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Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels?

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ABSTRACT

Agrivoltaic systems are mixed systems that associate, on the same land area at the same time, food crops and solar photovoltaic panels (PVPs). The aim of the present study is to assess whether the growth rate of crops is affected in the specific shade of PVPs. Changes in air, ground and crop temperature can be suspected due to the reduction of incident radiation below the photovoltaic shelter. Soil temperature (5 cm and 25 cm depth), air temperature and humidity, wind speed as well as incident radiations were recorded at hourly time steps in the full sun treatment and in two agrivoltaic systems with different densities of PVPs during three weather seasons (winter, spring and summer). In addition, crop temperatures were monitored on short cycle crops (lettuce and cucumber) and a long cycle crop (durum wheat). The number of leaves was also assessed periodically on the vegetable crops.

Mean daily air temperature and humidity were similar in the full sun treatments and in the shaded situations, whatever the climatic season. On the contrary, mean daily soil temperature significantly decreased below the PVPs compared to the full sun treatment. The hourly pattern of crop temperature during daytime (24 h) was affected in the shade. In this experiment, the ratio between crop temperature and incident radiation was higher below the PVPs in the morning. This could be due to a reduction of sensible heat losses by the plants (absence of dew deposit in the early morning or reduced transpiration) in the shade compared to the full sun treatment. However, mean daily crop temperature was found not to change significantly in the shade and the growth rate was similar in all the treatments. Significant differences in the leaf emission rate were measured only during the juvenile phase (three weeks after planting) in lettuces and cucumbers and could result from changes in soil temperature. As a conclusion, this study suggests that little adaptations in cropping practices should be required to switch from an open cropping to an agrivoltaic cropping system and attention should mostly be focused on mitigating light reduction and on selection of plants with a maximal radiation use efficiency in these conditions of fluctuating shade.

1. Introduction

Agrivoltaic systems (AVS) were defined by Dupraz et al. (2010) as "mixed systems associating solar panels and crop at the same time on the same land area". They may contribute to conciliate food security and green energy supply. In these mixed production systems, photovoltaic panels (PVPs) partially shelter the crop growing below. PVPs create intermittent shading and reduce the average available light for the crop. Marrou et al. (2013) showed that light reduction had a significant impact on final crop yield of spring and summer lettuces in AVS. Biomass accumulation was mainly driven by the capture of light resource while other resources such as water and nitrogen were not limiting. By using a light driven prediction of plant biomass accumulation (Monteith, 1977), it was showed that high crop productivities can be expected from these dual purpose systems (food and electricity) (Marrou et al., 2013). Marrou et al. (2013) found that light reduction was not necessarily detrimental for crop production. Indeed, an experiment conducted on spring and summer lettuces in AVS showed that lettuce yield was maintained, despite shading, by an improved radiation interception efficiency (RIE) in the shade. Enhanced RIE was explained by an increase in total leaf area per plant despite a decrease in the number of leaves.

The aim of the present study is to determine if other climatic variables are significantly modified in the shade of solar panels and

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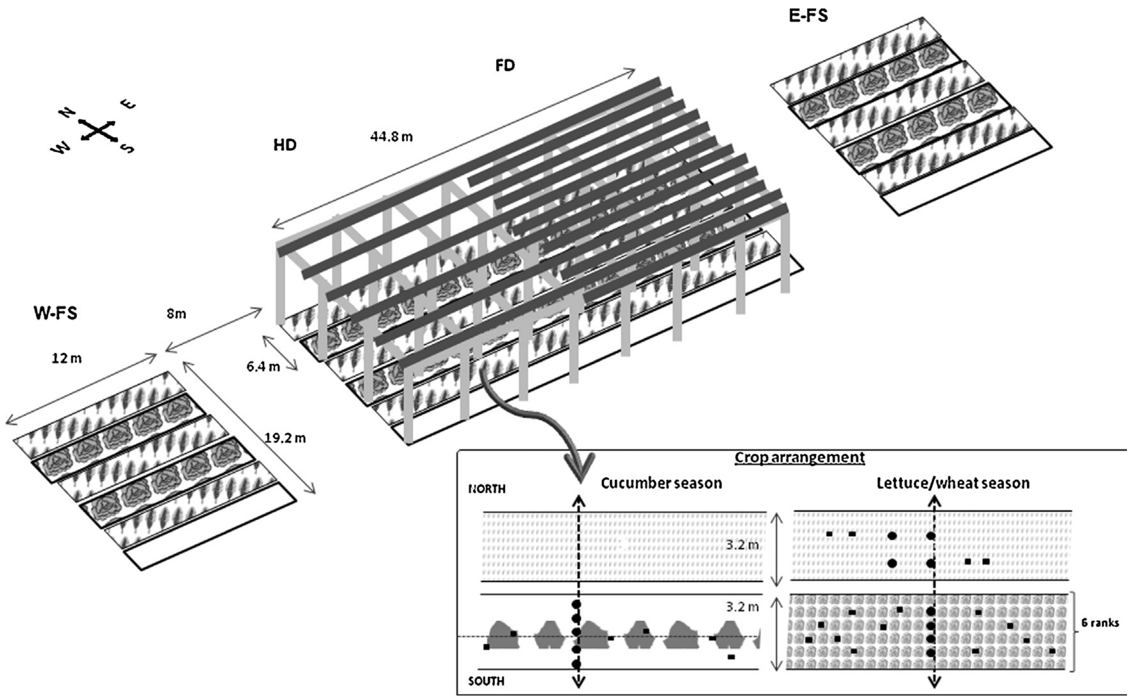

Fig. 1. General map of the experimental device during the wheat/lettuce season. In the bottom right frame, a zoom on the two central crop strips during wheat/lettuce season and cucumber season is represented. Closed circles represent radiation sensors, located on North-to-South transects; closed square symbols represent thermocouples or microthermistances. FD represents the shaded plot with PVPs at full density whereas HD represents the shaded plot with PVPs at half density. W-C and E-C stand respectively for Western control plot and Eastern control plot.

to what extent this could affect crop temperature and plant development rates in AVS. Former work on shaded glasshouses (Baille et al., 2001; Kittas et al., 2003) or agroforestry systems (Lott et al., 2009; Monteith et al., 1991) suggested that air temperature and vapor pressure deficit at crop level are reduced by shading. Effects of shading on crop temperature and growth rate were also reported. Lott et al. (2009) showed that, under 50% of available radiation, the meristem temperature of shaded maize plants was reduced by 2–9 °C (depending on the climatic seasons). At the same time, they noticed a significant delay in flowering date. Moreover, in the case of AVS, the shade pattern under PVPs varies from one season to another and among different latitudes as the limits between shade and light move with sun elevation. For this reason, the effect of the PVP shelter may have a different impact on the productivity of winter crops compared to summer crops, or on short cycle crops compared to long cycle crops. We therefore analyze in this study the impact of PVPs on the microclimate at crop level (air temperature, air vapour pressure deficit (VPD) and wind) as well as crop and soil temperature. The experiment was conducted on three crop species and cropping seasons: durum wheat (winter to summer), lettuces (spring and summer), and cucumbers (summer).

2. Materials and methods

2.1. Experimental device

Data were collected on an experimental prototype of agrivoltaic systems, in Montpellier, France (43.15° N; 3.87° E) from July 2010 to September 2011 (Marrou, 2012; Marrou et al., 2013). In this experimental prototype, photovoltaic panels (PVPs) were arranged in East–West orientated strips, 0.8 wide and inclined southward with a tilt angle of 25°. PVPs were hold at 4 m above-ground by wooden pillars spaced on a 6.4 m × 6.4 m grid, in order to allow mechanical cropping of the plants below, using tractors (Fig. 1).

The experimental design enabled to compare three shading intensities, corresponding to two densities of solar panels and a full sun control (FS): (1) the full density treatment (FD), which corresponds to the PVPs density optimized for electricity production. In this treatment the distance between 2 strips of PVPs is 1.6 m, which lets an average of 50% of the incident radiation to the crop, (2) the half density treatment, which is obtained from FD by removing one strip of PVPs out of two (distance between 2 PVPs strips: 3.2 m) and thus letting through an average of 70% of incident radiation available to the crop, and (3) the full sun control plot (100% of incident radiation available) (Marrou, 2012). Shading treatments were applied on four land plots. They were aligned from East to West as following: eastern full sun control plot (E-FS), FD plot, HD plot, and western full sun control plot (W-FS). Each plot is 12 m wide in the East–West direction and separated from each other by a buffer zone of 8 m (between control plots and shaded plots) or 6 m (between FD an HD plots). In the North South direction, each control plot is 19 m long. In FD and HD plots, plant and meteorological measurements were taken only in the first 15 m in the Northern part of the plots to avoid a border effect due to the higher incident light in the southern side of the prototype. The total area covered by PVPs (including FD and HD plots as well as the surrounding buffer zones) is 860 m^2 (19.2 m × 44.8 m) and corresponds to the minimum standard size of an agrivoltaic system adapted for vegetable production. Due to the large size of any agrivoltaic system required to avoid unwanted border effects and the cost of work and material to build an experimental agrivoltaic system, it was not possible to replicate FD and HD plots and design a complete randomized experimental device. However, as E-FS and W-FS were the two most distant plots in the experimental field, they controlled the environmental variability in the East–West direction. Moreover, environmental variability in the North–South was assessed during the first experimental season (2010) and controlled by subdividing both control and shaded plots into three blocks in the North–South. Variance analysis showed that there was no significant difference in lettuces' dry matter, neither between blocks within the same full sun plot, nor between the W-FS and the E-FS. Identical soil type (loamy clayish deep alluvial soil) and field history (10 years of homogenous non tillage cropping) also contributed to homogenous soil conditions between treatment plots. Moreover, the homogeneity of soil properties was checked across the treatment plots using soil hygrometry measurements on samples evenly collected over the area of the experimental field (Marrou, 2012).

2.2. Crop management

Three different species were tested on the prototype for various cropping seasons spanning from July 2010 to September 2011: lettuces – *Lactuca sativa* spp. (two cropping cycles, five subspecies), durum wheat (*Triticum durum* L.), and cucumbers (*Cucumis sativus* L.). Thus, a wide range of growing conditions in terms of temperature, VPD, and sun elevation was covered.

Lettuces were planted during one summer and one spring season. Firstly, lettuces were grown from July 21, 2010 (day of the year, DOY 202) to September 6, 2010 (DOY 249). Two varieties were then planted at the same time: one variety of crisphead lettuce, called "Kiribati" (noted FC+), and one butterhead lettuce, called "Tourbillon" (noted B0). Secondly, lettuces were planted on March 22, 2011 (DOY 81) and harvested on May 24, 2011 (DOY 144). For this second cropping season, two varieties of crisphead lettuces (FC+, and a second one called "Bassoon" and noted FC−) and two new varieties of butterhead lettuces (variety "Model" noted B+ and variety "Emocion" noted B−) were tested simultaneously. Cucumbers (variety "Marketmore") were planted on June 25, 2011 (DOY 178) and fruits were picked from August 8, 2011 (DOY 220) to August 31, 2011 (DOY 239), twice a week. Durum wheat (variety "Claudio") was sown at a density of 150 kg/ha on November 26 (DOY 331), 2010, and harvested at maturity on June 17, 2011 (DOY 168) (Fig. 2).

