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Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops

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HIGHLIGHTS

- Combining solar panels and crops on the same land increases the total productivity.
- Use of solar trackers permits to balance or promote food/energy production.
- Controlling mode of trackers strongly affect the total production per unit area.
- Dynamic agrivoltaic systems increases productivity without competing with food.

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ABSTRACT

Agrivoltaic systems, consisting of the combination of photovoltaic panels (PVPs) with crops on the same land, recently emerged as an opportunity to resolve the competition for land use between food and energy production. Such systems have proved efficient when using stationary PVPs at half their usual density. Dynamic agrivoltaic systems improved the concept by using orientable PVPs derived from solar trackers. They offer the possibility to intercept the variable part of solar radiation, as well as new means to increase land productivity.

The matter was analysed in this work by comparing fixed and dynamic systems with two different orientation policies. Performances of the resulting agrivoltaic systems were studied for two varieties of lettuce over three different seasons.

Solar tracking systems placed all plants in a new microclimate where light and shade bands alternated several times a day at any plant position, while stationary systems split the land surface into more stable shaded and sunlit areas. In spite of these differences, transient shading conditions increased plant leaf area in all agrivoltaic systems compared to full-sun conditions, resulting in a higher conversion of the transmitted radiation by the crop. This benefit was lower during seasons with high radiation and under controlled tracking with more light transmitted to the crop. As expected, regular tracking largely increased electric production compared to stationary PVPs but also slightly increased the transmitted radiation, hence crop biomass. A large increase in transmitted radiation was achieved by restricting solar tracking around midday, which resulted in higher biomass in the spring but was counterbalanced by a lower conversion efficiency of transmitted radiation in summer. As a result, high productivity per land area unit was reached using trackers instead of stationary photovoltaic panels in agrivoltaic systems, while maintaining biomass production of lettuce close or even similar to that obtained under full-sun conditions.

1. Introduction

Among the challenges humanity will have to face by 2050, limiting climate change while feeding 9–10 billion people are the most indisputable [1]. This requires new sources of energy which could solve the food, energy and environment trilemma [2]. In this context, biofuel appeared in the 2000s as a turnkey alternative to fossil carbon, but potentially raised two major problems. First, expanding cultivated land area for food and energy production inevitably increases agriculture's carbon footprint [3]. More importantly, biofuels compete for land use

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with food production, directly threatening food safety [4]. Recent improvements in photovoltaic (PV) technology have forced the reconsideration of the position of biofuels. Light-use efficiency of PV panels (PVPs) has now reached an average of 15% compared to only 3% for crop photosynthesis [5]. The fact that PV systems may be developed without competing with crops for land use has therefore been re-examined.

An original solution arose with so-called agrivoltaic systems combining food production and PVPs on the same land at the same time [6]. An initial prototype in open field was built in France in 2010 with PVPs installed 4 m above the plants, allowing for usual crop mechanization [7]. Different species were studied within this new, mixed system, placing plants in the partial shade of the PV structure. The possible benefits of agrivoltaic systems was determined using the Land Equivalent Ratio (LER) defined, just as for mixed crops [8], as the relative land area needed to produce the same yield and energy production when separated as when associated on the same land surface [7]. Preliminary results on agrivoltaic systems showed values of LER far above 1 (1.35–1.73) indicating that 35–73% of additional land area would be needed to produce the same amount of energy and biomass on separated surfaces as the productions observed in agrivoltaic systems [7]. This opened promising developments for such systems, and studies in the US or Italy more recently confirmed their benefits [9–11]. In addition, agrivoltaic systems were shown to improve crop performance relative to available radiation. Specifically, plants can acclimate to the shading conditions induced by PVPs by increasing their radiation interception efficiency [12]. PVPs installed above plants can also reduce evaporative demand at crop level thereby increasing water-use efficiency - that is, the water amount required per gram of biomass produced [13].

Yet, most recent research on agrivoltaic systems focused exclusively on the microclimate changes at plant level in photovoltaic greenhouses [14–17] while the effects of shading by PVPs on plants remain poorly documented apart from Marrou's publications [12,13,18]. Moreover, all the published studies considered stationary PVPs while orientable PVPs, tracking the daily courseof the sun, have emerged as a new technology that may boost energy production. LER for such systems has never been characterized with actual measurements of biomass production.

In the present study, we concomitantly characterized microclimatic conditions, crop and PV performances of an improved agrivoltaic system, using solar trackers instead of stationary PVPs. Solar trackers were installed beside the original, stationary agrivoltaic system in Montpellier with the same density when oriented horizontally. In regular tracking mode, PVPs follow the daily course of the sun azimuth in order to maximize the interception of solar radiation yielding up to 29% more electricity production per year compared to stationary systems [19]. Beyond the regular tracking mode, we originally considered that trackers could also be orientated in order to modify the microclimate during specific time periods according to crop needs. Specifically, appropriate control of the orientation of trackers could prevent the damaging effects of excessive light, or limit evapotranspiration during peaks of evaporative demand. Regular solar tracking may conversely be programmed between crop cycles to maximize electricity production. The control law can therefore lean on crop needs, climate and land status (free/occupied). With this system, a degree of flexibility was added to support either food or electricity production throughout the crop cycle. Here, we analysed the possible benefits of orientable PVPs by comparing full-sun conditions under two different control laws for orientable PVPs and the original, stationary agrivoltaic system. The microclimate was highly affected by these different systems, creating highly fluctuating conditions where shading alternated at varying rates with full-sun exposure during the whole day. In addition to crop biomass, physiological traits related to radiation use by the plant (projected area, leaf number, specific leaf area and leaf shape) were also characterized. Electric production was then simulated to calculate the LERs of the different agrivoltaic systems. We will discuss the effects of agrivoltaic systems on crop and electric production with the prospect of optimizing control laws for orientable panels.

2. Methods

2.1. Agrivoltaic systems

A new agrivoltaic prototype was built using orientable PVPs surrounding an original stationary device at IRSTEA experimental site in Lavalette near Montpellier, France (43°6N, 3°8E) [7]. The stationary device, which was built in 2010, was composed of PVPs installed a in fixed position with a 25° angle to the horizontal. For plot arrangement reasons, PVPs did not exactly facesouth, but formed an 11° aspect angle towards the southwest. Individual panels consisted of 0.808 m wide and 1.580 m long monocrystalline modules (JT185Wc, Jetion Solar Holdings Limited, Jiangsu, China). PVPs were installed as 44.8 or 22.4 m long strips of jointed panels from west to east (again with a slight, 11° deviation angle towards the northwest - southeast) and were elevated to 4 m above ground. Two 18 m wide, 22.4 m long, stationary subsystems were considered at either “Full Density” (FD), very close to the optimum design for energy production with 1.6 m between panel strip axes [7], or “Half-Density” (HD) with one strip out of two removed to increase light transmission to the crop.

Two independent, 1-axis, orientable PV systems were added in 2014 on the eastern and western sides of the stationary subsystem, with 3 and 4 strips of horizontal PVPs respectively. Each strip, 1.980 m wide and 19 m long, was made of joint PVPs, rotating around a horizontal axis, oriented south to north (still with an 11° deviation angle) and placed 5 m above the ground (Fig. 1). Supporting pillars were installed below the rotating axes, 6.4 m apart and axes were also separated by a 6.4 m distance between PVP strips to +50° angles to the horizontal. The distance between supporting pillars was kept similar to stationary device. It has been optimized to allow crop mechanization, lower the cost and maximize the mechanical resistance. The size of the PVPs was standard. The orientation of PVPs was chosen to minimize the number of number of supporting pillars, and to obtain similar light transmission with trackers when set in a horizontal position as with HD [7], about 70% of transmitted light.

2.2. Light conditions for plants in the different agrivoltaic systems

In addition to full-sun (FS) conditions, half-density (HD) and full-density (FD) stationary PV systems, two different control laws for orientable panels were studied, hereafter called solar tracking (ST) and controlled tracking (CT). These tracking modes were designed as a first step towards optimizing control laws in the future.

The ST mode corresponded to PVPs moving as usual during the whole day to keep facing the sun within the −50/+50° limit angles to the horizontal. The orientation of the PVPs was adjusted every time there was a 1° offset between the trackers azimuth and the computed position of the sun going from east in the morning to west at the end of the day (see supplementary information). Backtracking optimization was also implemented in the pilotage instructions to avoid self-shading between arrays at early and late hours for this mode [20].

