air temperature values while lower shading intensity (τ = 0.6 or 0.8) results in crop temperature values higher than the air temperature. In that case, other means for greenhouse cooling along with shading are necessary such as fogging combined by natural ventilation (Katsoulas et al., 2007; 2009).

Crop Response

The canopy transpiration rate (fig. 6) was affected to a lesser extent than the solar radiation intensity by shading. During the summer period, the difference in λE_c between the non-shaded greenhouse and that shaded by 35% was approximately 25% when integrated over the whole diurnal period, which is considered moderate. The same type of feedback was reported when a mist system was used for cooling, which decreased the vapor pressure deficit in the greenhouse air (Baille et al., 2001).

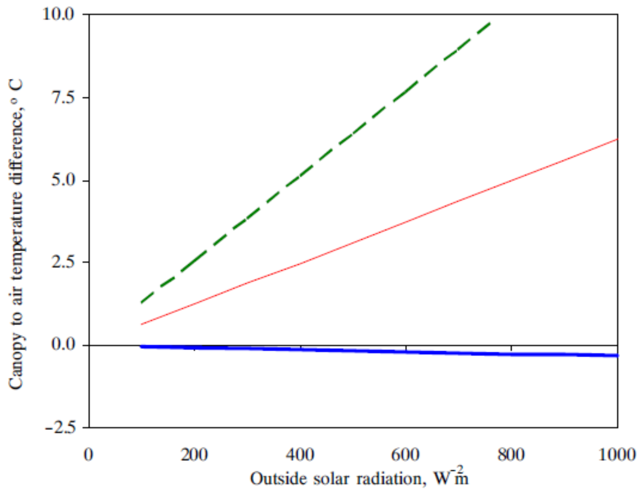


Figure 8. Canopy to air temperature difference as a function of outside solar radiation for several values of greenhouse transmission coefficient τ calculated using eq. 10. Continuous thick line: τ = 0.4; continuous thin line: τ = 0.6; discontinuous line: τ = 0.8.

The higher leaf area index and crop production observed under 35% shading compared to no shading conditions could probably be due to better water status and higher photosynthetic rates of plants under shading. Reducing crop temperature and vapor pressure deficit could greatly affect plant growth through different processes: (a) by improving the leaf water status (Stirzaker et al., 1997) which increases leaf conductance and hence CO_2-assimilation (Bakker, 1990) and (b) by decreasing fruit transpiration (Leonardi et al., 2000). Ogren and Evans (1992) mention that exposure of leaves to excessive light causes photoinhibition that is associated with photosynthesis decrease. The above, along with the fact that diffuse fraction of solar radiation is higher under shading (Abdel-Ghany and Al-Helal, 2010), favoring radiation penetration in the lower parts of the canopy and increasing canopy interception, could explain the increase in crop production observed under 35% shading compared to no shading conditions. Similar results were also found by other authors for tomato crop (El-Gizawy et al., 1993; Naraghi and Lotfi, 2010). Crop production under shading higher than 35% was not improved. The higher production was accompanied by a higher number of fruits. Since no statistical significant differences in number of nodes-flowers between the greenhouses were detected, the higher yield under 35% shade could be attributed to flower and fruit abortion of unshaded plants, which was also observed by El-Gizawy et al. (1993) and Naraghi and Lotfi (2010). Abortion of flowers and fruit depends on the source/sink ratio of carbon in the plant (Marcelis et al., 2004). Kitao et al. (2000) noted that excessive light intensity affects plant growth by promoting photo oxidation of chloroplast components which provoke reduction of productivity as a result of photo inhibition. The number of flowers and fruit creates a demand for plant resources, and if the plant cannot meet the demand due to decreased photosynthetic rates, resulting from exposure of unshaded plants to high or low light levels, high rates of abortion of newly formed fruit can occur (Bakker 1989). It appears that a physiologically-based optimal value of shading intensity exists, and that this value depends on several factors: the outside climate conditions (solar radiation, air temperature, and humidity), the greenhouse characteristics (ventilation rate, radiation transmission coefficient, cooling system), which affect the thermal and hydrological negative feedback effects, namely the impact of stomatal opening variation on crop transpiration rate (Jarvis and McNaughton, 1986; Aubinet et al., 1989), crop water status (transpiration and stomatal conductance), and production and quality characteristics (Abdel-Mawgoud et al., 1996). All these factors have to be taken into account when searching for the optimal (and time-variable) value of shading intensity. Considering the complexity of the mechanisms and the high number of interactions, the challenge is difficult, but might be met because the understanding and modeling of the coupling mechanisms between outside-inside atmospheres and canopy-inside atmosphere markedly progressed in the last decades. Furthermore, models that account for the various physical and physiological feedback mechanisms prevailing in the greenhouse system (Gonzalez-Real and Baille, 2001) could provide more insight into the influence of shading intensity on crop production.