Lettuces and cucumbers were planted in lines. Planting rows were parallel to PVP strips. The distance between two planting rows was 0.33 m for lettuces and 3 m for cucumbers. To allow simultaneous cultivation of wheat and vegetable crops in 2011, the entire experimental field was divided into 3.2 m wide block strips in the North–South direction. Blocks were dedicated alternatively to the cultivation of cereals or vegetables. In spring 2011, three blocks of wheat were intercalated with two strips of 6 rows of lettuces. Each block of lettuces was replaced by one row of cucumber in June 2011.

Vegetables were irrigated with sprinklers (summer 2010) or drip lines (spring and summer 2010), in the day-time. Irrigation was monitored with tensiometers (SDEC, Reignac sur Indre, France). In order to avoid plant water stress, soil water potential at 0.3 m depth was kept above −0.02 MPa (Gay, 2002).

2.3. Plant development rate

Development rate of vegetable crops was assessed by counting the number of leaves, over 1 cm long, that were emitted every 3 weeks for lettuces and twice a week for cucumbers. For lettuces, the number of leaves per plant was assessed through destructive sampling at three dates (DOY 223, 236, and 249 in summer 2010, and DOY 104, 125, and 144 in spring 2011. 12–15 plants per treatment and per variety were collected at each sampling date. Samples were stratified to warrant that each sample contained the same number of plants collected from each planting rank, and to explore the intra-treatment variability. Leaf emission rates (τ) were calculated by fitting linear models between the number of leaves measured on each sampled lettuce plant and the thermal time (calculated from air temperature at 2 m above-ground with a base temperature of 3 °C, Thicoïpé, 1997) for each period between two sampling dates. Analysis of covariance (ANCOVA), using shading treatment as a factor, was performed to determine whether a single linear model could be fit for all the treatments. If not, development rate were considered as significantly different between treatments, for the corresponding time period.

Concerning cucumbers, the number of leaves on the main stem and on each secondary branch was counted in the field twice a week on 16 plants. These plants had been randomly chosen at planting date (3 plants both in E–C and in W–C and 5 plants in FD and in HD). After plotting the dynamic of the total number of leaves per plant over the entire cropping period, three time periods with nearly constant τ were identified, and a mean τ was calculated in the three treatments for each period. To do so, we applied the same methodology as for lettuces: linear models were fitted to predict the number of leaves as a function of thermal time (calculated from air temperature at 2 m above-ground with a base temperature of 15 °C, Perry et al., 1986) for each time period. Shading effect on τ was tested with ANCOVAs.

For wheat, phenological stages such as tillering, flowering, and maturity were determined according to the Zadoks scale (Zadoks et al., 1974) in each plot. A given phenological stage was reported as attained when 50% of the plant population had reached this stage (visual assessment).

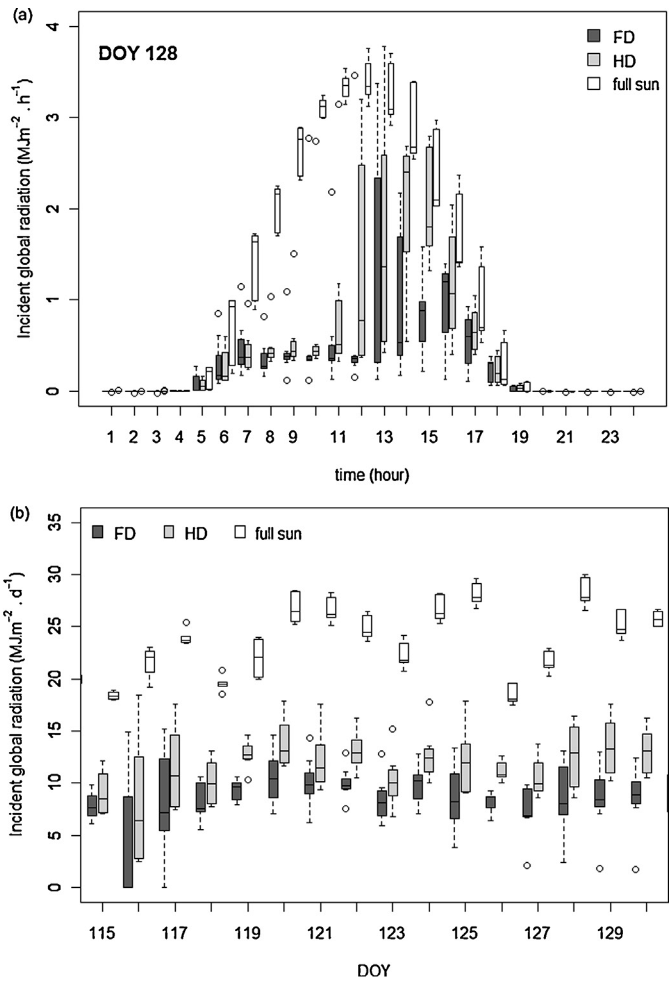

Fig. 2. Hourly (a, for DOY 128) and daily (b, from DOY 115 to DOY 230) incident radiation in the FS treatment (white background boxes), in HD (gray background boxes) and FD (dark gray background boxes). The boxes feature the spatial variability of the incident radiation (radiation was recorded at the same time by sensors settled at different locations on the North–South axis).

2.4. Microclimate monitoring

2.4.1. Air temperature, air humidity and wind speed at standard height

Air temperature (±0.2 °C) and air relative humidity (±2%) at 2 m above-ground were measured respectively with a capacitive thermohygrometer (HMP 45, Vaisala, Helsinki, Finland) placed in radiation screens with natural ventilation (MET20, Campbell Scientific, Inc., USA) and connected to dataloggers (CR1000 Campbell Scientific, Inc., USA). Three probes were set in the middle of each treatment plot from DOY 222 to 249 in 2010 (for second half of the summer season for lettuces) and from DOY 36 to 239 in 2011 (for the complete cycle of summer lettuces and cucumber, and from "3 leaves" stage to maturity for the wheat cycle). Wind speed (u, m s^{-1}) was measured at 2 m above-ground with a mechanical wind monitor (05103-5, Young, Traverse City, MI, USA), in the E-FS plot and in the FD treatment from DOY 36 to 239 in 2011. All these data were collected every 5 s on a datalogger (CR1000, Campbell Scientific Inc., Logan, UT, USA) and averaged over 1 h.

Analyses of variance (ANOVA) and least significant difference (LSD) tests were performed successively on T_A and VPD, using the shading level as treatment to determine the effect of the shading treatments on mean daily air temperature and VPD. These statistical analyses were done over the whole the measurement period at a daily (to compare mean daily values) or hourly (to compare daily microclimatic patterns) time-step.

2.4.2. Soil temperature

Soil temperature (±0.4 °C) was measured below the wheat crop in 2011 (from DOY 36 to 165) at 0.05 m (T_{S5}) and 0.25 m (T_{S25}) below the ground surface with thermistors (107 thermistors, Campbell Scientific, Inc., USA) at 2 positions along a North South transect between two strips of solar panels. Soil temperature at 0.25 m depth was also measured in irrigated soil during the crop cycle of summer lettuce (from DOY 220) until after the harvest of the lettuces (DOY 279). 6 probes were dug both in the FD and in the HD plots, at different positions on North South transects, and 3 probes were dug in the control plots. All probes were connected to dataloggers (CR1000, Campbell Scientific, Inc., USA), and data were recorded with a time step of 5 s, and then averaged over 1 h for storage in the datalogger memory. Soil temperature was not collected during the spring lettuce cycle, because it would have required a higher number of probes as the crop was irrigated with drip lines.

2.4.3. Crop temperature

Crop temperatures (T_L) were measured on spring lettuces from DOY 117 to 149 in 2011, with copper-constantan thermocouples, inserted between the lettuces leaves, close to the central axis of the plant. Leaf temperatures were measured on cucumber (DOY 178–244) and durum wheat (DOY 36–168) with microthermistors taped on the bottom side of the leaves (Thorpe and Butler, 1977). Thermistors were moved from one leaf to another during the crop cycle so that they would measure the temperature of a non-senescent leaf. We chose leaves that were located in the middle of the main stem for cucumber, or at mid-height of the plant cover for wheat. Measurements from thermocouples and microthermistors were recorded on dataloggers (CR10X and CR1000, Campbell Scientific, Inc., USA) with the same time steps as mentioned above. The precision of the data was estimated at ±0.4 °C in the worst case.

2.4.4. Incident radiation

2.4.4.1. Incident global radiation received on an horizontal surface at crop height. Incident solar radiation (R_s, W m^{-2}) was measured during the wheat and cucumber cycles with pyranometers (SKS 1110, Skye Instruments, Powys, UK) set horizontally at the height of the crop. For lettuces, photosynthetically active radiation (R_p, W m^{-2}) was measured with PAR sensors (spring and summer). R_s and R_p measurements were treated equally after conversion, as R_p/R_s is constant, equal to 0.48 in outdoors conditions, provided all measurements are taken above plant foliage.

In the FD and the HD treatments, several sensors were set along North–South transects, perpendicularly to the PVP strips. We thus captured the hourly and daily intra-treatment variations below the panels. One sensor acquired data above each row of lettuce, while 5 sensors were regularly placed (spacing of 40 cm) on a diagonal transect centered on the cucumber rows. As for the wheat experiments, two pairs of sensors were set on a transect perpendicular to the crop strip: one was just below a PVP strip and the other was in-between two PVP strips. All sensors were connected to dataloggers (CR1000 Campbell Scientific, Inc., USA), and data were recorded with a time step of 5 s, and then averaged over 1 h.

2.4.4.2. Spatial distribution of the incident beam rays. The spatial distribution of the incident radiation was assessed through modeling and field measurements in the FS treatment as well as in the two shaded treatments (FD and HD) in order to test whether there were significant scattering effects below the PVPs and to characterize the proportion of diffuse and direct radiation in the different treatments.

2.4.4.2.1. Field measurements. Complementary measurements were conducted in spring 2012, from DOY 124 to 134 to quantify incoming radiation from different directions, using a turtle PAR sensor. This device has been described by Chenu et al. (2008). It is made of six faces with equal solid angles, so that the entire sky hemisphere is covered without overlapping. Each face of the turtle sensor is a pentagonal PAR sensor. Face 1 was horizontal, while faces 2–6 were inclined with a tilt angle of 63.4°, and directed to 5 different azimuth directions. Face 4 was oriented northwards. The directional measurement of incident radiation was repeated for different locations within the FD and HD plots: the sensor was set for 2 days of acquisition at each location where the PAR sensors had been placed in 2011 above each lettuce planting row. The sensors were connected to a datalogger (CR10X Campbell Scientific, Inc., USA), and data were recorded with a time step of 5 s, then averaged over 10 min.