The controlled tracking (CT) mode aimed at increasing solar radiation at plant level by minimizing the area shaded by panels in the morning and late afternoon whilst maximizing the shading of the plant just at solar noon when temperature, evaporative demand and light conditions peaked with possible limitation of plant growth. The CT mode was achieved by moving PVPs parallel to sunrays (90° away from the position of PVPs in ST mode), excepting from 11 a.m. to 3 p.m. (solar time) when control of PVPs shifted to solar tracking for 4 h (see supplementary information).

The FS condition, considered as a control for crop production, was placed to the south of the agrivoltaic systems where the influence of

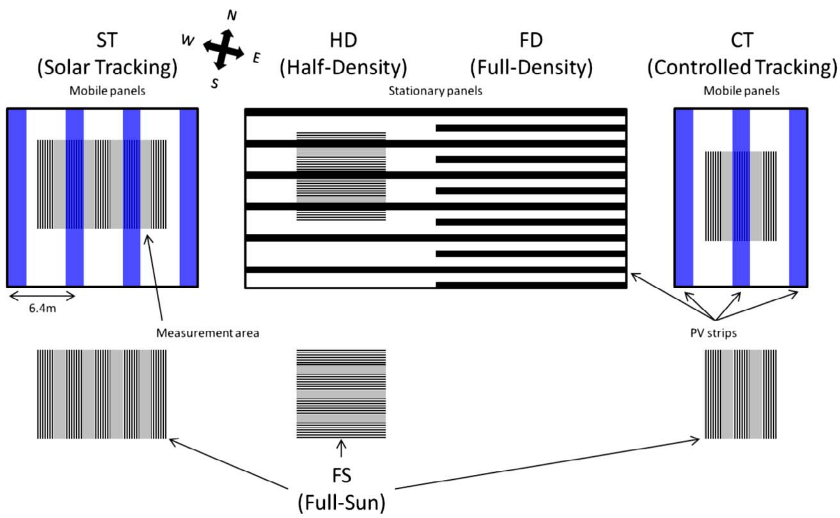

Fig. 1. Experimental design of agrivoltaic systems. PV strips in blue were orientable while black ones were stationary and elevated towards the south. Planting rows (thin lines) within cultivated plots (grey areas) were parallel to the photovoltaic panel strips above. ST: solar tracking; HD: half-density stationary panels; FD: full-density stationary panels; CT: controlled tracking; FS: full-sun conditions.

photovoltaic panels was negligible.

2.3. Climate and microclimate characterization

Climatic conditions outside agrivoltaic systems were monitored in the FS area to the south of the whole set of agrivoltaic systems. Sensors for air humidity and temperature (HMP45C, Campbell Scientific Inc., UK) and global and diffuse radiation (BF5, Delta-T Devices, Cambridge, UK) were installed 2 m above soil level and data were stored every 3–12 min. Vapour Pressure Deficit (VPD) in the air was derived from temperature and humidity measurements. A diffuse index (DI) was computed as the ratio of diffuse to global radiation, ranging from 0 on ideally bright, sunny days to 1 on extremely cloudy days [21].

The microclimate in agrivoltaic systems was measured at plant level with additional sensors using copper-constantan thermocouples for leaf temperature and home-made sensors for Photosynthetic Photon Flux Density (PPFD). Ten pairs of PPFD and temperature sensors were installed on each plantation board and distributed among the rows, either in an upright position below panel strips or between two strips. Sensors were regularly moved so as to maintain thermocouples in contact with the abaxial side of upper leaves and home-made PPFD sensors at the same height as upper leaves. Home-made PPFD sensors were individually calibrated against a reference sensor (PAR Quantum, Skye Instruments, Llandrindod Wells, Powys, UK) and they delivered values which tightly correlated with that of the reference (with regression coefficients higher than 0.95). Degree-days were computed by cumulating daily mean temperature above the base temperature of 3.5 °C [22].

In order to compute direct and diffuse components of the solar radiation at any point and any time in the different systems, the whole set of agrivoltaic systems were modelled as a three-dimensional virtual scene (Fig. 2). The optical properties of the PVPs were taken into account as well as their edge effects. Incident radiation above PVPs was extracted from meteorological data measured onsite with a BF5 sensor (Delta-T devices, Cambridge, UK). When missing, incident diffuse radiation above PVPs was derived from the Skartveit-Olseth model [23]. A ray tracing algorithm, based on the MIR MUSC RADBAL model [24], was used to compute the direct and diffuse components of solar radiation at soil level with a 30 cm^2 spatial resolution.

Computed radiation were fairly well correlated with values measured using home-made PPFD sensors for different locations within agrivoltaic systems ($R^2 > 0.98$, see supplementary information). Simulated radiation was used in the following to get continuous data for all plots during the whole crop cycle.

2.4. Plantation design and crop management

Two lettuce varieties, Kiribati and Madelona were planted in autumn (2014-09-25), spring (2015-04-16) and summer (2015-07-21). Kiribati belongs to the subspecies “Oakleaf” (L. sativa var. acephala), while Madelona is a “Romaine/Cos” lettuce (L. sativa var. longifolia). Kiribati was already studied in previous works under stationary, agrivoltaic systems [12,13,18]. Madelona was chosen for its more planar leaves to facilitate morphological descriptions.

For each shading condition, three to five elementary plots were designed using simulation maps of transmitted radiation, cumulated over the different growing periods. Specifically, edge effects were avoided by eliminating positions where transmitted radiation could be markedly perturbed by the neighbouring environment at the beginning and end of the day with low sun incidence. Within each board of plantation, 6 rows of a minimum of 25 lettuces were planted, with a 30 cm mean distance between two lettuces within and between rows. Planting rows were arranged parallel to the orientation of panel strips (approximately north-south under trackers in ST and CT modes and east-west under HD, still respecting the 11° deviation angle of panel strips) so that all plants in the same row could be considered as replicates with respect to shading by PVPs. In the HD system, two Kiribati and two Madelona boards were planted in autumn, and one Kiribati and three Madelona boards in the other two seasons. In the ST system, two boards of Kiribati were planted in all three seasons, while Madelona was planted in two boards in autumn and three boards in the spring and the summer. The CT system included only one Kiribati and two

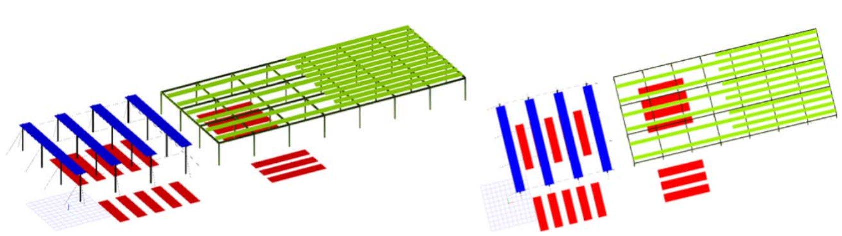

Fig. 2. Screenshots of the 3D agrivoltaic scene used to estimate the available radiation at ground level. Blue PVstrips are orientable while green ones are fixed. Red rectangles correspond to plots where irradiance was computed. The scene presented here only shows ST and HD. CT was modelled by removing 1 row strip to ST systems and positioning the structure to the east of HD. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Madelona boards in spring and summer experiments.

Fertilization was applied just before plantation. Nitrogen status was controlled with a chlorophyll meter (SPAD-502, Konica Minolta Inc., Japan) to verify that nitrogen was not limiting. Plants were irrigated with drip lines every 2 days to prevent soil water stress.

2.5. Plant measurements

Crop production was estimated as the mean dry weight of plants harvested in each plot (18 plants per board). In order to compare agrivoltaic systems, a unique harvest date was considered for all systems and corresponded to the commercial maturity stage of full-sun (FS) plants when their mean fresh weight reached 400 g [25].

On the day of harvest, plants were washed to remove soil particles, leaves longer than 1 cm were counted and disks were sampled from top leaves with a puncher. Plants and leaf disks were then weighed after oven drying for 72 h at 60 °C. Specific Leaf Area (SLA) was calculated on leaf disks as the surface area to dry mass ratio.

In order to determine projected leaf area, plants were photographed the day before harvest in the morning within a short time span (from 09:00 to 10:30 a.m.). Photographs were taken with a standard camera and analysed with ImageJ [26] in autumn, while Raspberry Pi cameras were used for the spring and summer experiments and images were analysed using a script developed in Python. A reference area was included in the images for calibration.