Greenhouse Energy Balance

Seginer (1997) noted that ε ranges between 0 and 1, with the value of 1 representing "rich vegetation in desert conditions." The higher the value of the evaporation coefficient is, the lower the needs for greenhouse cooling are. Values of the evaporation coefficient near 1 indicate that there is no need for extra cooling since canopy transpiration is sufficient to counteract the heat load and maintain suitable humidity levels for optimum physiological status of the crop (Seginer, 1997; Katsoulas et al., 2006). Baille et al. (1994) calculated ε values between 0.50 and 0.75 in a hydroponic rose crop grown in Southern France. Similar values (0.60-0.70) were also reported by Boulard et al. (1991) for a tomato crop in the same area.

Generally, low values in the ε coefficient correspond to high solar energy loads in the greenhouse ($R_{s,i} \approx 700$ W m^{-2}) (Katsoulas et al., 2002) which may be not compensated for by crop transpiration. As a result, the plants encounter stress conditions caused by the extreme greenhouse microclimate. This is clearly the case that has to be avoided when growing greenhouse crops during summer. The ε values calculated for the spring period using the greenhouse energy balance method were close to 0.3 for all three greenhouses. This level indicates that transpiration was insufficient to eliminate adverse effects of excessively high solar radiation levels on crop performance and reduce the need for greenhouse cooling. This could be partially attributed also to the fact that the crop had a relatively low leaf area [$I_{LA} \sim 1.5$ m^2 (leaf) m^{-2} (ground)]. Thus, it is reasonable to conclude that under summer conditions in the area Velestino-Volos, shading up to 50% and natural ventilation are insufficient measures to maintain optimum greenhouse microclimate for cucumber plant growth when the plant density is up to 2.4 plants·m^{-2}. Accordingly, it is necessary either to expand the crop leaf area by increasing plant density, thereby enhancing evaporative cooling by crop transpiration (Katsoulas et al., 2002) or to introduce an evaporative cooling system (Katsoulas et al., 2001) to further reduce the energy load caused by excess solar radiation. Nevertheless, a plant density of 2.4 plants·m^{-2} is considered relatively high for greenhouse cucumber and a further increase may reduce light interception by individual plants, thereby decreasing the mean size and the overall quality of the fruit (Papadopoulos, 1994).

The differences between the ε values calculated by the two methods (19% lower values of ε when using eq. 3 rather than eq. 1) are possibly due to the many factors required for the implementation of greenhouse energy balance using equation 1 as compared to equation 3. Application of equation 3 requires measurements of crop transpiration rate which is not feasible in most commercial greenhouses. Hence, the energy balance method could be considered an easily applicable tool to estimate ε, even if it requires some greenhouse-related characteristic constants, and assess the effectiveness of cooling systems to improve the greenhouse microclimate under hot weather conditions.

Conclusion

From the growers' point of view, one of the main problems when using shading for alleviating the greenhouse heat load is the right decision on the intensity of shading and the correct timing of shading application. The analysis of greenhouse microclimate and crop production data showed that under Mediterranean conditions, shading is necessary with intensity no higher than 35% to 40%.

From the engineering point of view, it could be noted that solar radiation decrease due to shading by shade nets does not always involve a notable air temperature and vapor pressure deficit decrease, especially when the ventilation rates are low. Analysis of greenhouse energy balance showed that shading up to 50% and natural ventilation are not always sufficient measures to maintain optimum greenhouse microclimate for cucumber growth when the plant density is up to 2.4 plants·m^{-2} and leaf area index is low. Accordingly, it is necessary either to expand the crop leaf area by increasing plant density, thereby increasing evaporative cooling by crop transpiration or to introduce an evaporative cooling system to further reduce the energy load caused by excess solar radiation, with the first option being costless.