2.4.4.2.2. Simulation of the light captured by an inclined surface. The spatial distribution of incoming radiation measured below the PVPs needed to be compared that in the full sun conditions (FS). To do so, the solar energy that would have been captured by each face of the turtle PAR sensor in full sun conditions (FS) for the same days of the year was simulated. The spatial distribution of solar energy, in the absence of sheltering, abides to astrological laws and can be predicted with precision according to existing models (Liu and Jordan, 1960; Spitters et al., 1986; Allen et al., 1998; Bindi et al., 1992; Anderson, 1966). A model was coded, and implemented with the R-cran software (http://cran.r-project.org/), to simulate the energy captured by each face of the turtle sensor in FS, with a time step of 10 min, for a given day of the year (DOY). Model algorithm uses astrology equations currently in use in existing astrological models (Marrou et al., 2013), with a few adaptations. Firstly, extraterrestrial radiation was calculated with the De Jong formula (Bindi et al., 1992), which is more suitable at infra-daily time steps. Secondly, the calculation step integrating the incident radiation over one day was removed. Inputs of the model were latitude of the site, orientation of the sensor and incident global radiation measured on a horizontal surface at the model time step. Radiation data were collected at an hourly time step from a weather station located 400 m from the experimental field (INRA, Lavalette weather station). Linear interpolation was performed between hourly data in order to get a dataset with a time step of 10 min that can be used as an input for the radiation model. Model quality was verified by comparing

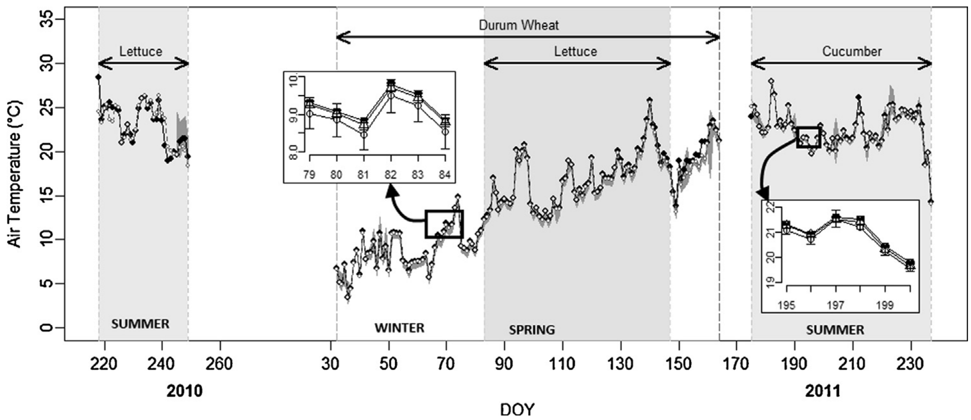

Fig. 3. Mean daily temperature (T_A) measured at 2 m above-ground during every cropping cycles from July 2010 to August 2011. Zooms on 6-day periods (6 days in winter and 6 days in summer) are provided. FS is represented with shaded intervals on the main graph (95% confidence interval for T_A measured in FS with three different probes) and with open circles (○) in the zoom areas, while FD and HD are represented respectively with open triangles (Δ) and closed squares (■). In the zoom areas, vertical error bars feature standard errors for all the treatments.

simulation with measurements taken in FS from DOY 196 to 199 in 2012. A linear model was fitted for each sensor face with a correction coefficient higher than 0.94, and the slope coefficient was always between 0.88 and 1. It was concluded that the model was a good predictor and that simulated data in FS needed no correction coefficient to match measured values. More details on the model specifications and validation are given in Appendix A.

2.4.4.3. Long wave radiations. In spring 2012 (DOY 174–202) upwards ($R_{\ell\downarrow}$) and downwards ($R_{\ell\downarrow}$) longwave radiation, and upward ($R_{s\uparrow}$) and downward ($R_{s\downarrow}$) short wave radiation were measured for each treatments. The four types of radiations were measured successively in the FD, HD, and FS treatments with two net radiometers (Q-7.1, Campbell Sci, USA) and 2 pyranometers (SKS 11110, Skye Instruments, Powys, UK). All the sensors were set on an East–West orientated line, below a PVP strip, for FD and HD. The ground was then covered with spring barley sown on DOY 89, with an almost closed canopy.

2.5. Theoretical background: crop energy balance and consequences on crop temperatures

The temperature of any plant organ results from the balance between incoming energy and energy loss. The energy balance of a plant organ (or a canopy) can be written as:

$$R_n - H - \lambda E - G = 0 \qquad (1)$$

where R_n is the net radiation, H and λE are the sensible and latent heat fluxes between the considered vegetation and the surrounding air, and G is the rate of heat storage in the vegetation and soil.

During daylight, the main energy input is radiation, both solar and longwave radiation (Eq. (2)). If crop or leaf temperature is different from air temperature at the same height ($T_A(z)$), energy may be absorbed or released as sensible heat by convection (Eq. (3)). Part of this energy can also be released by evaporation through stomata (Eq. (4a)). Moreover, energy may be transferred to and from storage in plant canopies and in the soil by conduction (Eq. (5)). During the night, the sign of must fluxes change to the opposite. The radiation balance is negative then, and water vapor may condense on plants (Eq. (4b)).

$$R_n = (1-\alpha)\cdot R_s + \varepsilon \cdot R_\ell - \varepsilon \cdot \sigma \cdot T_L^4 \qquad (2)$$

$$H = \frac{\rho \cdot C_p}{r_a}(T_L - T_A(z)) \qquad (3)$$

$$\begin{cases} \lambda \cdot E = \dfrac{\rho \cdot C_p}{\gamma \cdot (r_a + r_s)}(e^*(T_L) - e_a(z)) & \text{for transpiration} \quad \text{(a)} \\ \lambda \cdot E = \dfrac{\rho \cdot C_p}{\gamma \cdot r_a}(e^*(T_L) - e_a(z)) & \text{for dew deposition or evaporation} \quad \text{(b)} \end{cases} \qquad (4)$$

$$G = \frac{\rho \cdot C_p}{r_0}(T_0 - T_{z_0}) \qquad (5)$$

where R_ℓ is the downwards incoming longwave radiation, e_a is the vapor pressure of the air surrounding the plant organ, $e^*(T_L)$ is the saturated vapor pressure at leaf temperature, r_a is the aerodynamic resistance to water vapor and sensible heat mainly function of wind speed, r_s the stomatal resistance, ρ is the air density, C_p is the specific heat of air at constant temperature, γ is the psychrometric constant, T_0 is the soil surface temperature, and T_{z0} is the soil temperature at depth z_0.

The organ or plant temperature balances the energy budget equation (Eq. (1)). For certain sets of environmental conditions (air temperature, solar radiation, vapor pressure and wind speed), only one surface temperature that balances the energy budget equation exists.

Net radiation is influenced by the PVPs through (1) the reduction of the solar incident radiation during day-time only (R_s), (2) the modification of downwards long wave radiation (R_ℓ) coming from the sky and from the PVPs in the case of agrivoltaic systems. Latent heat flux H could change under PVPs if air temperature or wind speed were modified by the PVPs (leading to variations in the aerodynamic resistance of the crop). Heat storage is negligible for leaves or small canopies. For the wheat crop, there is no heat conduction between leaves and ground as the crop stands at a sufficient height (more than 50 cm) above-ground in the second part of the crop cycle. In the case of short or creeping plants (lettuce and cucumber), conduction occurs and the intensity of this flux depends on the vertical gradient of soil temperature. Any change in soil temperature could result in a modified G flux under PVPs. Finally, energy can be released as latent heat (λE) through crop transpiration or dew evaporation in the morning, which are monitored by aerodynamic and stomatal (for transpiration only) resistances. PVPs could modify the latent heat exchanges between the plant and the surrounding air by a change in leaf stomatal resistance or air vapor pressure.

2.6. Statistical analysis

All statistical analyses were performed with the R software. Analyses of variance (ANOVA) and covariance (ANCOVA) were realized with the 'lm' procedure and boxed linear models were

Table 1
Sum of T_A calculated for the totality or a part of each cropping season. Differences in crop cycle length between the shaded situations and FS are expressed in thermal time (°C d) and in equivalent number of leaves, according to the literature. Sums of temperature are calculated with a base temperature of 3 °C for lettuces, 0 °C for wheat, and 15 °C for cucumbers.

From planting to harvest		FS	FD	HD
Spring lettuces (2011)				
Crop cycle length (°C d)	Sum of T_A (°C d)	797	819	812
	Difference (°C d)	0	22.8	15.6
Equivalent NB of leaves	Min development rate 0.052 leaves (°C d^{-1})	0	1.18	0.81
	Max development rate leaves (°C d^{-1})	0	2.96	2.03
From mid-cycle to harvest		FS	FD	HD
Summer lettuces (2010)				
Crop cycle length (°C d)	Sum of T_A (°C d)	465	465	471
	Difference (°C d)	0	0.00	5.5
Equivalent NB of leaves	Min development rate 0.052 leaves (°C d^{-1})	0	0.00	0.29
	Max development rate 0.130 leaves (°C d^{-1})	0	0.00	0.72
From planting to harvest		FS	FD	HD
Cucumbers				
Crop cycle length (°C d)	Sum of T_A (°C d)	467	474	469
	Difference (°C d)	0	7.4	1.5
Equivalent NB of leaves	Min development rate 0.069 leaves (°C d^{-1})	0	0.51	0.10
	Max development rate 0.083 leaves (°C d^{-1})	0	0.61	0.12
From tillering to harvest		FS	FD	HD
Durum wheat				
Crop cycle length (°C d)	Sum of T_A	1820	1872	1845
	Difference (°C d)	0	52.98	24.54
Equivalent NB of leaves	Min development rate 0.0014 leaves (°C d^{-1})	0	0.07	0.03
	Max development rate 0.0147 leaves (°C d^{-1})	0	0.78	0.36

compared according to the maximum of likelihood ratio ('anova' procedure). Mean comparison between treatments was performed using Student tests (t-test procedure) and least significant differences test (LSD-test procedure). Sigmoid adjustments were fitted for the number of cucumber leaves using the nls procedure.

3. Results

3.1. Incident radiation

The average proportion of daily radiation transmitted below the PVPs (FD and HD treatments) compared to the FS treatment ranged around 32% in FD, and 48% in HD during the lettuce crop cycle (DOY 117–143), 52% in FD and 68% in HD during the wheat crop cycle (DOY 35–168) and 37% in FD and 62% in HD during the cucumber crop cycle (DOY 181–240) (Fig. 2). The average proportion of radiation transmitted daily below the PVPs varied from one day to another one with a coefficient of variation equal to 37% in FD and 46% in HD over the whole measurement period (DOY 35–240). The fraction of transmitted variation also varied within day-time (C_v = 57% in FD and 60% in HD, between 09:00 and 18:00, in average over all the days with means).

For a given day of the year, the proportion of transmitted radiation over 24 h varies depending on the position of the plants on the North–South axis. The coefficient of spatial variation of the transmitted radiation equals 29% in FD and 38% in HD, in average over the measurement period (DOY 35–244).