In order to determine changes in leaf morphology, six plants were sampled in ST and FS systems at the end of the spring experiment. For each plant, individual leaf length, width and dry mass were measured.

2.6. Performance of agrivoltaic systems

In order to assess the performance of the different agrivoltaic systems in terms of land surface requirements, Land Equivalent Ratio was computed as follows:

$$LER_{AV} = \left(\frac{\text{Dry mass}_{AV}}{\text{Dry mass}_{FS}}\right) + \left(\frac{\text{Electric production}_{AV}}{\text{Electric production}_{FD}}\right) \tag{1}$$

where index AV (agrivoltaic) refers to either of the studied agrivoltaic systems (HD, ST, or CT), FS refers to full-sun conditions considered as a control for the sole crop production and FD refers to stationary, full-density, considered as a reference for the original, stationary PV system being close to the optimum design for energy production [7]. Dry mass of plants at harvest was preferred to fresh weight as a measure of crop production due to variations in water content between plants depending on their shading conditions. Electric production was estimated over the whole crop growing cycle using the Sandia model[27,28] considering the similar solar efficiencies of PVPs in all agrivoltaic systems (15.2% of the incoming radiation is converted into electricity, considering a theoretical maximal performance of 303 W).

3. Results

3.1. Climate in full-sun conditions

Three experiments were carried out under the agrivoltaic systems in 2014 and 2015, in different seasons: in the spring, summer and autumn (Table 1). Radiation largely varied across experiments, peaking at June Solstice, when the sun reached its highest position in the sky. Compared to the spring and summer experiments, mean daily radiation was reduced to less than half during the autumn experiment, with cloudier days and a lower elevation of the sun. Average air temperature was logically higher during the summer experiment (23.7 °C) compared to spring (17.8 °C) and autumn (15.5 °C) with large variations in mean daily temperatures between days (about 10 °C between max and min) within each experiment. Evaporative conditions as characterised by VPD also varied across seasons, with a lower mean value during the experiment in autumn (0.46 kPa), a medium value in the spring (0.97 kPa) and a higher value in summer (1.50 kPa).

Shading by PVPs was studied in these contrasted climates, with different values for the diffuse index depending on the relative frequencies of cloudy vs. sunny days. A higher percentage of cloudy days in autumn than in the spring and summer resulted in a higher diffuse index.

3.2. Plant microclimate in the different agrivoltaic systems

3.2.1. Radiation at plant level

Fig. 3 presents the transmission level of photosynthetic photon flux density (PPFD) radiation of the different agrivoltaic systems relative to FS conditions for the three contrasted seasons of experiment.

As could be expected, the mean daily transmission of radiation was substantially reduced, below 100% with respect to FS, under all PVP systems though with differences between systems and slight variations across the seasons. Controlled tracking (CT) resulted in a substantially higher fraction of transmitted radiation by about 30% compared to ST and by about 40% compared to stationary HD system whatever the season. Surprisingly, in spite of similar design, slight differences were observed between stationary HD system and trackers in ST mode with about 8% more radiation transmitted by the latter in the spring and summer experiments and up to 23% in autumn. The stronger difference between ST and HD observed in autumn compared to other seasons was the combined result of an increase in light transmission in ST associated with a decrease in HD. This was mostly associated with a larger proportion of cloudy days at this time of year (corresponding to the highest diffuse index in Table 1).

Fig. 4 confirmed that the fraction of transmitted light by the different agrivoltaic systems largely depended on the percentage of diffuse radiation on each day with typical examples for a very cloudy day (diffuse index of 0.97) and a sunny day (diffuse index of 0.31). During cloudy days, radiation under PVPs was only slightly reduced regardless of the agrivoltaic system due to the predominance of diffuse radiation (Fig. 4). In comparison, during sunny days, radiation was affected by shading by orientable PVPs for a short period (during 20 min to 1 h) three to four times a day according to the number of PVP strips above in each system (Fig. 1). During these shading periods, direct radiation was

Table 1
Experimental climate conditions encountered during autumn 2014, spring and summer 2015. *Degree days were computed using a base temperature of 3.5 °C. Average daily values were compared to obtain minimum and maximum values for each season and variable.*

Season	Planting date	Duration (days)	Degrees-days	Radiation (mol m^{-2})			Air temperature (°C)			Air VPD (kPa)			Diffuse index
				Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	
Spring	2015-04-16	46	712	6.82	43.06	57.88	12.52	17.76	22.54	0.19	0.97	1.67	0.44
Summer	2015-07-21	37	786	9.17	46.17	57.27	20.03	23.66	29.37	0.38	1.50	2.71	0.33
Autumn	2014-09-25	53	669	2.10	19.11	32.56	8.16	15.50	21.98	0.21	0.46	1.13	0.51

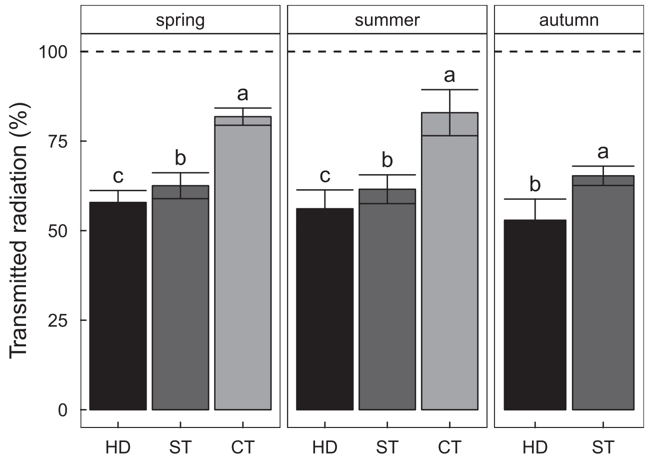

Fig. 3. Percentage of daily radiation transmitted by the three agrivoltaic structures (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking) during the whole duration of experiments. Black dashed line represents the percentage of transmitted radiation in full-sun (FS). Transmitted radiation was computed as the mean over the whole plot. Error bars represent the standard deviation between days during each experiment. Multiple comparisons were performed with ANOVA or Kruskal-Wallis analysis when ANOVA assumptions were rejected. Different letters indicate significant differences between treatments (P = 0.05).

mainly intercepted by PVPs, leaving only diffuse radiation as a light source for the crop.

Daily patterns of transmitted radiation were really different between the three agrivoltaic systems firstly due to the orientation of jointed PVPs strips. East to west strips of stationary PVPs generated a stable, spatial pattern at ground level with either sunlit or shaded rows for most of the day depending on the row position relative to the panel strips above (being parallel to rows in our experiments). As a consequence, a high spatial heterogeneity of transmitted radiation at plant level was observed in HD mode which was conserved over a whole day (Fig. 5). By contrast, the north-south direction of orientable PVP strips created a temporal alternation of shading periods with periods of full-sun exposure whatever the location at ground level. The spatial heterogeneity of transmitted radiation over a whole day was therefore largely attenuated in ST and CT modes (Fig. 5).

3.2.2. Leaf temperature

Leaf temperature was directly dependent on incident light, causing large differences between shaded and sunlit leaves (Fig. 6). On cloudy days, with a large proportion of diffuse radiation, differences in leaf temperature between shaded and sunlit plants were negligible whatever the shading conditions in the different agrivoltaic systems. Differences in leaf temperature between systems were also negligible at the beginning and the end of the day when the sun hit the plants directly with a low incidence angle. On the contrary, on sunny days, when direct radiation was predominant, the daily pattern of leaf temperature was highly affected by the differences between the agrivoltaic systems. As previously mentioned for transmitted radiation, orientable panels induced alternations for each plant in direct light and shade periods, making leaf temperature rapidly oscillate above and below values observed in FS conditions (Fig. 6). The rapid increase in radiation on sunny days after a shade period in agrivoltaic systems with orientable panels (ST and CT) led to an increase in leaf temperature, sometimes outreaching values of control (FS) plants by 1–2 °C for a few minutes before a resumption of leaf temperature to control values. In HD systems, depending on plant positions relative to panels, leaf temperatures could be simultaneously higher and lower than the temperature of control plants in full-sun conditions. Leaf temperature in ST mode fluctuated according to light status, but never outreached the leaf temperature of FS plants, potentially due to a short length of time between 2 shade periods in comparison with CT and HD, limiting leaf temperature increase. In CT mode, there was a compensation between periods of shading, when leaf temperature was lower for shaded plants in agrivoltaic systems than for plants in FS conditions (by up to 2 °C on bright sunny days), and periods of direct light when, less expectedly, the reverse was observed.