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3.2. Publication 2

Publication 2: **Kitta, E.** Katsoulas, N. Kandila, A. González-Real M.M., Baille A., 2014. Photosynthetic acclimation of sweet pepper plants to screenhouse conditions. *HortScience*, 49(2): 166-172

Extended summary

Leaf gas exchange and photosynthetic light acclimation of sweet pepper leaves were investigated from May to October 2011 under screenhouse (three different screens) and open field conditions. Three different screens were: two insect-proof (IP) screens (1) a pearl 50 mesh (20/10) AntiVirus™ screen with a mean PAR (400-700 nm) transmittance of 78%, that is, a PAR-shading factor of 22% (hereafter, IP-78); and (2) a white 50 mesh BioNet™ (BN) with a mean PAR transmission of 59% (hereafter IP-59). The third one was a green shade screen with a mean PAR transmission of 62% (hereafter GS-62).

The photosynthetic photon flux density (PPDF), leaf net CO_2 assimilation (A_n), transpiration rate (E) and stomatal conductance (g_s) were measured on leaves located in three canopy layers (at the beginning of crop season only Layer 1, at the end, Layer 3 corresponded to the top leaves and Layer 1 to the bottom leaves).

The amount of PPFD reaching the leaf layers was substantially lower for the screenhouse-grown crops than for the open-field crop. Despite the substantial difference observed on the incident PPFD between screenhouses and the open-field, A_n of the shaded crops was similar to or slightly lower than that of open filed crop.

The above resulted in substantially higher light-use efficiency under shading than in the open-field. Thus, the relative increase in LUE of shaded adult and old leaves with respect to open field plants was substantially higher than the corresponding relative decrease in incident PPFD, with more than 100% increase in LUE under the 34% shade treatment. A possible explanation might be that the amount of light under screenhouse after DAT 100 did not reach the saturation level (approximately 1000-1200 μmol m^{-2} s^{-1} for the uppermost leaves, depending on cultivars and growth conditions of light, Gonzalez-Real and Baille, 2006). As the top layer leaves received less than that level around noon, they were likely to have a higher efficiency to light than their counterparts in the open-field, which were submitted to PPFD conditions exceeding the amount of photosynthetic light saturation near noon.

In overall, the seasonal trend of A_n was similar in all treatments, with a plateau followed by a sharp decline at DAT 90 (first flush in fruit set) for leaves of Layer 1, and at DAT 140 (second flush in fruit set) for leaves of Layer 2. The sharp decline in A_n was concomitant with leaf ageing, but probably also with a decrease in photosynthetic N allocation to the leaves, which are competing with high N-demanding organs (fruits) for N resources. These results suggested that cyclic patterns of yield (fruit flushes, typical of peppers crops) affect the priority with which N is attributed to leaves. Therefore, ontogenic processes (e.g. leaf ageing) along with N-allocation to leaves (Gonzalez-Real and Baille, 2000) seemed to be the predominant factor in driving the seasonal pattern of leaf net CO_2 assimilation.

The overall trend of leaf transpiration rate throughout the crop cycle was characterized by a continuous decrease in all layers, although in a more progressive way than that observed for A_n. The higher values of stomatal conductance along the crop cycle in the shade treatments (although not always statistically significant) with respect to the open-field did not result in corresponding higher E rates except in some treatments around the middle and at the end of the crop cycle. As for A_n, E decreased as leaves aged and the differences in within-canopy light regime among screenhouses and the open-field only had no clear effect on the magnitude of E or its seasonal pattern. The generalized decreasing trend of E with leaf ageing could be related to that of g_s, although the two attributes showed different short term adjustments.

Both leaf ageing and shading affected the internal CO_2 concentration. The values of the ratio C_i/C_a were higher (i.e. lower values of the intercellular-to ambient CO_2 gradient since the C_a was constant during the period of measurements) in shaded plants compared to those of the open-field. This behaviour suggests that g_s is not the main determinant of the corresponding decrease experienced by A_n with both leaf ageing and shading by restricting the CO_2 availability in the mesophyll (Lawlor, 2002). It can be drawn that the tendency towards higher g_s under shade was counterweighted by a lower CO_2 gradient, therefore explaining the similar magnitude of A_n in open-field and screenhouse plants.

Overall, shaded sweet pepper plants display a physiological light-acclimation allowing them maintaining the photosynthetic activity to a level similar to that observed in non-shaded plants across a wide range of growth light regimes, irrespective of the type of net and its shading intensity.