3.2. Aerial microclimate

A wide range of climatic conditions was explored over the four crop cycles: air temperature (T_A) varied from 3 to 28 °C and daily incident solar radiation varied from 1 to 31 MJ m^{-2} d^{-1} in FS. However, T_A in the shaded treatments (both FD and HD) remained nearly equal to that in the FS during all cropping cycles, from July 2010 to August 2011 (Fig. 3), according to ANOVAs. ANOVAs were repeated for every day, using shading treatments as an explicative factor of mean daily T_A. Only 12 days were found to have a risk p-value below 5% (i.e. with a significant effect of shading on air temperature). During days with low wind speed (u < 1.2 m s^{-1} and u_{max} < 6 m s^{-1}) or high global radiation (R_s > 24 MJ m^{-2} d^{-1}), air temperature below the solar panels tended to be higher than in FS.

Variations in daily T_A between shade treatments resulted in variations of the crop cycle length in thermal time that never exceeded 23 °C d for lettuces, 8 °C d for cucumber and 53 °C d for wheat. According to literature references, these differences were too small to allow the production of even one more leaf in the case of cucumber (Horie et al., 1979) and wheat (Porter and Gawith, 1999). For lettuces, in 2011 only, two to three extra leaves (on a total of 80 leaves in average, Marrou et al., 2013) could have been emitted in FD as mean air temperatures tended to increase in average over the second part of the cropping cycle. However, as the thermal time required for lettuce leaves to reach the length of 1 cm is over 200 °C d at 20 °C in FS (Bensink, 1971), this increase in the number of leaves may have little impact on lettuce size or dry weight. Results are summed up in Table 1. When carrying the same type of analysis at an hourly time step over the measurement period, differences in hourly records of air temperature were never found between the shaded (FD or HD) and unshaded treatments at the same time of the day.

Similarly, no significant effect of shading was found on air relative humidity or VPD, neither at a daily nor at an hourly time step. The maximal increase in VPD in shaded treatments compared to FS was 0.11 kPa, while the mean VPD over the measurement period is 0.91 kPa, in FS.

Besides, the horizontal wind speeds measured at an hourly time step in FS and in each of the shaded treatments (FD and HD) were found to be similar, regarding the precision of measurements

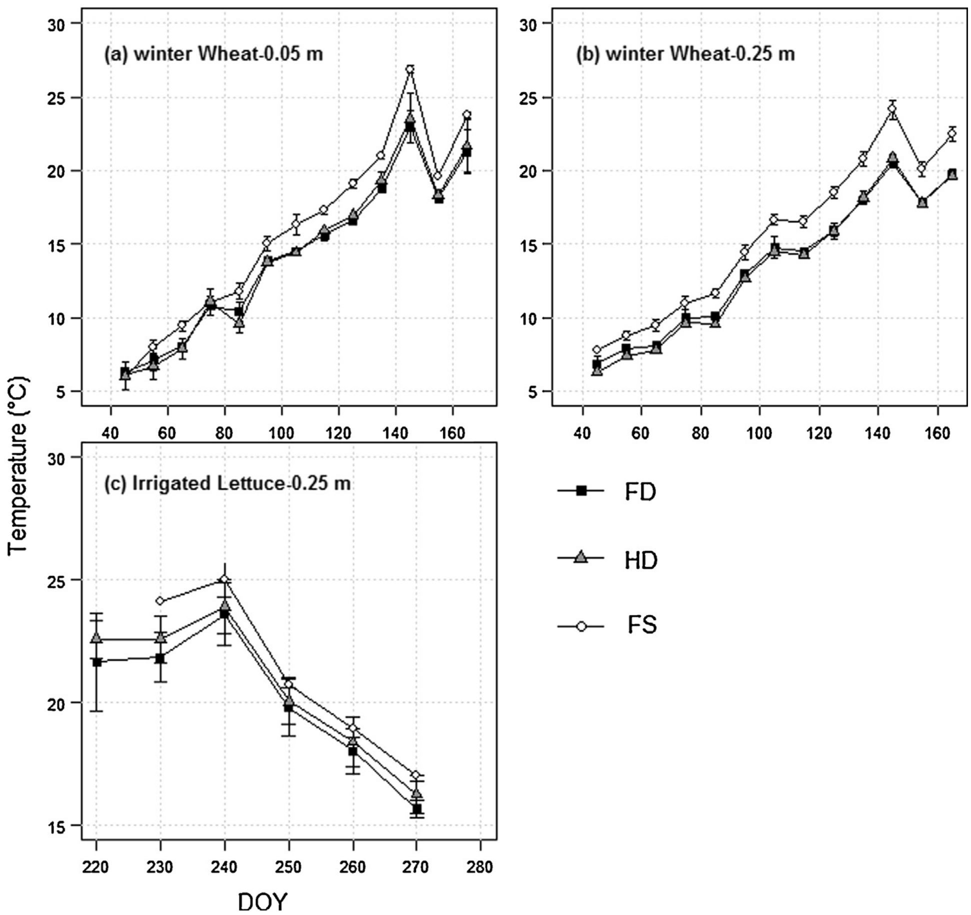

Fig. 4. Mean daily ground temperature measured in non-irrigated winter wheat at (a) 0.05 m and (b) 0.25 m depth; and in sprinkler irrigated summer lettuce at (c) 25 cm depth.

($\pm$0.3 m s^{-1}). However, the significance of differences between treatments could not be tested due to the lack of replications.

3.3. Soil temperature

During the wheat cycle, soil temperature at 0.05 m depth (T_{S5}) decreased by 1.9 °C in FD and 1.8 °C in HD compared to FS (Fig. 4). A covariance analysis using shade treatment as a factor and LSD comparison tests on mean values showed that these differences were significant (p-value < 5%). The temperature at 25 cm depth (T_{S25}) was also significantly reduced in the shade, both for non-irrigated wheat (−2.1 °C in FD and −2.3 °C in HD) and irrigated lettuces (−0.5 °C in HD and −0.6 °C in FD), according to ANCOVA and LSD tests. These daily differences resulted in a decrease of T_S

Table 2
Number of days when significant differences were detected in the hourly pattern of T_L for at least one hour or for at least 4 h. The mean variation in T_L in the shaded treatments (FD or HD) compared to FS was calculated over the times when T_L is significantly higher or lower than in FS, as well as the number of days during which these significant increases/decreases were observed.

Number of days when . . .	Wheat		Spring lettuces		Cucumbers	
	FD	HD	FD	HD	FD	HD
TL significantly different from FS for at least 1 h						
Number of days	119	116	26	26	40	60
% of the crop cycle	98%	95%	100%	100%	65%	97%
TL significantly different from FS for at least 4 h						
Number of days	117	114	25	25	26	43
% of the crop cycle	96%	93%	96%	96%	42%	69%
TL significantly decreased compared to FS						
Number of days	109	106	26	26	40	60
Mean decrease	3.04	2.9	5.66	5.03	4.96	5.71
Time in the day	09:00 → 18:00	08:00 → 23:00	11: 00 → 18:00	15:000 → 18:00	11:00 → 17:00	08:00 → 17:00
TL significantly increased compared to FS						
Number of days	117	115	26	18	0	0
Mean decrease	2.26	1.93	4.34	5.76	–	–
Time in the day	18:00 → 09:00	18:00 → 08:00	20:00 → 01:00	11:00 → 13:00	–	–
Length of the measurement period (in days)	122	122	26	26	62	62

by 214–278 °C d for wheat (with a basal temperature of 0 °C) over the measurement period (for HD and FD, 5 or 25 cm depth). In 2010, in the lettuce crop, the cumulated soil surface temperatures were reduced by 73 °C d in FD and 48 °C d in HD.

3.4. Crop temperature

3.4.1. Pattern of the crop temperature (T_L) at hourly time step

When looking at crop temperature (T_L) with an hourly time step, daily pattern appears to be affected by shading for all the tested crops. The results of the LSD tests performed with p-value < 5% for every hour and every day are summarized in Table 2. In the case of wheat, crop thermal pattern was significantly affected by shading every day, from tillage to flowering. Wheat T_L significantly increased during night (+2 °C, both in FD and in HD, in average, between 18:00 and 09:00). On the contrary day-time temperatures significantly decreased by 3 °C in FD and in HD (from 18:00 to 09:00). For vegetables, T_L was also significantly cooler in the shade than in FS during day-time along most of the crop cycle. In the case of spring lettuces, significant reduction of temperature below the PVPs occurred earlier in the day in FD (before noon) than in HD where significant reduction of T_L started later in the afternoon than in FD. On the contrary, T_L significantly increased in HD compared to FS, between 11:00 and 12:00. However, this event lasted for only 1–2 h and was detected as significant only for 13 days over the cropping season. For cucumbers, no significant decrease of T_L was detected during night in the shaded treatments (FD and HD). However the power of the ANOVA (i.e. the probability to find a difference when it does exist) was below 40% during night-time, for cucumbers.

As an example, patterns of T_L evolution at an hourly time step are presented (Fig. 5) for a sunny day (DOY 128 for wheat and spring lettuce, DOY 202 for cucumber), for the three crops.

3.4.2. Day/night-time steps

Significant differences were found between shaded and unshaded treatments (Fig. 6) when comparing mean night-time (19:00–05:00 Universal Time) and mean day-time (06:00–18:00 Universal Time) crop temperatures, which confirm the results of Section 3.4.1. Mean day-time temperature was significantly lower in the shade (FD and HD) for every crop, during at least 25% of the crop cycle duration (LSD test). Mean crop temperature averaged over night-time ($T_{L,N}$) increased significantly for wheat in the shade (FD and HD) and for lettuce in FD compared to FS during 80% of the cycle (LSD test). No significant difference in $T_{L,N}$ was found for cucumbers in the shade compared to FS, but no conclusion can be drawn because the statistical power of the ANOVA was of 27% in average at night for cucumbers (mean power equal to 27%).

3.4.3. Daily time steps (24 h)

The temperature increases in the shade during night-time and decrease during day-time tended to compensate each other on a 24 h cycle. Consequently, differences between mean daily (24 h) T_L occurred more seldom, for all the tested crops.

Significant differences in the mean daily crop temperature (T_L, 24 h average) between FS on the one hand, and FD and HD treatments on the other hand were detected for the wheat crop with LSD tests (p-value < 5%) for 40 days in FD and 30 days in HD, out of a measurement period of 122 days (Fig. 6). No particular weather conditions were noted for those days, but they correspond to time periods with a high variability between records from the thermistors in FS. For lettuces, significant differences from FS occurred only in HD (8 days out of 26), and for cucumbers, significantly differences were detected only for 2 days in FD and 5 days in HD, over a crop cycle of 62 days, as the spatial variability in T_L records (from one plant to another), for every treatment, was higher for cucumbers and lettuces compared to wheat.