In spite of the large instantaneous effect of PVPs on leaf temperature, the impact of shading conditions was much lower when averaged over whole plots over a whole day. When averaged on a 24 h time scale, mean leaf temperatures were very similar during cloudy days while only slight differences were observed during sunny days. As an example on 2015-05-29 (sunny day), the daily average leaf temperature (8 thermocouples) of the different entire boards were 18.3 °C (HD), 18.4 °C (ST) and 18.9 °C (CT and FS).

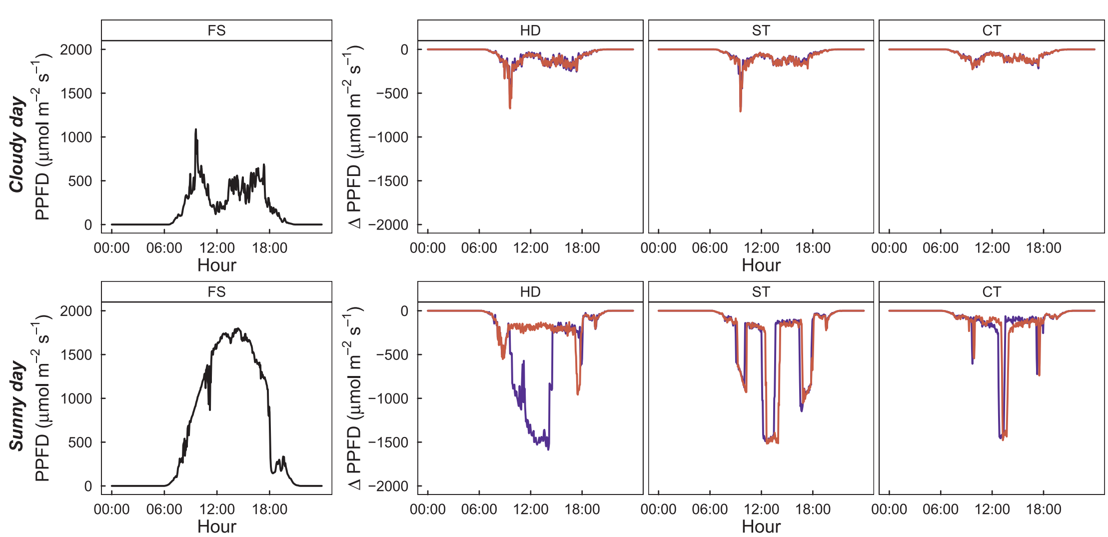

Fig. 4. Daily patterns of photosynthetic photon flux density (PPFD) in full-sun (FS) conditions during a cloudy (upper left) and a sunny day (lower left) and reductions in transmitted PPFD (ΔPPFD, zero being absence of shading by the panels) at plant level in three agrivoltaic systems (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking) during the same cloudy (upper 3 right panels) and sunny day (lower 3 right panels). Radiation in agrivoltaic systems was estimated for two vertical row positions directly below the panel strips for each agrivoltaic system. Blue lines correspond to northern (HD) or eastern (ST and CT) rows (row 1 or 2) while red lines correspond to southern or western rows (respectively row 3 or 4). Cloudy day: 2015-05-03, sunny day: 2015-05-29. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

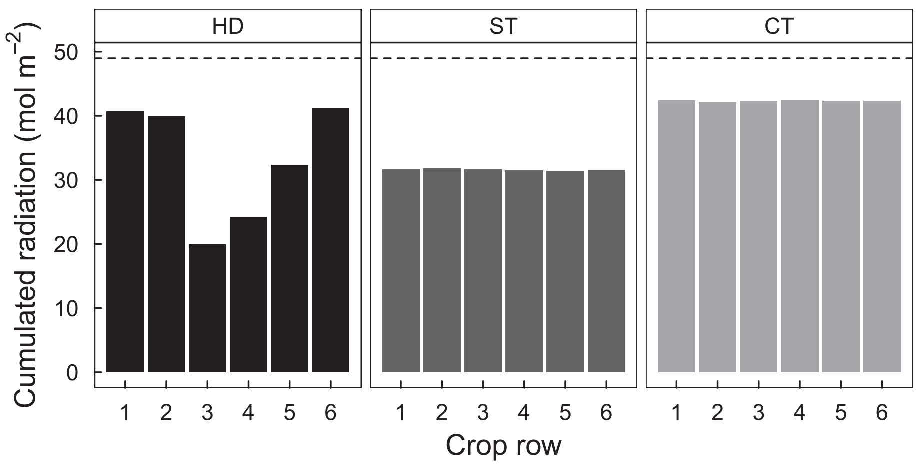

Fig. 5. Cumulated PPFD for a typical sunny day (2015-05-29) as estimated with the MIR MUSC RADBAL model at plant level for each row in agrivoltaic plots. The black dashed line is the cumulated radiation measured in full sun (FS). Photovoltaic panels were joined in strips orientated north-south for trackers (ST and CT) and east-west for stationary systems (HD). Crop rows were planted parallel to the above PVP strips and are numbered from south to north (HD) or west to east (ST and CT) depending on their position relative to the closest PVP strip (the vertical of PVP strips being between rows 3 and 4).

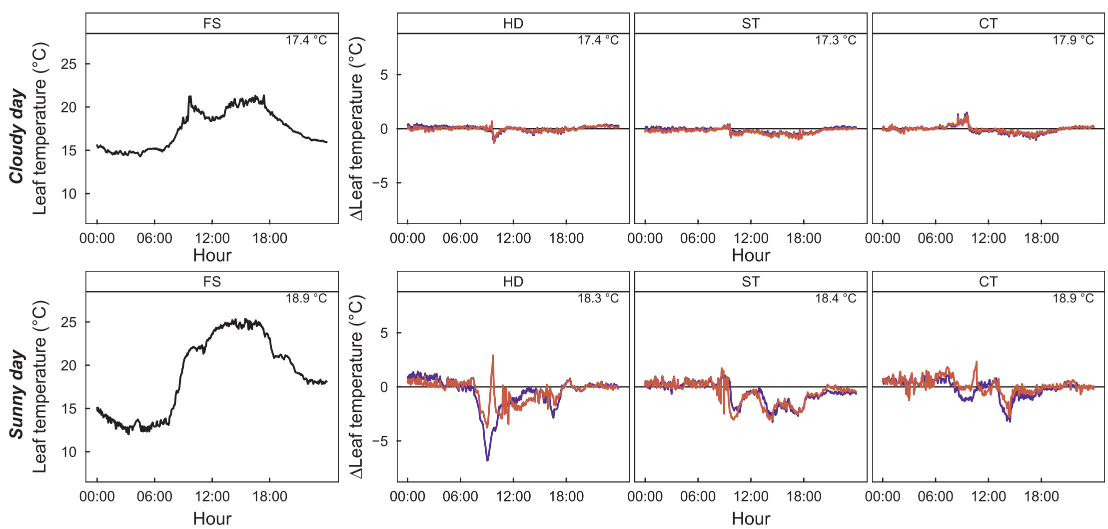

Fig. 6. Daily patterns of leaf temperature in full-sun (FS) conditions during a cloudy (upper left) and a sunny day (lower left) and changes in leaf temperature of plants in the different agrivoltaic systems (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking) during the same cloudy (upper 3 right panels) and sunny day (lower 3 right panels). Leaf temperature was determined on at least 2 mature leaves of lettuces located on two vertical row positions directly below the panel strips for each agrivoltaic system. Blue lines correspond to northern (HD) or eastern (ST and CT) rows (row 1 or 2) while red lines correspond to southern or western rows (respectively row 3 or 4). Temperatures in the upper right corner are the daily average leaf temperatures of the considered rows for each condition. Cloudy day: 2015-05-03/ sunny day: 2015–05-29. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.3. Crop measurements

3.3.1. Plant dry mass

Plant dry mass was directly affected by the microclimate changes induced by the different agrivoltaic systems, with a seasonal effect (Fig. 7). Overall, compared to FS conditions, dry mass was reduced in relation to the decrease in transmitted radiation for all agrivoltaic systems and all seasons, excepting in autumn with the Kiribati oak leaf variety (Fig. 7). Madelona was more sensitive to limitation in transmitted radiation than Kiribati and reductions in dry mass in agrivoltaic systems were more important in the spring and summer than in autumn. In autumn, this reduction in dry mass compared to FS conditions was limited to 18% in HD and ST modes for Madelona and no significant differences were noted for Kiribati. Interestingly, for about 10% more transmitted radiation in ST compared to HD system, the biomass production of Madelona was 13–15% higher in ST than in HD in the spring and summer. CT further increased biomass compared to ST mode in the spring for the two varieties (Fig. 7), logically resulting from higher transmitted radiation in CT than in ST (Fig. 3). However, the difference in biomass production between the two modes was not significant in summer although transmitted radiation remained higher for CT.