3.3. Publication 3

Publication 3: **Kitta, E.**, Baille, A., Katsoulas, N., Rigakis, N., González-Real, M.M., 2014. Effects of cover optical properties on screenhouse radiative environment and sweet pepper productivity. *Biosystems Engineering*, 122:115-126

Extended summary

The effects of screens optical properties on screenhouse radiative environment and sweet pepper productivity were investigated under experimental conditions during two consecutive years (2011-2012). The differences in air temperature and vapour pressure deficit among screenhouses and open field were very small. This observation suggests that the above parameters are not likely to explain any differences in biomass and yield observed among screenhouses, neither between screenhouses and open field.

The season-averaged spectral transmittance determined in situ under the three screenhouses. All screens induced impoverishment in the blue wavelength band (B, 400-500 nm) and enrichment in near-infrared broadband (NIR, 700-1100 nm) with respect to PAR (400-700 nm).

All broadband ratios show a slight downward seasonal trend throughout the two periods of observation, which could be ascribed to seasonal changes in beam incidence angle, dust accumulation and ageing.

Broad band transmittance to B, NIR and PAR was correlated to the global solar radiation transmittance. The relationships linking the broad wavelength bands transmittance to the global solar radiation transmittance, τ_G, were quasi linear, the slope of the relationships being indicative of the sensitivity of each broadband transmittance to changes in global transmittance for solar radiation induced by the screen material. The slope of the τ_{NIR} *vs* τ_G was close to 1 ($\tau_{NIR} = 0.99\tau_G - 1.56$), whereas the slope of τ_{PAR} *vs* τ_G and τ_B *vs* τ_G were 1.20 and 1.39, respectively, indicating that τ_B was the transmittance most affected by the presence of the screen material.

All screens presented slight but significant changes in light quality parameters with respect to those measured in the open-field. The phytochrome-related ratios (ζ and R:FR) and the cryptochrome-related ratio B:FR showed significantly lower values under screens than in the open-field.

To summarise, although differing in colour, porosity and mesh size, the three screens shared several common characteristics in what refers to the changes they induced in light environment: (i) A relative enrichment in NIR with respect to PAR and B light. The higher impoverishment in B light was observed under the two insect-proof screens, which have a low transmittance in this wavelength band. (ii) An enrichment in FR light with increased shading intensity, which led to a decrease in all the FR-related parameters (ζ, B:FR and R:FR) and (iii) The relative decrease in FR-related parameters was highly correlated with τ_{PAR}, especially the R:FR ratio.

The values of the attributes characterising crop productivity (aboveground biomass and fruit yield) were greater under the screens than in open-field. Both attributes showed with respect to the open-field crop a slight and similar increase under the screens with the highest shading factor (≈ 40%, IP-59 and GS-62), and a substantial increase under moderate shading (≈ 20%, IP-78). On average over the two years, IP-78 was found to be the best performing screen in what refers to fruit productivity, with a 40% higher yield than the two other screens. That is, heavy shading appears to negatively affect the performance of sweet pepper crops in Mediterranean areas with respect to moderate shading.

The increasing trend of aboveground biomass (W_a) and fruit yield (Y) with screenhouse transmittance seems to indicate that the amount of PAR-light incident on the canopy is the main factor driving biomass production (Monteith, 1977, 1994) and yield whenever the PAR-transmittance is lower than at least 78%, the value of the IP-78 screen. Below this value, screens reduced crop productivity more or less proportionally to the decrease in PAR-transmittance. A decrease of 1% in PAR-transmittance would lead to a decrease of approximately 9.5 g m^{-2} of shoot dry biomass, and 0.091 kg m^{-2} in fresh fruit production. Taking as reference the maximum W_a and Y reached in IP78 (748 g m^{-2} and 5.58 kg m^{-2}, year 2011), it can be drawn that a 1% change in τ_{PAR} in the range 60-80% would lead to a change of 1.3 % (= 9.5/748) in W_a, and 1.6 % (=0.091/5.58) in Y. Such a result could be explained by the concomitant effect of increase in PAR and R/FR ratio, the former acting on the amount of incident PAR, and the latter acting on the interception efficiency through changes in leaf number and leaf area index. It might be also possible that the screenhouse plants allocated more biomass to the aerial organs (leaves and fruits) than to the roots, as abovementioned. Although the values of R:FR ratio did not show great differences among the treatments, they appear to induce significant changes in plant height since the 2-year pooled data indicated a clear increasing trend of plant height with decreasing R:FR.