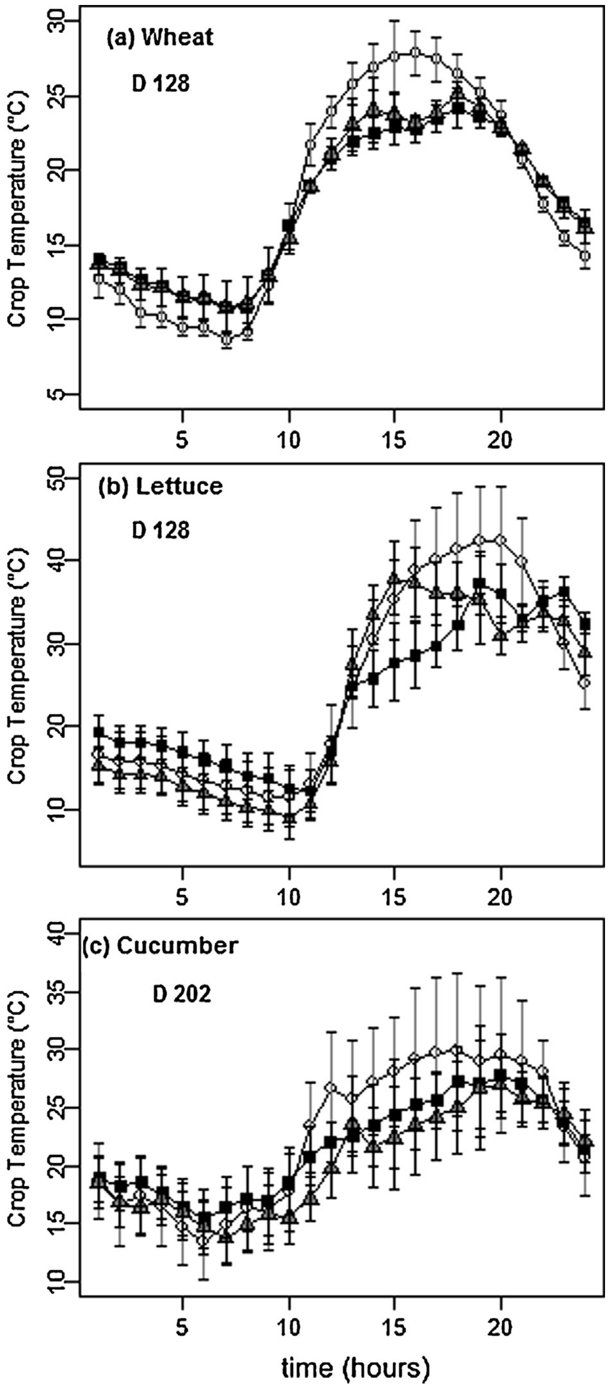

Fig. 5. Thermal pattern of hourly T_L measured on (a) wheat crop, (b) lettuce crop, and (c) and cucumber crop, during a sunny day (DOY 128 for wheat and lettuce, DOY 202 for cucumber). Symbols ■▲○ stand respectively for treatments "FD", "HD", and "FS". Vertical error bars represent standard deviation.

3.5. Radiative drivers of crop temperatures

3.5.1. Photothermal patterns of shaded and un-shaded plants within day

As the plant temperature is directly and indirectly (through net radiation and stomatal aperture) influenced by the incident global radiation (R_s) (De Boeck et al., 2012; Jones, 1992), we compared the photothermal trajectory (T_L–T_A as a function of R_s) in the shaded

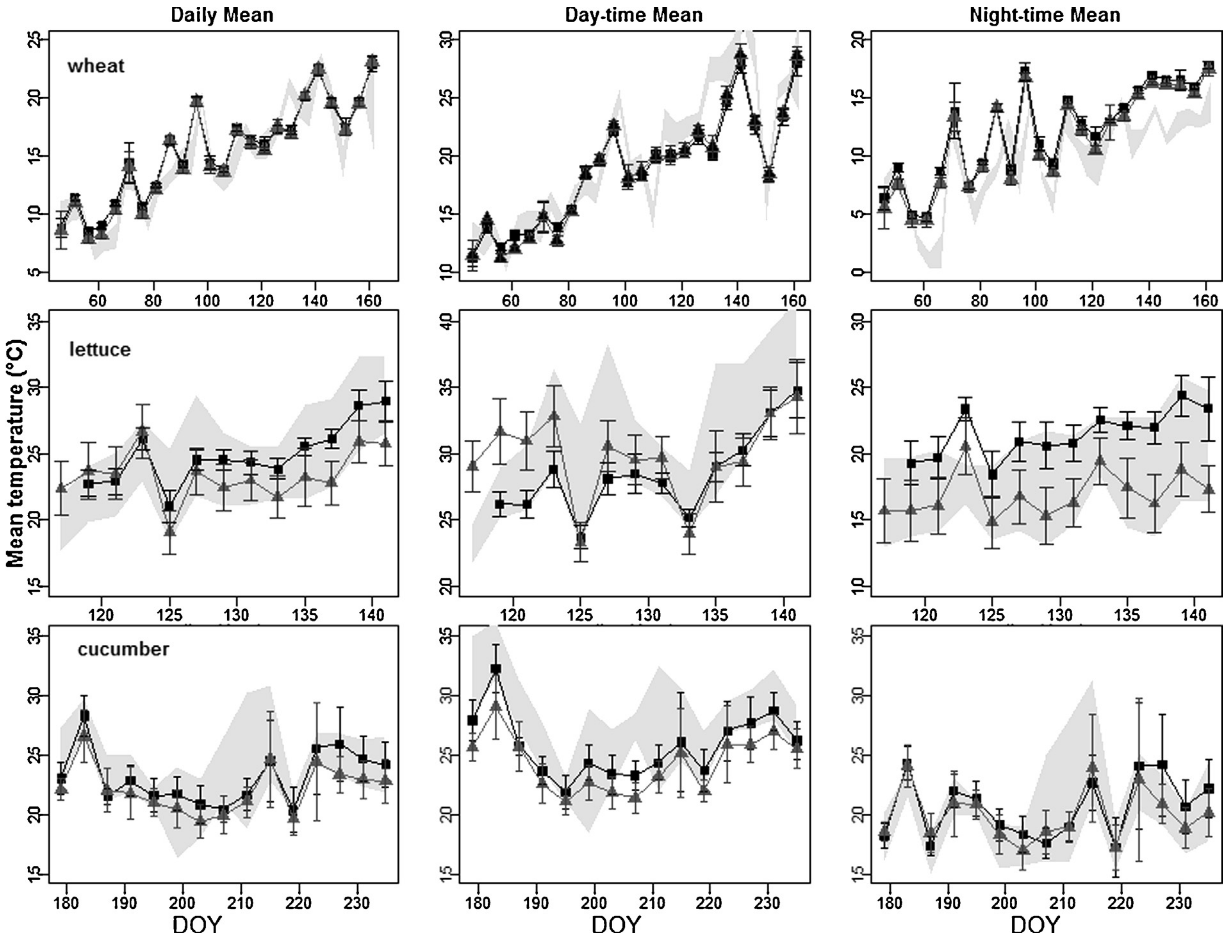

Fig. 6. Mean daily (24 h) crop temperature (T_L), mean day-time temperature ($T_{L,D}$), and night-time temperature ($T_{L,N}$) measured for each crop monitored in 2011. Shaded intervals represent mean values ± standard error for T_L, $T_{L,D}$, and $T_{L,N}$ in FS. The line with gray triangles (▲) features the average of T_L, $T_{L,D}$, and $T_{L,N}$ records (4–13 probes depending on the crop) in HD, while the line with closed squares (■) features the average of T_L, $T_{L,D}$, and $T_{L,N}$ records (4–13 probes depending on the crop) in FD. Vertical error bars represent standard deviation.

treatments for a sunny day in the late spring (wheat and lettuces) or in midsummer (cucumber). The purpose of this analysis was to determine to which extend the variation of incoming shortwave radiations explain the differences observed on crop temperature T_L in the shade compared to FS, at hourly time step. In order to compare crop temperature measured on different days, the difference between crop temperature and air temperature (T_L–T_A) was considered for each treatment. In FD and HD, the photothermal trajectory did not follow the same pattern as in FS. In FS, from sunrise to 14:00, the (T_L–T_A)/R_s ratio was nearly constant and equal to 0.0124 °C m^2 W^{-1} for wheat, 0.0232 °C m^2 W^{-1} for lettuces, and 0.0086 °C m^2 W^{-1} for cucumbers (Fig. 7). In the shade, lettuce temperatures increased more rapidly: the (T_L–T_A)/R_s ratio was equal to 0.047 both in HD and FD. In the case of wheat and cucumber, (T_L–T_A)/R_s was lower in the shade (FD and HD) compared to FS. Maximal temperatures were reached around midday in all the treatments and were similar in the shade and in FS, except in the case of lettuces in HD, where the maximal temperature of shaded plants exceeded that of the lettuces grown in FS.

3.5.2. Long wave radiation and radiative balance of shaded and un-shaded plants

In order to compare radiative balance assed from data collected on different days for the three treatments, all radiation measurements were normalized by the maximal $R_{s\downarrow}$ of the day in the full sun. During day-time, the main effect of the PVP cover was a reduction of the downwards shortwave radiation ($R_{s\downarrow}$) (Fig. 8) while, the downward longwave radiation ($R_{\ell\downarrow}$) remained similar in the three treatments (respectively 43%, 41%, and 44% in FS, HD, and FD). Thus, the PVPs did not contribute consistently to the long wave radiation input and did not compensate the loss of $R_{s\downarrow}$ in the radiative balance.

During night-time, no clear modifications were observed in downwards radiations, while the radiative losses were lower under the PVPs (41% both in FD and HD) than in FS (46%).

3.5.3. Spatial distribution of photosynthetically active shortwave radiations in the shade

For each face of the sensor, the amount of radiation received every 10 min in the shaded treatments never exceeded the one received by the same face at the same time in FS (data not shown). Thus, the hypothesis according to which PVPs could be responsible for radiation scattering, resulting in a significant increase of radiation reaching the crops with low elevation angle under the PVPs can discarded.