To analyse whether differences in crop productivity between agrivoltaic systems were due to differences in transmitted radiation, plant dry mass at harvest was divided by the transmitted radiation cumulated over the whole growth period (Fig. 8). This ratio indicates to what extent the fraction of radiation which was not used for energy production was converted into biomass and benefited crop growth.

Overall, the less radiation was transmitted according to the agrivoltaic system, the better it was converted into biomass except in the spring with Madelona (Fig. 8). With the highest fraction of transmitted light, the CT system showed no difference in biomass produced per unit light transmitted compared to FS conditions for both summer and spring experiments and both varieties. By contrast, with less transmitted radiation, HD and ST systems resulted in more biomass produced per unit radiation transmitted. Interestingly, an even higher conversion ratio was observed under HD and ST modes in autumn when absolute radiation level was at its lowest. This indicates that the less radiation was transmitted at plant level, the more plants experienced physiological changes to acclimate to the different shading conditions induced by the agrivoltaic systems.

3.3.2. Leaf number and projected leaf area

In most experiments for both varieties, the number of leaves (longer

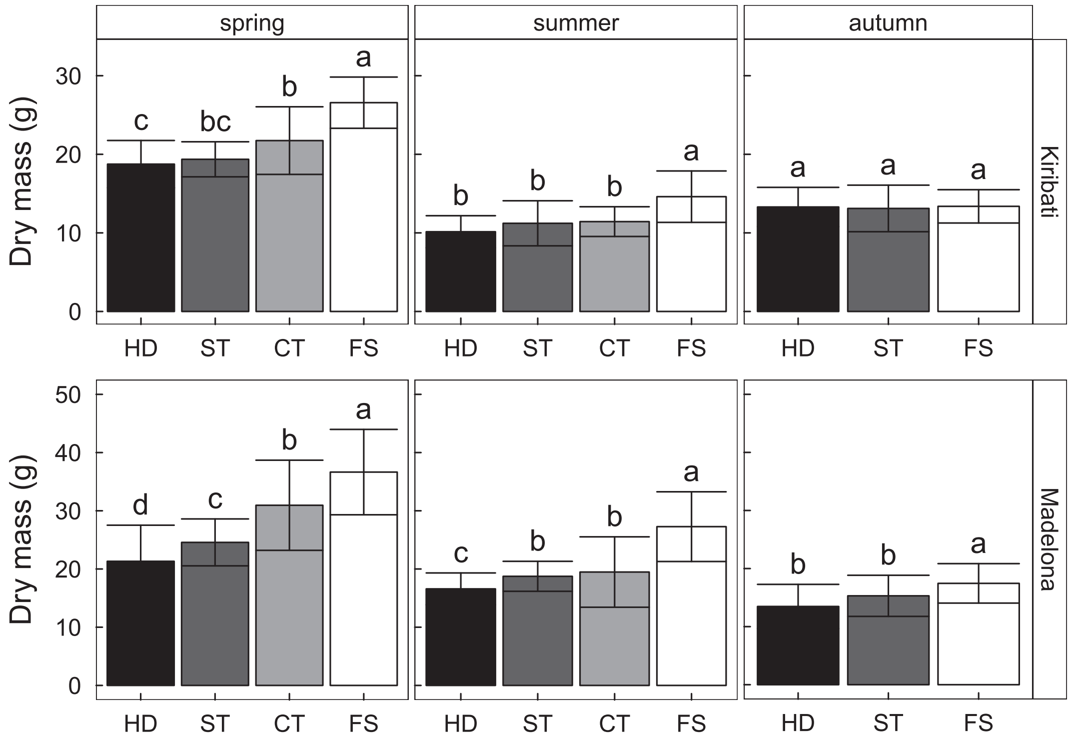

Fig. 7. Plant dry mass at harvest of lettuce crop in the different agrivoltaic systems (HD: half density stationary panels; ST: regular solar tracking; CT: controlled tracking). Two varieties were compared in the spring, summer and autumn: Madelona as a Cos lettuce and Kiribati as an oak leaf lettuce. Error bar: standard deviation for plants grown under the agrivoltaic system (n > 16 plants). Multiple comparisons were performed with ANOVA or Kruskal-Wallis analysis when ANOVA assumptions were rejected. Different letters indicate significant differences between treatments (P = 0.05).

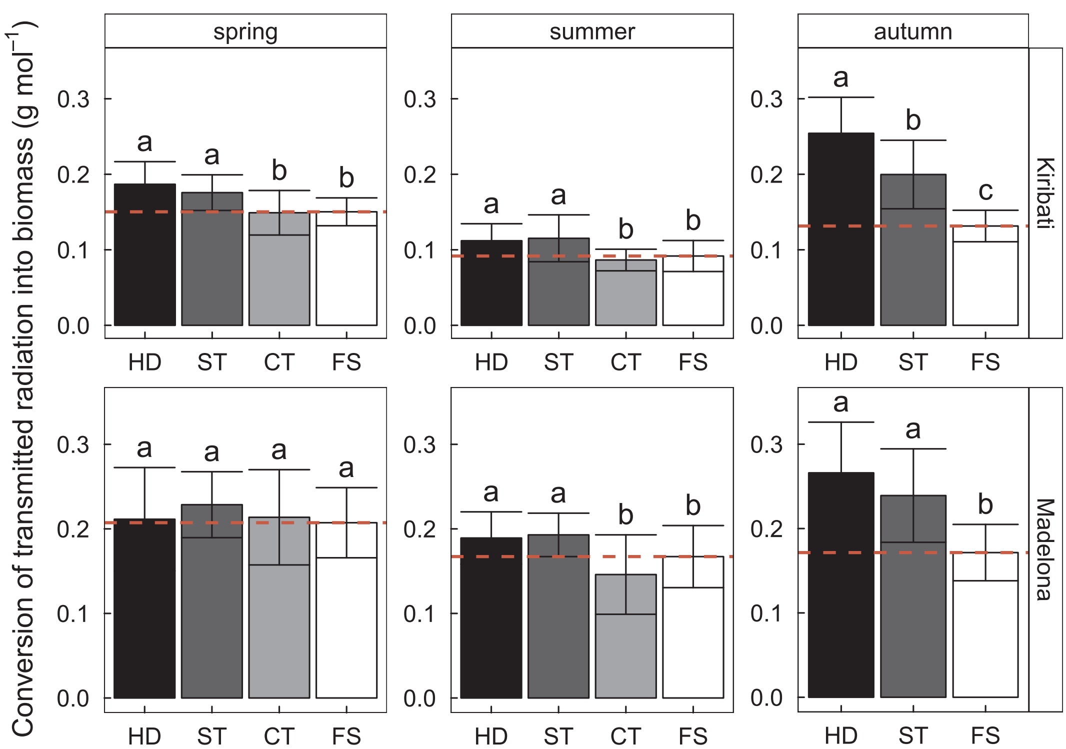

Fig. 8. Conversion of transmitted radiation into biomass for two varieties of lettuce (Kiribati and Madelona) grown in full-sun conditions (FS) or in different agrivoltaic systems (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking). Conversion of radiation was computed as the ratio of mean plant biomass (min 16 plants) at harvest to cumulated incident radiation at plant level from planting date to harvest. Multiple comparisons were performed with ANOVA or Kruskal-Wallis analysis when ANOVA assumptions were rejected. Different letters indicate significant differences between treatments (P = 0.05). Red dashed lines represent the conversion of transmitted radiation into biomass obtained in FS as a reference. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Projected leaf area, number of leaves and specific leaf area of lettuce plants grown in full-sun (FS) conditions or different agrivoltaic systems (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking). Only leaves longer than 1 cm were taken into account. Means were calculated with at least 18 plants per system for leaf area, 30 plants for leaf number and 27 plants for specific leaf area. Comparisons with full-sun (FS) were performed with ANOVA or Kruskal-Wallis analysis when ANOVA assumptions were rejected. ·, *,**,*** statistically significant from FS at 10, 5, 1 and 0.1% levels.