Furthermore, the results suggested that (i) the more diffuse radiation regime prevailing under screenhouse is likely to be at the roots of the higher crop performances observed under the screenhouses and (ii) τ_{PAR} and R:FR are likely to act synergistically in light capture.

The lower performance of the open field crop with respect to the screenhouse crops could be ascribed to two main causes: (i) to the fact that the open field crop was subjected to a higher level of stress than the screenhouse crops, in other words, net covering might substantially mitigate the stress suffered by open field plants in summer conditions and (ii) to the positive effects resulting from the qualitative changes in light regime due to the presence of the net.

3.4. Publication 4

Publication 4: **Kitta, E.**, Baille, A., Katsoulas, N., Rigakis, N. 2014. Predicting reference evapotranspiration for screenhouse-grown crops. *Agricultural Water Management* (In press)

Extended summary

In order to estimate the reference evapotranspiration of screenhouse-grown crops ($ET_{o,in}$) from routine outside weather data and main screenhouse characteristics, all the microclimatic variables required to calculate $ET_{o,in}$ by means of the standard FAO-56 Penman-Monteith formula were measured under the three sweet-pepper cultivated screenhouses for two months (Aug-Sept 2012). The ratio of inside-to-outside wind speed (ω) was measured under the three screenhouse and was found (i) 0.19 under the IP-78, (ii) 0.20 under the IP-56, and (iii) 0.43 under the GS-62 green shading screen.

The time evolution of daily reference evapotranspiration for the open-field and screenhouses followed a similar time-pattern to that observed for solar and net radiation (R_s and R_n , respectively). Compared to $ET_{o,out}$, the absolute reduction (ΔET_o, mm day^{-1}) observed in the screenhouses was -0.60, - 1.58 and -1.57 mm day^{-1} for IP-78, IP-56 and GS-62, respectively in August, and – 0.41, -1.01 and -0.99 mm day^{-1} respectively in September. Over the two months periods, the mean relative reduction with respect to outside ET_o was 17.4%, 41.3% and 42.6 % in IP-78, IP-56 and GS-62, respectively.

The daily scale the evolution of the radiative ($ET_{rad,in}$) and advective ($ET_{adv,in}$) components of $ET_{o,in}$ where analysed and quantified.

On a monthly scale, $ET_{rad,IP-78}$ (3.61 and 2.43 mm day^{-1} in Aug. and Sept., respectively) was very close to $ET_{rad,out}$ (3.68 and 2.54 mm day^{-1} respectively, Table 3). $ET_{rad,IP-56}$ and $ET_{rad,GS-62}$ were substantially lower than $ET_{rad,out}$ (2.71 and 2.50 mm day^{-1}, respectively in August and 1.82 and 1.71 mm day^{-1}, respectively in September). Over the whole period of observation, this reduction amounted to 3.0%, 27.1% and 31.9 % in IP-78, IP-56 and GS-62, respectively.

The advective component, ET_{adv} followed a distinct time evolution from ET_o and ET_{rad}, showing maximum and minimum values that were concomitant with those of air vapour pressure deficit and wind velocity outside the screenhouses. Over the two months, the mean relative reduction of ET_{adv} inside the screenhouses with respect to outside ET_{adv} was 75.1%, 74.0% and 55.8 % in IP-78, IP-56 and GS-62, respectively.

$ET_{rad,in}$ and $ET_{adv,in}$ were expressed as a function of the corresponding outside values ($ET_{rad,out}$ and $ET_{adv,out}$) through two reduction ratios ($\zeta_{rad} = ET_{rad,in}/ ET_{rad,out}$ and $\zeta_{adv} = ET_{adv,in}/ET_{adv,out}$). ζ_{rad} and ζ_{adv} could be expressed as linear functions of screenhouse transmission coefficient (τ) and the inside-to-outside wind speed ratio (ω), respectively.

It was found that the change in solar transmittance was not traduced by a proportional change in net radiation transmittance and in $ET_{rad,in}$. The radiative reduction factor ζ_{rad} was not directly proportional to solar transmittance. Actually, the correlation obtained between the daily values of ζ_{rad} and τ indicated a significant offset and a slope close to 2. This means that, for the range of solar transmittance ($0.6 < \tau < 0.8$) of the present study, the sensitivity of ζ_{rad} to τ is high, stressing the need to get accurate knowledge of this screenhouse parameter.