However, the proportion of the radiation incoming from the different directions changed in the shade of the PVPs (Fig. 9). It seems that incident radiation distribution was more homogenous in the shade of PVPs than in FS, especially in the morning. In FS, the model predicted that the proportion of radiation incoming from North–East and North directions (F3 and F4 faces) dramatically decreased between 8:00 am and 14:00 (C_v = 53% for F3 and 48% for F4). In the shade (FD or HD), the proportion of radiation measured on inclined faces F3 and F4 varied less than in FS (C_v = 36% for F3 and 29% for F4) between 8:00 and 14:00. This different spatial balance

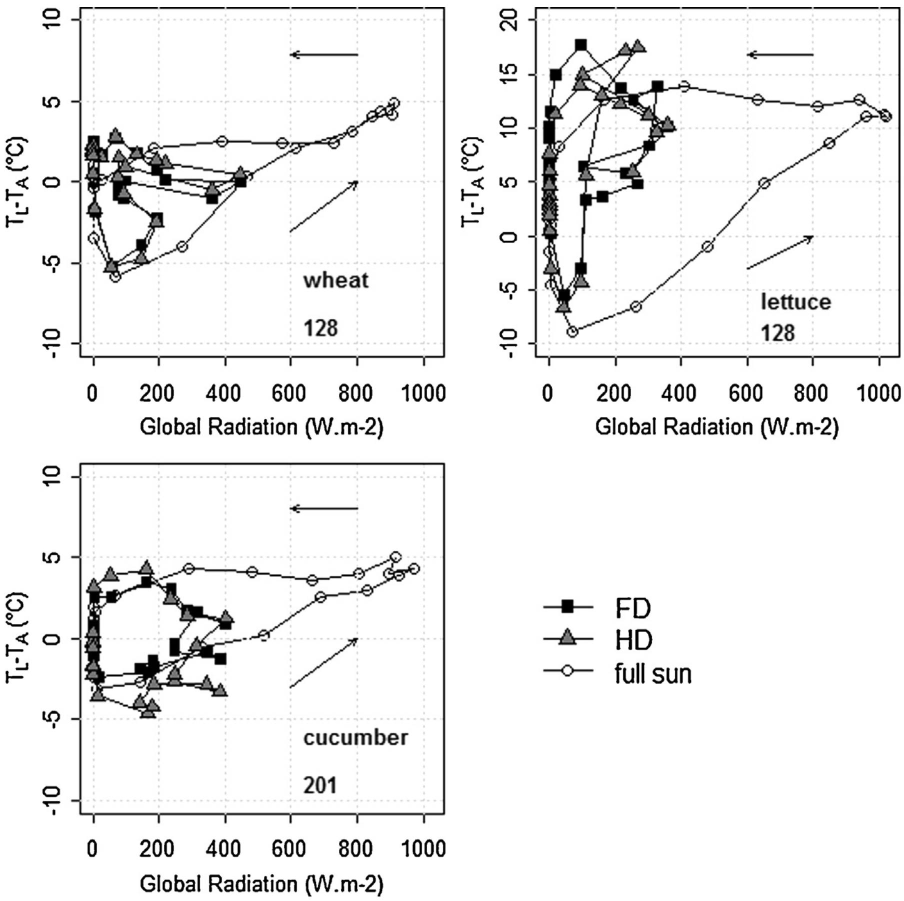

Fig. 7. Photothermal paths measured on sunny days for (a) wheat and (b) lettuce on DOY 128, and for (c) cucumber on DOY 201. The line with open symbols (○) represents FS situation, while lines with closed symbols feature the FD (■) and the HD situations (▲). Arrows indicate the direction of the trajectory in the morning (upward orientated arrow) and in the afternoon (horizontal arrow).

of radiation direction also highlights the increase of diffuse radiation proportion in the incident radiation at the crop level below the PVPs.

3.6. Plant development rate

3.6.1. Lettuce

Leaf numbers were plotted separately for the two varieties cropped in summer 2010 as this dataset was not collected for variety FC+ at the final harvest. For the two cropping seasons and the three shade levels, the leaf apparition rate was constant or increased from planting to harvest date (Fig. 10), which is consistent with former observations (Gay, 2002; Horie et al., 1979). In 2010, the analysis of covariance (ANCOVA) on leaf number, as a function of the thermal time and the shade treatment, showed that the leaf apparition rate was significantly reduced in FD and HD compared to FS during the first 3 weeks after planting (0–418 °C d), for both varieties. After DOY 223, differences in development rate were evidenced for variety FC+ only. In 2011, the ANCOVA showed that leaf apparition rate was significantly reduced in FD and in HD compared to FS, only during the first three weeks after planting (0–336 °C d). Afterwards, the leaf apparition rate was the same in all treatments, when considering all the varieties pooled together or individually (except variety B− for which apparition rates were significantly different between treatments up to 6 weeks after planting).

3.6.2. Cucumbers

Cucumber leaf apparition rate (leaf emitted on the main stem only or both on the main stem and on secondary branches pooled together) followed a sigmoid dynamic in the three shading treatments (Fig. 11). Consequently, development dynamic was decomposed into three successive phases: (P1) from DOY 180 (planting, 0 °C d) to 192 (196.5 °C d), (P2) from DOY 192 to 214 (404.1 °C d), (P3) from DOY 214 to 229 (567 °C). Phase 1 (P1) corresponds to the juvenile development phase, also called “initial lag phase” by Horie et al. (1979), Phase 2 (P2) corresponds to the maximum vegetative development (also called “stationary phase” by Horie et al., 1979), while Phase 3 (P3) corresponds to fruit development and plant senescence. The dates of transition from one phase to another were not affected by shading (Marrou, 2012).

The ANCOVA showed that the leaf apparition rate on the main stem (Fig. 11a) was not affected by the shade during P2; however, leaf emission rate was significantly reduced in FD and HD compared to FS during P1, and P3. On the opposite, when considering the total pool of leaves (Fig. 11b), the ANCOVA showed that the leaf apparition rate was reduced significantly only during P2. Considering the whole cropping season, the dynamics of the total number of leaves was more affected by shading than that of the number of leaves on the main stem, although it is also much more variable within treatments.

3.6.3. Wheat

Heading was reported on DOY 109 in FS, DOY 111 in the HD plot and DOY 115 in the FD plot (visual determination at 50% of heading). On DOY 157, wheat grain was in stage 89 in FS, while it was in stages 85–87 in FD and HD according to Zadock’s phenological scale (Zadoks et al., 1974). The grains maturity was reached on DOY 168 in HD and FD while it was 2–3 days earlier in FS. These observations

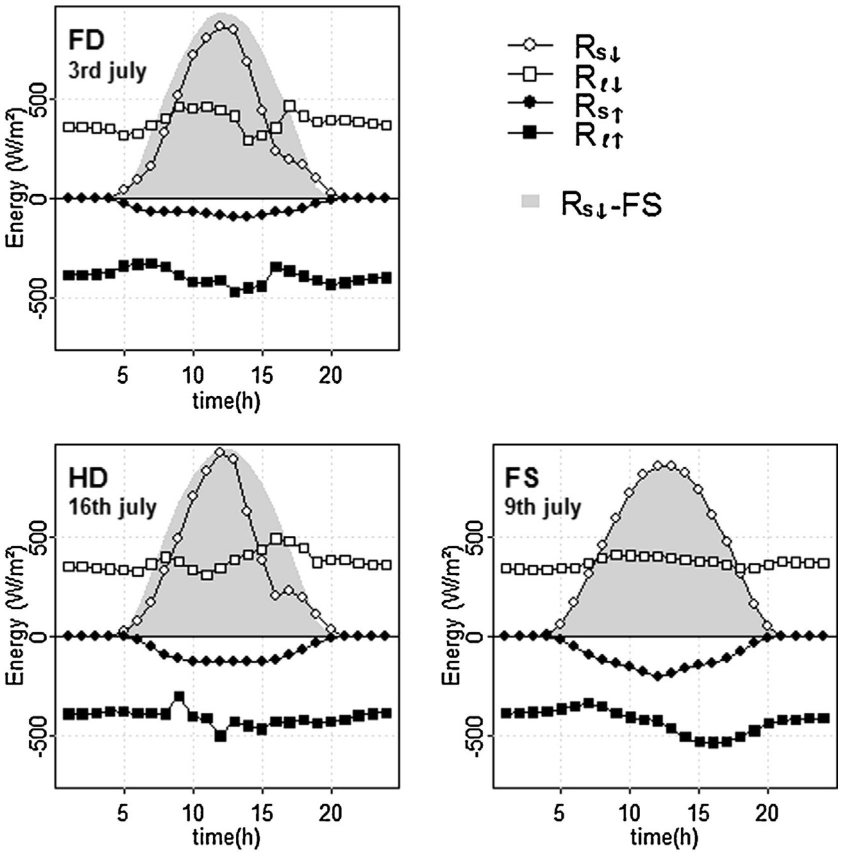

Fig. 8. Evolution of upward ($R_{\ell\uparrow}$) and downward ($R_{\ell\downarrow}$) longwave radiations and upward ($R_{s\uparrow}$) and downward ($R_{s\uparrow}$) shortwave radiations in the three treatments for three close sunny days. The shaded area represent the shortwave downwards radiation (global radiation) in the full sun for the day of the measurement.

are consistent with phenological delays reported by Sudmeyer and Speijers (2007) on wheat cropped under wind breaks.

4. Discussion

4.1. Unchanged air masses characteristics in agrivoltaic systems (AVS)

The comparison of air temperature at reference height (2 m) showed that there was no significant difference between partially shaded treatments and FS, neither at daily time step nor at hourly or infra hour time steps at the latitude of the experimental site (43° N). Similarly, no significant difference was found between treatments for VPD and wind speed at 2 m: the maximal increase in VPD in shaded treatments compared to FS corresponds for cereals to (1) a decrease in CO_2 assimilation rate of 0.5 μmol m^{-2} s^{-1} according to Dai et al., 1992), and (2) to a decrease in water use efficiency of 1.4 g m^{-2} mm^{-1} according to literature (Abbate et al., 2004; Tanner and Sinclair, 1983). This result indicates that our prototype of AVS (around 45 m length and 860 m^2) with PVPs far above-ground (4 m) is a highly aerated system where air masses are in equilibrium with the outside environment. We could have expected significant differences in air temperatures or humidity on no wind days, but this was proved not to be true. Convection air movements seem therefore to be powerful enough to homogenize air characteristics across the system. However, our prototype was small compared to AVS that could be used for crop production. The mean average standard size for an AVS could be reasonably – on a technical point of view – comprised between 0.5 and 2 ha. Under such extensive devices, some changes in air temperature and wind speed profiles could be observed. It is difficult to know in which extent because AVS combine numerous sources of variation in T_A and wind speed profiles such as shading, windbreak effects, development of boundary layers, changes in plant and soil temperature. Further experiments should be conducted to explore the impact of PVPs on air characteristics and heat exchanges in case of bigger size AVS. Nevertheless, agrivoltaic system are not closed system and should not be assimilated to photovoltaic greenhouses, as described by Carlini et al. (2012), Kadowaki et al. (2012), and Poncet et al. (2010). Therefore air temperature cannot be monitored in AVS as in greenhouses and crop adapted to outdoor conditions should be more suitable for AVS. One of the main negative effects of shading on crops is usually the increase of fungal diseases, as reported by Roberts and Paul (2006) and Wu et al. (2005). Fungus development is directly enhanced in confined environments with increased air humidity and reduced air circulation (Sudmeyer and Speijers, 2007). Therefore we can expect that pest and diseases will not be stimulated in AVS, compared to similar cropping systems and genotypes in FS, thanks to the maintenance of air circulation below the structure.

4.2. Variability of crop temperature at infra-daily time steps

Crop temperature solves the energy balance equation (Eq. (1)) which is dominated by the radiant exchanges (Chelle, 2005; Jones, 1992). Consequently, we analyzed the variation of crop temperature in the shade compared to the full sun regarding the modification of the radiative climate.