Variety	Season	Light treatment	Plant degrees-days (°Cj)	Plant projected area (cm^2 $plant^{-1}$)		Leaf number		Specific leaf area (cm^2 g^{-1})	
Kiribati									
	Spring								
		Full-Sun	*ND*	813	±194	*ND*		634	±72
		Half-Density	*ND*	704 (·)	±235	*ND*		781 $^{(***)}$	±96
		Solar Tracking	*ND*	1048 $^{(***)}$	±87	*ND*		738 $^{(***)}$	±92
		Controlled Tracking	*ND*	731$^{(**)}$	±160	*ND*		662 (*ns*)	±29
	Summer								
		Full-Sun	*ND*	785	±171	*ND*		890	±106
		Half-Density	*ND*	*ND*		*ND*		1026$^{(*)}$	±142
		Solar Tracking	*ND*	809 (*ns*)	±166	*ND*		1091 $^{(***)}$	±127
		Controlled Tracking	*ND*	702$^{(**)}$	±163	*ND*		1048$^{(**)}$	±169
	Autumn								
		Full-Sun	*ND*	851	±174	59.0	±4.2	710	±105
		Half-Density	*ND*	903 (*ns*)	±172	51.1 $^{(***)}$	±3.9	852 $^{(***)}$	±72
		Solar Tracking	*ND*	879 (*ns*)	±185	51.1 $^{(***)}$	±5.6	670 $^{(*)}$	±79
Madelona									
	Spring								
		Full-Sun	669	1331	±425	97.4	±14.2	353	±54
		Half-Density	653	1293 (*ns*)	±432	81.9 $^{(***)}$	±7.1	449 $^{(***)}$	±56
		Solar Tracking	649	1378 (*ns*)	±189	82.3 $^{(***)}$	±5.7	424 $^{(***)}$	±61
		Controlled Tracking	670	1048$^{(**)}$	±382	89.9 (·)	±7.5	369 (*ns*)	±30
	Summer								
		Full-Sun	742	1096	±194	111.9	±9.2	430	±51
		Half-Density	733	*ND*		84.5 $^{(***)}$	±7.4	627 $^{(***)}$	±58
		Solar Tracking	731	1250 $^{(***)}$	±187	91.2 $^{(***)}$	±13.1	453 $^{(*)}$	±31
		Controlled Tracking	770	1063 (*ns*)	±280	84.0 $^{(***)}$	±13.1	481 $^{(***)}$	±52
	Autumn								
		Full-Sun	*ND*	1088	±274	62.0	±5.4	445	±37
		Half-Density	*ND*	984 (·)	±326	50.1 $^{(***)}$	±5.2	502 $^{(***)}$	±53
		Solar Tracking	*ND*	940 (·)	±274	52.3 $^{(***)}$	±4.9	462 $^{(*)}$	±48

than 1 cm) per plant was significantly reduced by the shading conditions in all agrivoltaic systems compared to FS conditions (Table 2). To analyse whether these differences in leaf number resulted from differences in plant temperature driving organogenesis, growing degree-days were cumulated using a base temperature of 3.5 °C in the spring and summer for the Madelona variety and each agrivoltaic system. The slight differences in leaf temperatures across agrivoltaic systems, as reported above, only had a mild impact on cumulated degree-days which could not explain the much larger differences in leaf number. The consequences of leaf number on plant leaf area were not straightforward as contrasted effects of the different agrivoltaic systems were observed on the projected leaf area per plant (Table 2). Stationary panels (HD) hardly modified plant leaf area compared to full-sun conditions. By contrast, trackers in regular, solar tracking mode (ST) induced a substantial increase in plant leaf area in the spring and summer for both varieties while their effect was weaker and less clear in autumn. On the contrary, controlled tracking (CT) reduced the plant leaf area in most cases (by 3–21%).

3.3.3. *Specific leaf area and leaf dimensions*

Specific leaf area (SLA) increased in most cases for plants grown in agrivoltaic systems compared to full-sun conditions (Table 2). However, this typical acclimation to shade conditions, corresponding to thinner leaves which were more expanded per unit biomass, was weaker in autumn and spring than in summer. Specifically, for each variety, SLA hardly changed in the spring for CT and in autumn for ST. Interestingly, for these same conditions, plant biomass at harvest was also maintained or slightly reduced. Overall, SLA correlated fairly well with harvested biomass for Madelona ($R^2 = 0.9$) while the relation was weaker for Kiribati ($R^2 = 0.27$).

To further understand the morphological responses of plants to shading, we studied the shape of leaves for plants grown in solar tracking and full-sun conditions during the spring (Fig. 9).

As mentioned above (Table 2), the reduction in leaf number per plant in ST compared to FS conditions was confirmed in this detailed study on leaf morphology (Fig. 9) with 119 (±8) leaves per plant in ST versus 142 leaves in FS (±17) on average. Overall, patterns of leaf dimensions versus leaf rank (from crown basis) showed peaks of maximal leaf length and width around rank 45, except for leaf length of FS plants with a peak at rank 60. Leaf dimensions sharply declined for the last emitted ranks. The decline in leaf dimensions was noticed with a shift of 10 ranks towards early emitted leaves for plants grown in ST compared to FS conditions, consistent with the lower, total leaf number per plant. As a result, leaves which were emitted between ranks 30 and 50 were significantly longer (+15%) and slightly narrower in plants grown in ST compared to FS (ANOVA, $P = 0.05$). By contrast, from rank 70 to the last emitted ones, leaves were shorter but still narrower in plants grown in ST compared to FS.

The dry mass of individual leaves was lower for shaded plants grown in ST conditions than for plants grown in FS. The patterns of leaf dry mass as a function of leaf rank followed the same bell shape as leaf dimensions in both conditions, still with a peak around ranks 40–45.

3.4. *Electricity production by the PV panels*

3.4.1. *PV production with contrasted cloud coverage*

Photovoltaic production was estimated for the three agrivoltaic systems and exemplified for typical cloudy and sunny days (Fig. 10). As expected, electricity production was 2.7 and 4.8 times higher on sunny days than on cloudy days for CT and ST conditions respectively. On sunny days, ST mode, where PVPs mostly faced the sun throughout the day, highly increased the total energy production per unit land area (+74%) compared to stationary systems (HD) while slightly increasing the transmitted radiation (about 10%) available to the crop. The CT

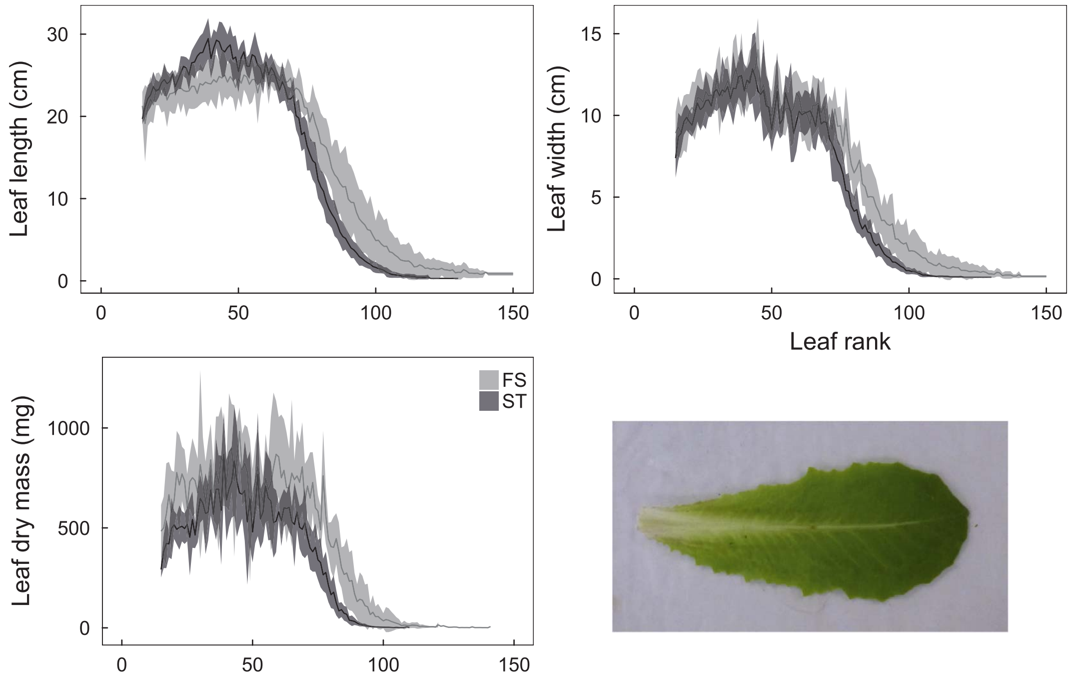

Fig. 9. Length, width and dry mass of all leaves from 6 plants (Madelona) sampled at final harvest in full sun (FS) or solar tracking (ST) conditions. Lines represent the mean and ribbons the standard deviation estimated from measurements on 6 plants for each leaf rank higher than rank 15. Black ribbons correspond to shaded plants (ST) while grey ones are from FS plants. The photograph shows the common leaf shape observed.