The advective term of ET_o depends on air temperature (T_a), vapour pressure deficit (D_a) and wind velocity (u). As T_a and D_a under the screenhouses were very similar to the outside values, it was logical to observe similar time patterns of ET_{adv} outside and under the three screenhouses, and to obtain a close relationship between $ET_{adv,in}$ and $ET_{adv,out}$. Such relationships made relatively straightforward the prediction of ζ_{adv} and $ET_{adv,in}$ only from the knowledge of ω.

Based on this finding, an additive model of the form $ET_{o,in} = \zeta_{rad}\ ET_{rad,out} + \zeta_{adv}\ ET_{adv,out}$ was proposed. The predictive performance of the model was fair (RMSE = 0.15 mm day^{-1}).

The proposed model, based only on outside climate data and the knowledge of two screenhouse-related parameters, provides a straightforward way to estimate screenhouse ET_o, a necessary step towards the determination of screenhouse-crops water requirements.

It was also found that the screenhouses enhanced the predominant role of the radiative component observed in open field conditions. The radiative component largely outweighed the advective component in all screenhouses, where ET_{rad} contributed to 96, 94 and 90% of ET_o in IP-78, IP-56 and GS-62, respectively, against 85% outside. This result underlines that great care should be taken in assessing the radiative component of ET_o, for which small errors in the main driving variable – i.e. solar transmittance – could lead to significant errors in $ET_{o,in}$. A robust estimate of τ is therefore required, that should be based on in situ measurements of the transmittance, and not on laboratory data. As corollary, the small weight of the advective component indicates that large uncertainties in the determination of the wind ratio would not be critical to the overall model performance.

4. Summary of contribution to knowledge and conclusions

This section summarises the main findings of the work, highlighting its contribution to knowledge in the field of protected cultivation.

4.1. Moderate shading is beneficial to greenhouse crops during the warm season

Shading of horticultural crops in protected structures is a common, simple and widely used method for maintaining favourable conditions for crop growth and production and alleviating the negative heat stress effects caused by excessively high solar radiation, air temperature and vapour pressure deficit levels during summer. The effects of greenhouse shading on greenhouse microclimate and energy balance, and on tomato crop production were investigated (Publication 1). The results presented clearly demonstrated the beneficial effect of shading on both the microclimate and crop behaviour mainly under Mediterranean summer conditions. The strong stress conditions experienced by the crop under no shading were reduced under shading as demonstrated by the enhanced crop stomatal conductance.

From the growers' point of view, one of the main problems when using shading for alleviating the greenhouse heat load is the right decision on the intensity of shading and the correct timing of shading application. The analysis of greenhouse microclimate and crop production data showed that under Mediterranean conditions, shading is beneficial whenever the light reduction is not higher than 35% to 40%, since higher shading may lead to production loss due to low radiation levels. On the other hand, analysis of the greenhouse energy balance showed that shading up to 50% and natural ventilation are not always sufficient measures to maintain optimum greenhouse microclimate for cucumber growth when the plant density is up to 2.4 plants·m^{-2} and leaf area index is low.

From the engineering point of view, it could be noted that solar radiation decrease due to shading by shade nets does not always involve a notable air temperature and vapour pressure deficit decrease, especially when the ventilation rates are low. Accordingly, it is necessary either to expand the crop leaf area by increasing plant density, thereby increasing evaporative cooling by crop transpiration or to introduce an evaporative cooling system to further reduce the energy load caused by excess solar radiation, with the first option being costless.

4.2. Screenhouses improve light use efficiency

The results presented in Publication 2 demonstrated that, within the relatively large range of shade provided by the tested screenhouses (*ca*. from 20 to 40 %), the magnitude and temporal trend of net CO_2 assimilation were only slightly affected with respect to natural light conditions, therefore leading to a substantial increase in leaf light-use efficiency. More substantial changes, but still moderate, were observed for leaf transpiration rate, stomatal conductance and intercellular-to-ambient CO_2 concentration ratio, resulting in a lower leaf intrinsic water use efficiency of screenhouse plants. In other words, the cost for screenhouse plants of maintaining similar assimilation levels (A_n) to open-field plants was a decrease in water use efficiency WUE. Leaf ageing and shading both acted in the same direction, lowering the values of intrinsic water use efficiency (WUE_i). WUE_i of sweet pepper leaves progressively decreased throughout the crop cycle.