4.2.1. Crop temperature decreases

Unlike the air temperature and humidity, the crop temperature pattern within a day was affected by shading. We showed that day/night amplitude tends to decrease in the shade of solar panels

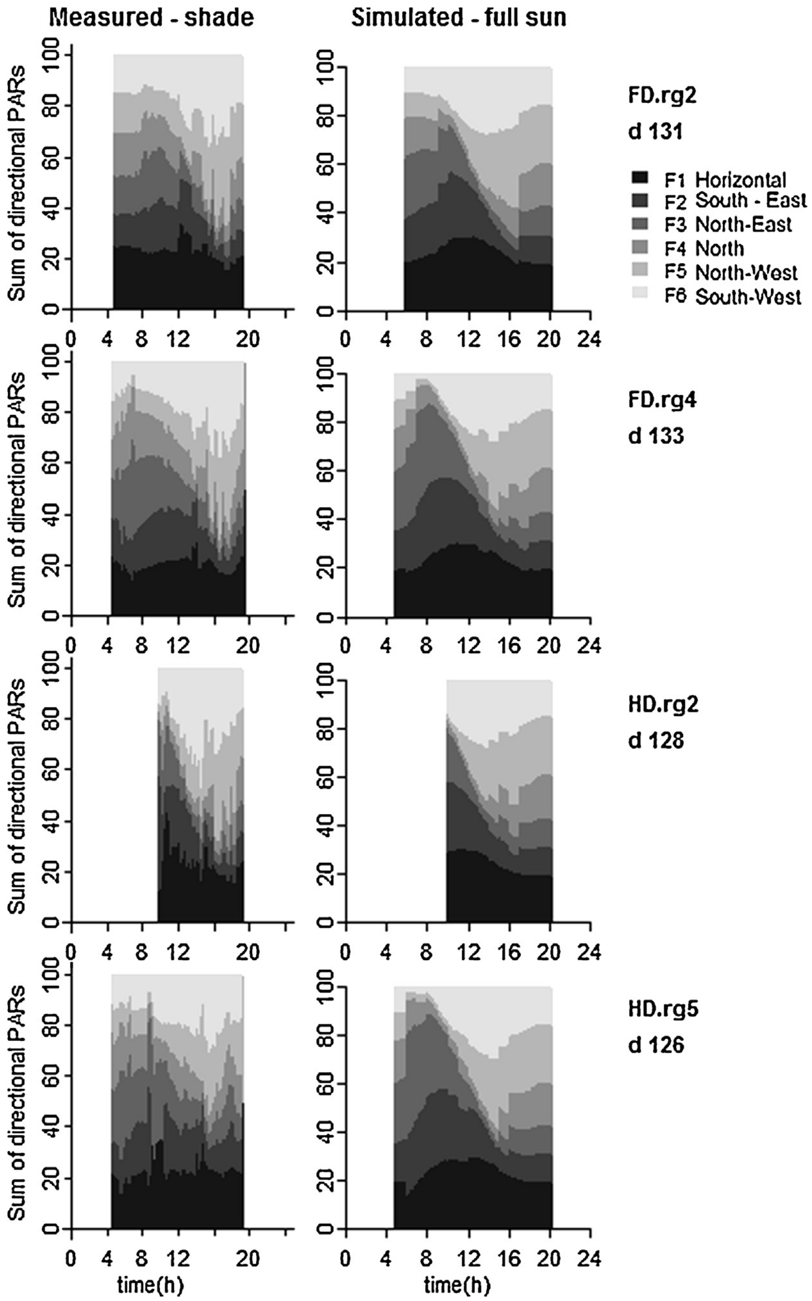

Fig. 9. Distribution of the proportion of incident photosynthetically active radiation captured by each face of the turtle sensor when placed at two locations in the HD plot (HD.rk2 and HD.rk4) and in the FD plot (FD.rk2 and FD.rk5), corresponding to different planting row positions during the lettuce cropping season in spring 2011, and in FS, on the same day. Incident radiation distribution in FS has been simulated using the model of radiation parameterized with the latitude of the site and the same orientation for the sensor as it was recorded on the day of measurement in the shaded treatment.

at the latitude of the experimental site (43° N). Crop temperature around midday decreased significantly for each tested crop in the three seasons.

T_L was found to have higher spatial variability (from one plant to another within the same treatment plot), for every treatment, for cucumbers and lettuces compared to wheat. This result is probably due to (1) the fact that wheat temperature was measured in the center of the plant cover, at mid plant height, and was consequently less affected by variations of the incident global radiation, (2) the influence of soil temperature variations that should be higher on small crops close to the ground surface (lettuces, cucumbers) than on tall crops such as wheat, (3) the number of plant positions where measurements were taken that was higher for lettuces than for wheat (5 planting ranks on a North South transect in the case of lettuces compared to 2 locations on a transect for wheat).

Decrease in crop temperature under PVPs was mainly due to the reduction in the incoming shortwave radiations as variations in long wave radiations between shaded and unshaded treatments were found to remain small (Section 3.5.2) compared to variation in net shortwave radiation ($(1 - a){\cdot}R_s$, with a the crop albedo).

4.2.2. Crop temperature increases

During night-time, crop temperature increased under PVPs (FD and HD treatments) compared to FS, which could be partly explained by reduced radiative losses under PVPs as shown in Section 3.5.2. Heat conduction from the soil could also contribute to

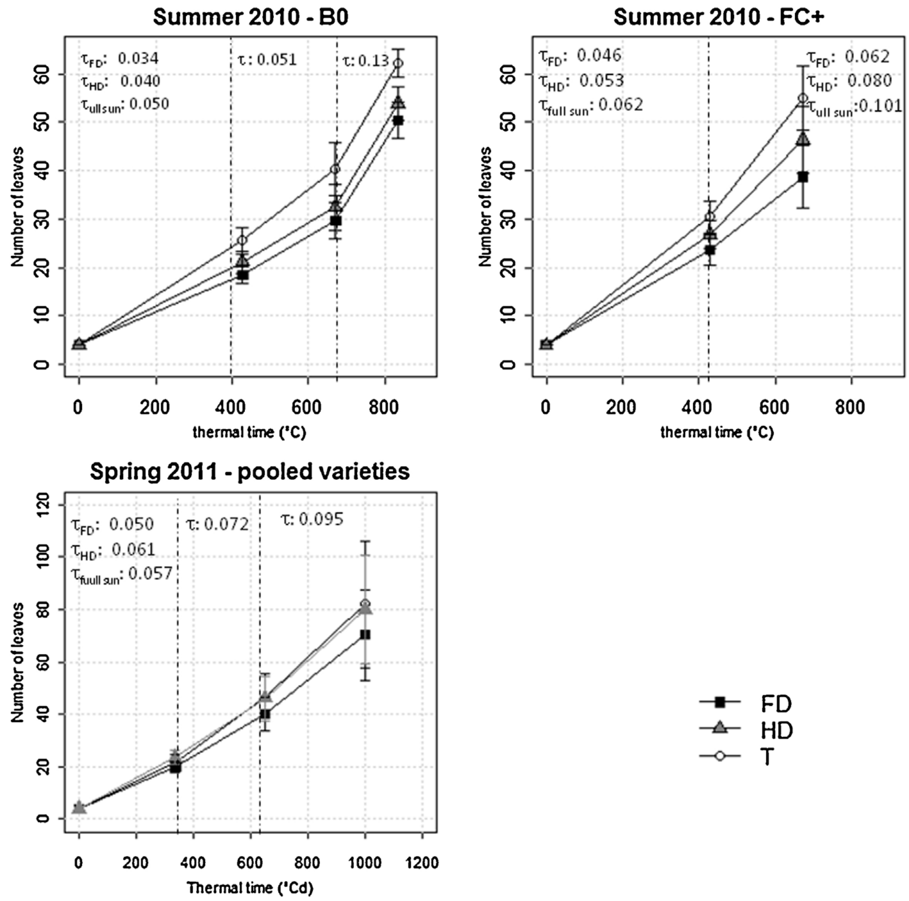

Fig. 10. Number of leaves measured on (a) summer lettuces variety B0, and (b) variety FC+ in 2010, and (c) spring lettuces (all varieties pooled together) in 2011. Lines with symbols ○, ■, ▲ refers respectively to measurements in FS, FD plot and HD plots. Vertical error bars feature standard errors. Leaf emission rate (τ, leaves °C d^{-1}) is represented for each period between two sampling dates.

modify crop temperature. Further measurements to quantify the radiative balance and heat fluxes from the soil are required to quantify and rank the main drivers of crop temperature increases during night-time.

During day-time, we observed a rapid increase of T_L in the morning in the case of lettuce in the HD treatment, whereas the radiative balance is lower under the PVPs compared to FS. Considering lettuces as hemispherical object, scattering effects increasing plant irradiance in the morning could be suspected. Turtle measurements as well as FS simulation showed that the proportion of radiation incoming from different sky directions changed in the partially shaded situations compared to FS. Differences in the light distribution were mainly significant in the morning, during sunny days: whereas most of the incident radiation comes from the sun direction in FS, it is homogeneously distributed among the sky sectors in the shaded situation. However, the total amount of energy received

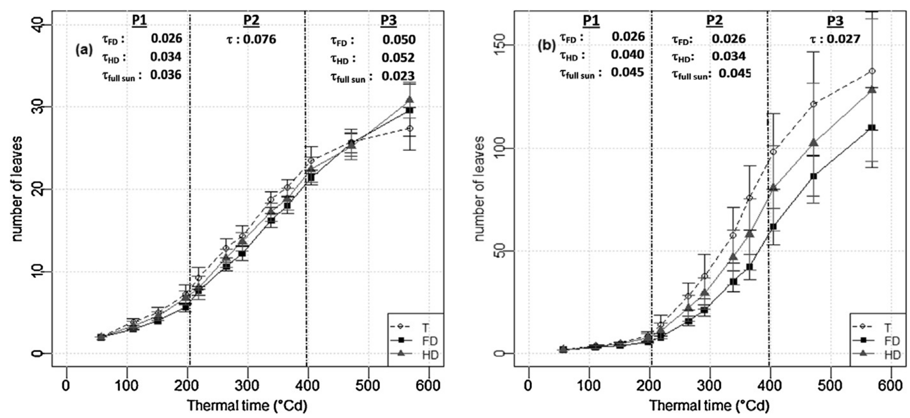

Fig. 11. Number of leaves measured on cucumbers, in 2011. (a) Accounted for leaves on the main stem only. (b) The total number of leaves (main stem, as well as secondary and tertiary branches). ○, ■, ▲ refers respectively to measurements in FS, FD plot and HD plots. Vertical error bars feature standard errors. Leaf emission rates (τ) are given for each development phase.

from any direction was always smaller below the PVPs compared to FS treatment. Consequently, strong scattering effects are unlikely to happen in agrivoltaic system, and do not explain that the plant temperature tends to increase more rapidly between 7:00 and 12:00 TU in the shaded situations compared to FS.

It is also important to notice that the more homogenous repartition of the spatial distribution of incident radiation below the PVPs is related to an increase of the diffuse/direct ratio of incident light. This characteristic of the radiative environment of agrivoltaic systems could be favorable to plant growth. Indeed, several authors already reported an increase of the radiation use efficiency when the proportion of diffuse radiation increases (Gu et al., 2002; Sinclair et al., 1992).