mode largely decreased electric production yielding even less energy than HD (−23%) due to the erasing of the PVPs from solar radiation in the morning and the afternoon.

Even on cloudy days with diffuse conditions, orientable PVPs maintained an advantage over stationary ones (Fig. 10). Electric production in ST exceeded that in HD by 51%. More surprisingly, electric production was also higher for CT than HD system on cloudy days, contrary to what was obtained on sunny days.

3.4.2. PV production in the 3 seasons

Electricity production per land area unit was estimated for all agrivoltaic systems in the three experimental seasons over the whole duration of plant growth taking into account radiation conditions for each day (Fig. 11). Differences in electric production between the three seasons were due to a much lower cumulated radiation in autumn (less than half the radiation of the spring and summer experiments) and to differences in the duration of the growth cycle between the spring (46 d) and summer (37 d) experiments which cumulated similar radiation (Table 1).

Compared to the stationary HD system, ST increased total electricity production whatever the seasonspring and summer (Fig. 11). The lower benefit of trackers in autumn was consistent with a high number of cloudy days as indicated by the higher mean diffuse index for this season (Table 1).

In the CT system, due to periods of PVPerasing with respect to sun radiation, total electricity production was reduced compared to ST and even to HD, although to a lesser extent. This deficit in production for the CT system compared to HD was slightly more detrimental in the spring (−14%) than in summer (−12%), probably due to differences in cloudy conditions between seasons.

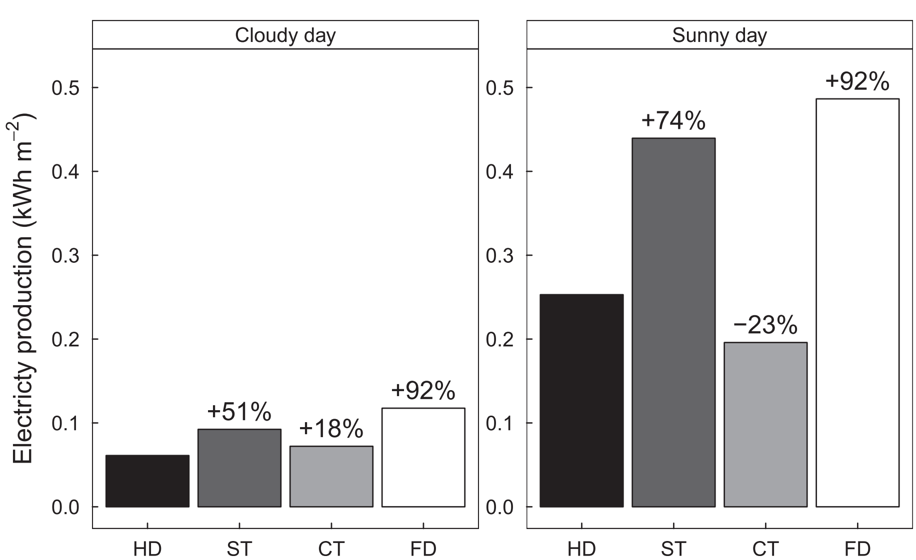

Fig. 10. Estimated photovoltaic production on a cloudy (left) and sunny (right) day for the different agrivoltaic systems. (HD: half density stationary panels; ST: regular solar tracking; CT: controlled tracking; FD: full-density). Percentages above histogram bars are related to HD production for each day. Cloudy day: 2015-05-03/ sunny day: 2015-05-27.

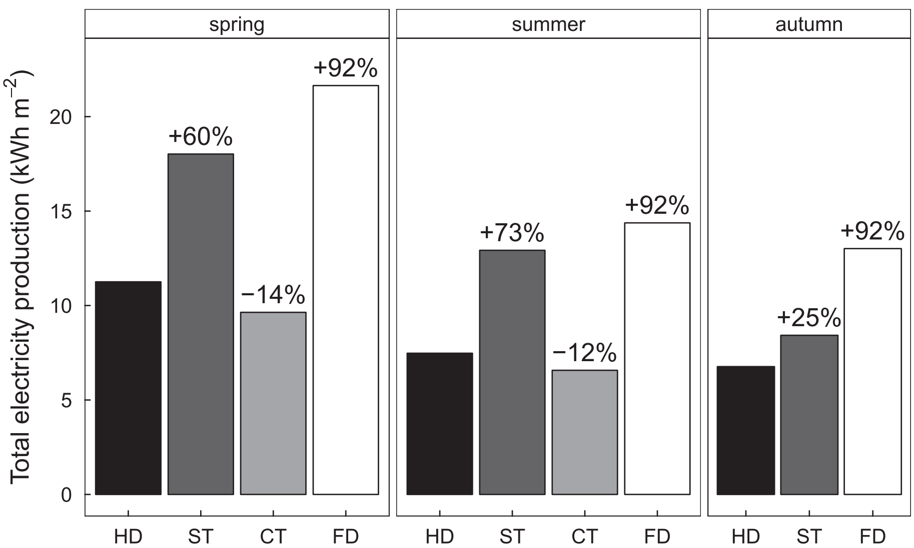

Fig. 11. Total photovoltaic production estimated for each agrivoltaic system over the whole cycle of lettuce growth over three seasons of experiment (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking; FD: full-density). Percentage changes above histogram bars are related to HD production.

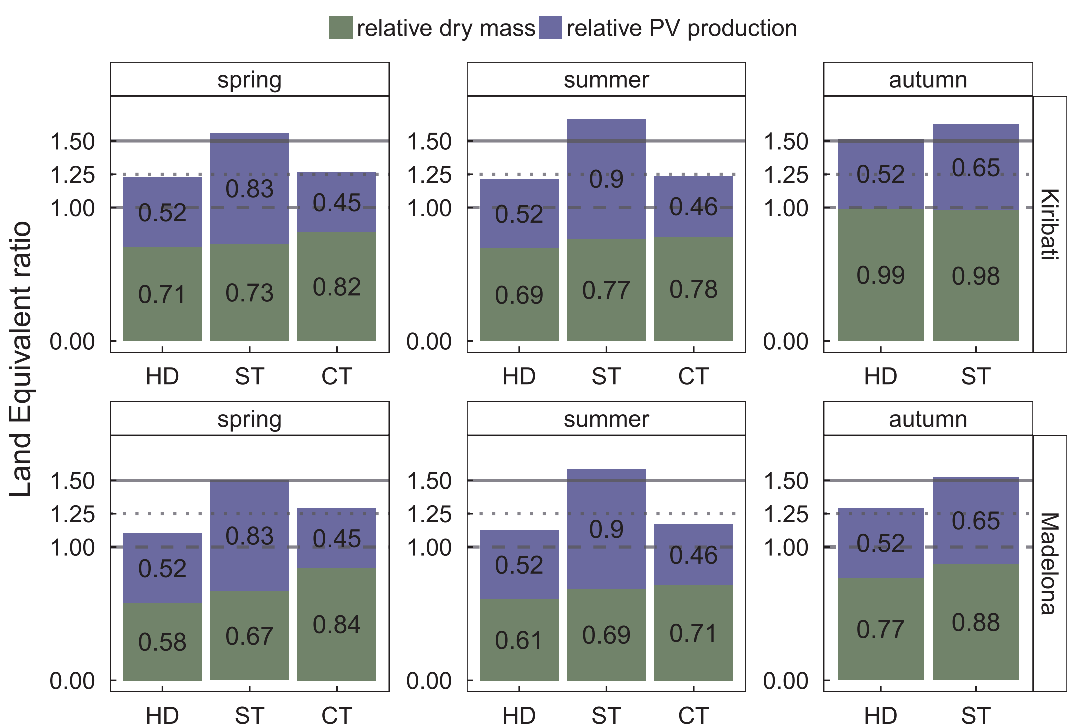

Fig. 12. Land Equivalent Ratio of each agrivoltaic system for two lettuce varieties (Kiribati and Madelona) and three seasons of experiment (HD: half-density stationary panels; ST: regular solar tracking; CT: controlled tracking). Relative biomass productivity (green histogram bars and figures inside) was computed as the ratio of mean dry mass measured in agrivoltaic systes to that measured in full-sun conditions. Relative electric productivity (blue histogram bars and figures inside) was computed as the ratio of production in agrivoltaic system relative to that determined for the Full Density PV systems, computed as 1/0.52 of the production of HD [7]. Relative productivities were added to obtain LER. Dashed, dotted and solid lines represent LER values of 1, 1.25 and 1.5 respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.5. Land equivalent ratio