The positive behaviour of shading on leaf stomata conductance (g_s), as a result of lower radiation load and leaf-to air vapour pressure deficit, was not overcompensated for reductions in light on A_n, as it can be derived from the higher values of the ratio of intercellular-to ambient CO_2 concentration gradient (C_i/C_a) observed under screenhouse. The increase in C_i/C_a under shade suggests that internal mesophyll limitations dominate the moderate reductions observed in A_n at the end of the growth cycle over stomatal limitations.

Additionally, the analysis of the shade acclimation coefficient (σ) provided more insight into the short-term response of leaf photosynthetic attributes to a reduction in the amount of incident light. Some short-term changes observed in σ before or during the flush in fruit set suggested that sweet pepper plants adjust the photosynthetic attributes to reach a balance between sources and sinks of assimilates. Parallel to short-term adjustments, ontogenic processes (e.g. leaf ageing) were found to be predominant in driving the seasonal decrease in leaf photosynthetic performances, independently of the light regime. In overall, sweet pepper plants grown under screenhouse displayed a light-acclimation similar to that observed for the field grown crop. This behaviour was observed across a large interval of shade intensity, irrespective of the colour and porosity of the screens.

4.3. Screenhouses increase yield with respect to outside crops

In Publication 3, the effect of screens with different shading intensity and permeability characteristics on screenhouse microclimate and crop production was evaluated. The presence of the screens, although reducing the air exchange rate, did not affect the screenhouse air temperature and vapour pressure deficit, which were found similar under screenhouse and open field conditions. The three different screens we tested provided a reduction of solar radiation above the crop varying between 20%-40%, depending on the optical properties of the screen. Interestingly, it was shown that aboveground dry biomass and total yield at final harvest of screenhouse crops were linearly and positively correlated with the transmission in PAR (τ_{PAR}), while plant height was negatively correlated with the ratio R:FR. The results suggested that (i) the more diffuse radiation regime prevailing under screenhouse is likely to be at the root of the higher crop performances observed under the screenhouses and (ii) τ_{PAR} and R:FR are likely to act synergistically in light capture.

We therefore concluded that both changes in transmittance and light quality must be accounted for when analysing productivity and yield regulation of screenhouse-grown crops. From a practical point of view, a shading factor not higher than 20% is recommended for sweet pepper cropping under Mediterranean conditions similar to those of this study. It has to be stressed that the results presented herein require confirmation for other netting-materials and crop species, through complementary experimental and/or modeling studies The critical issues (changes in light quality parameters, especially the ratio diffuse-to-global and the ratio R:FR) and (alleviation of radiation-induced stress (photoinhibition due to excess light, including the UV-band)) above mentioned offer room to novel research lines that would be especially useful for developing innovative photoselective net materials and improving screenhouse design and crop management.

4.4. A model to predict screenhouse-crops water requirements

In Publication 4, we propose an original method to estimating the reference evapotranspiration of screenhouse-grown crops ($ET_{o,\ in}$). The proposed model, based only on outside climate data and the knowledge of two screenhouse-related parameters (transmittance to solar radiation and wind ratio) provides a straightforward way to estimate screenhouse ET_o, a necessary step towards the determination of screenhouse-crops water requirements. The two main inputs of the model, $ET_{rad,out}$ and $ET_{adv,out}$ can be provided by agricultural extension services without more computation requirements than those corresponding to the calculation of daily $ET_{o,out}$. The daily values of the radiative and advective components could therefore be supplied as specific information devoted to screenhouse-crops irrigation scheduling. Individual farmers could easily calculate $ET_{o,in}$ from the proposed model, provided they have a reliable estimation of the transmittance and wind ratio of their screenhouse. This model could be considered as a basic contribution to improving irrigation management in sreenhouses.

4.5. Overall conclusion

To conclude, we underline that selecting the most suitable protective structure for plant growth in Mediterranean regions should be based on multiple criteria, reflecting the prevailing climatic, economic and social constraints prevailing in the region. The main requirements to be fulfilled by the structure are (i) to supply the required level of photosynthetically active radiation (PAR) for plant growth and (ii) to maintain suitable temperature and vapour pressure deficit level to avoid abiotic stress. As economic criteria are generally the most constraining to farmers, the two basic requirements should be fulfilled at optimal cost, that is, at a cost that allows farmers to maximize net income. Our study provided scientifically and technically-based arguments to support the conclusion that a well-designed screenhouse, having the appropriate optical properties and porosity, is one of the most environmentally and economically-sustainable structures for increasing the productivity of horticultural crops in Mediterranean regions.