A comprehensive assessment of the energy balance, including the measurement of leaf transpiration at an hourly time step (Guilioni et al., 2000) would be necessary to determine the cause of the lettuce temperature elevation under HD treatment. The stomatal aperture is under the control of crop surface incident net radiation and has been reported to be sensitive to shade (Turner, 1991). However, the stomatal aperture/closure effect is expected to moderate changes in incident light, due to the quickness of the response of stomata conductance to shade (Fay and Knapp, 1996) and to be of a small order of magnitude compared to radiation fluxes (Baille et al., 2001). On the contrary, differential dew formation at night and evaporation in the morning could explain the different pattern of evolution of crop temperature in the morning in FD, HD, and FS treatments. Indeed, T_L is significantly lower in FS than in FD and in HD at night, and was checked to be less than dew point temperature during clear night. Consequently dew formation is expected (and was observed) in FS while it is not the case in the shaded treatment. In the morning, dew evaporation participate in the reduction of leaf temperature in the full sun and could lead to smaller rate if T_L increase than in shaded situations, even if incident radiation is higher.

4.3. Consequences on plants development rate in the agrivoltaic systems (AVS)

Although crop temperature in the shade of PVPs was reduced at infra-daily time step (Fig. 5), mean daily crop temperature remained close to the one in FS (Fig. 6). This result is consistent with the only slightly reduced leaf emission rate for partially shaded plants (Figs. 10 and 11a). Lettuces as well as cucumbers (considering the main stem only) were shown to grow at the same rate during the period of maximal vegetative growth (Figs. 10 and 11) whereas growth rates were reduced under PVPs at the beginning of the plant life cycle. This is likely to be caused by the reduction of ground temperature in the shade of the solar panels (explanation 1). Indeed, the development rate is monitored by the meristem temperature which is close to soil surface at the beginning of the plant life cycle and becomes to some distance to the soil surface when plant height further increases (Ritchie and NeSmith, 1991).

Several complementary explanations can be proposed for the reduction of growth at the beginning of each crop cycle and should be explored in further research and should be discriminated with further experimentation under controlled conditions (with potted plants or in growth chamber for example): (explanation 2) the increase of the crop temperature during night-time could entail an increase of the night respiration rate in shaded plants (Hüve et al., 2011; Vries et al., 1979), thereby reducing the carbon assimilates available for the plant development. A recent study showed that a reduction of the day-night temperature amplitude decreased the biosynthesis of vegetative structure from carbon reserves (Bueno et al., 2012). Consequently leaf emission could be delayed below the PVPs through a C limitation of the leaf and stem development. However, the increase of the crop temperature during night-time was significant only for wheat and night-time temperature remained below 20 °C during the first part of the cycle, which cannot entail a dramatic increase of respiration (explanation 3). The reduction of light resource could be directly responsible for the slower development of young plants in the shade. As the leaf area of a young plant is small, its light capture ability is limited, and shade can be more detrimental to young plants than to mature plants with wide light harvesting organs as suggested by Bensink (1971) for lettuces (explanation 4). Another possibility, relating directly the light reduction to the development rate decrease is that, at that stage of development, plant reserves are insufficient to overpass periods of light resource shortage. Young plants have smaller carbohydrates pool. So, when seedlings are punctually shaded during day-time, their non-structural pool of carbon may be emptied more rapidly through respiration as less carbon input would be provided by photosynthesis, as suggested by the Seginer's model (Seginer et al., 1994) (explanation 5). Low shoot/root ratio was reported as a plant adaptation to shade (Seidlova et al., 2009). During the first phase of development, biomass is preferentially allocated to root production: this could also explain why young plants have a reduced leaf emission rate in the shade, while older plants grow at the same rate in FS as in the shade. A new experiment with a monitoring of underground dry matter on plants grown in FS, in the FD and in the HD would be necessary to conclude on that point. Regarding our results, it seems that development rate decrease in the first plant stage should be attributed to light reduction, more than to temperature changes. Interaction between plant age and shade sensibility has already been reported (Niinemets, 2010; Valladares and Niinemets, 2008). It is likely that, for young lettuces and cucumbers in the shade of PVPs, light influence is predominant on temperature one and is the main limiting resource (as defined in Kho, 2000) for biomass accumulation. In accordance with this finding, a particular attention should be paid to juvenile stages of the plant development for the optimization of AVS. At these stages, not only biomass accumulation can be reduced but plant development can be delayed too.

5. Conclusion

This study shows small agrivoltaic systems can be handled as open field production systems, and not as closed greenhouse, because their main specificity is in the mean daily reduction of light availability for plant without significant modification of the other parameters of the microclimate at canopy level. Due to a sufficient air circulation below the open structure, air temperature and VPD were not significantly affected by the PVP shelters. Over the whole cropping season, and even for a long cycle crop, the crop temperature was marginally modified in the shade compared to FS, with regards to the impact on the plant development. This finding which was unexpected, as the energy balance was suspected to be impacted by the shelter, would make easy the establishment of agrivoltaic systems on farm. It suggests that little adaptation in cropping practices should be required to switch from open cropping to agrivoltaic cropping and attention should mostly be paid to light reduction mitigation (Marrou et al., 2013). Nevertheless, these results should be confirmed under larger AVS where air temperature and wind speed profiles could be modified under PVPs. Juvenile crop stages should be looked after with caution as strong shading at the beginning of the cycle could delay development for the whole cycle but may also have positive effects on vegetable plants establishment during warm season. A solution would be to use mobile panels that could be set in a direction that allows the maximal light penetration at the crop level at the plant setting time. Panels could be set back to an optimal position for energy production afterwards

(Marrou, 2012). Furthermore, AVS and light reduction are not necessary detrimental for crop production as Radiation Interception Efficiency (RIE) was showed to be increased in the shade (Marrou et al., 2013).

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Appendix A. Diagram of the simulated geometrical scene

See Fig. A1.

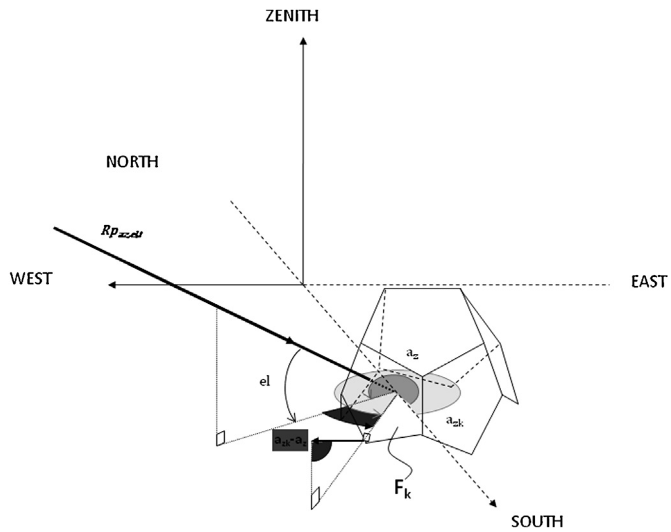

Fig. A1. geometric representation of the interception of light by the turtle sensor, as simulated by the radiation model. a_z: azimuth of the incident beam; el: elevation of the incident beam.

Appendix B. Model validation

See Fig. B2.

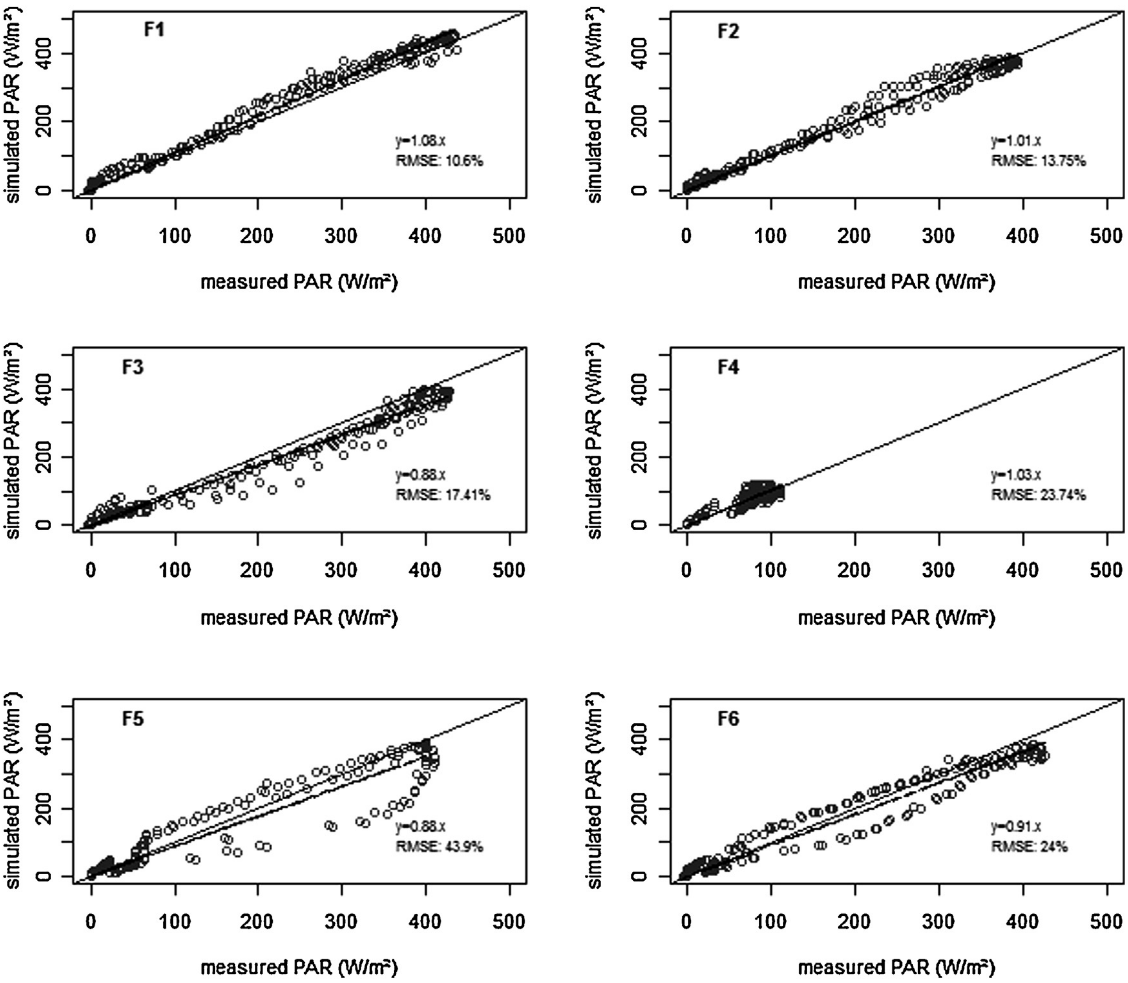

Fig. B2. simulated versus measured incident PAR radiation, for the measurement period (from DOY 196 to DOY 199, in 2012). Each graph corresponds to a different face of the turtle sensor – F1 (horizontal face) to F6. Equation of the regression line between simulated and measured data as well as RMSE calculated on the hypothesis that simulated data = measured data for each face of the sensor are plotted on the graph areas.

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