Land Equivalent Ratio (LER) for each agrivoltaic system, was computed according to Eq. (1) which gives the relative area required to produce the same amount of biomass and electricity with separated productions on different land surfaces when associated in agrivoltaic system (Fig. 12).

Interestingly, LER values always exceeded 1, regardless of the variety, the season and the agrivoltaic system. LER values above 1 denoted systems where the association of crops and PVPs were more efficient for land use than separateproductions. For example a LER of 1.5 (Madelona with ST during spring experiment) means that separating crop and electricity productions might use 1.5 times more space than combining both productions on the same land.

The highest LER values were achieved with ST, outreaching 1.5 for the 3 seasons and the 2 varieties. This was mainly due to the highest values of PV production obtained with this system, ranging from 65% to 90% relative to the reference production of the full-density (FD) system. In the spring and summer, biomass production in ST was not as high as with controlled tracking (CT) but was maintained at 67–77% of the reference biomass observed in full-sun conditions. Overall, ST systems resulted in the highest global land productivity with the highest combined productions of electricity and biomass. The controlled tracking (CT) system presented the highest biomass for the spring and summer, but at the expense of a large reduction in electricity production compared to ST due to the erasing of the PVPs during a large part of the day.

As a result, LER was lower for CT than ST systems, notably in summer when solar radiation was maximal.

Both tracking modes, whether controlled or not, resulted in higher LER than the stationary HD system even though differences in the radiation level transmitted at plant level were slight between ST and HD systems. The gain in LER obtained with the ST system compared to stationary HD panels was not only due to an increase in relative electric production but also to a slightly higher biomass production, possibly due to higher transmitted radiation. Although the CT system also resulted during a small gain in LER compared to HD in the two tested seasons, this was mostly due to a substantial increase in relative productivity of the crop while relative electric productivity was reduced, by contrast with the ST mode.

An interesting result was obtained in autumn with high biomass production, resulting in quite high LER values ranging from 1.25 to 1.50 in spite of limited, relative PV productivity not exceeding 65% of the reference production of the FD system. During this season characterized by the lowest radiation, the productivity of the crop in agrivoltaic systems relative to full-sun conditions was maintained above 77% for Madelona and reached up to 99% for the Kiribati oak leaf variety.

4. Discussion

4.1. Efficiency of agrivoltaic systems in relation to crop acclimation in the partial shade of PVPs

All the agrivoltaic systems that were tested in this study with lettuce crops confirmed their efficiency as regards radiation use efficiency per unit land area. In all cases, LER exceeded 1, indicating that, more land area would be required with separated productions than with their association in agrivoltaic systems to produce the same amount of electricity and biomass. By comparison with previously developed systems equipped with stationary panels [7], solar trackers further increased LER for the two tracking modes that were tested in this study. Not surprisingly, the best performances in terms of land use were observed with regular solar tracking in summer and were primarily due to higher electric production. More interestingly, all agrivoltaic systems, although with low radiation available for plants, also resulted in the maintenance of rather high biomass production relative to full-sun conditions. Even the regular tracking (ST) and the reference HD system yielded relatively high biomass. This indicated that plants acclimated to the shading conditions in agrivoltaic systems by increasing their use of transmitted radiation to produce biomass. Interestingly, a slight increase (by 10%) in transmitted radiation in ST compared to HD had a straightforward and even slightly better effect on plant dry mass which increased by 13–15%.

An increase in the conversion of transmitted radiation by plants grown in agrivoltaic systems was mostly noted in autumn, when global radiation was mainly diffuse and at its lowest level, with a stronger acclimation for the Kiribati oak leaf variety and most probably contributed to this acclimation to shading conditions. Compared to full-sun conditions, plants grown in agrivoltaic systems exhibited thinner (with higher SLA), longer and narrower leaves resulting in the maintenance of plant leaf area close to or even higher than the area of plants grown in full-sun conditions. This favoured light interception by those plants which were partially shaded by PVPs thereby compensating for the deficit in transmitted light in agrivoltaic systems. The Kiribati variety performed better than Madelona in agrivoltaic systems compared to full sun conditions in all seasons.

Light transmission and conversion through agrivoltaic systems were dependent on the season and cloudiness of the sky. The stationary elevation of panels in HD (25°elevation from the horizontal, facing south) was less favourable for light transmission in autumn when the solar elevation angle was lower. This was not the case for orientable panels (CT and ST) which were installed so as to be horizontal when the sun was at its zenith. By contrast, the higher transmission under ST in autumn was likely due to a larger proportion of cloudy days at this time of year which limited the shading effect of PVPs. The better performance of PVPs in CT system than in HD system on cloudy days, when radiation was isotropically distributed, was likely due to a better exposure of PVPs in CT mode to the sky hemisphere. Despite similarities in light transmission with HD and flat oriented panels on ST, solar tracking controlling provided a double benefit in relation to HD: it transmitted more radiation at crop level at crop cycle scale while producing substantially higher amounts of electricity.

Beyond the overall reduction in transmitted light, agrivoltaic systems also introduced specific, daily fluctuations in radiation and temperature at plant level. These modifications of the plant microclimate were directly related to the spatial arrangement of the agrivoltaic system in strips of joined panels with the strip axis oriented west to east in HD system and south to north in ST and CT systems. Thus, all the plants in tracking systems underwent an alternation of light and shade bands several times a day whatever their position, while previous, stationary system split the land surface into nearly stable shaded and sunlit areas on a given day. In comparison with plants grown outside the agrivoltaic systems, lower leaf temperatures were observed as expected when plants were in the shade of PVP strips, whereas not awaited, higher values were observed when plants intercepted radiation between bands of shade from PVP strips. This was mainly due to transient peaks of leaf temperature following the rapid increase in radiation after a shade period. This possibly resulted from delays in stomatal reopening upon an abrupt rise in radiation which likely limited leaf evaporation cooling during this period. Supporting this interpretation, delays of 10–60 min were reported for stomata to fully reopen following a transition from shade to sun [29]. In spite of these differences in leaf temperature dynamics and distributions, cumulated leaf degree-days remained similar between plants in agrivoltaic systems and in full-sun conditions, due to compensations between plants in shaded and non-shaded areas in HD and between periods of higher and lower temperatures in other systems. The slight differences in cumulated degree-days observed between these different systems were unlikely to account for differences in plant biomass.

A secondary objective of this study was to test for a possible gain in plant growth when using trackers to shade plants during midday periods of high temperature and high evaporative demand. This period is known to impair leaf growth due to hydraulic limitation [30]. Controlled tracking (CT) was expected to favour growth by alleviating these periods for part of the plants as for ST but also, contrary to ST, by increasing daily radiation transmitted to the plant as a result of moving PVPs parallel to direct sun radiation in the morning and evening. As expected, higher biomass was obtained for CT than ST but this increase was most likely due to the higher radiation at plant level in CT since the conversion of transmitted radiation into biomass remained similar or even higher in ST compared to CT. Importantly, lettuce crop was irrigated in our study and the conclusions on the possible gain with CT compared to ST should be re-examined under conditions of soil water deficit.

4.2. Further considerations to keep on optimizing agrivoltaic systems

The controlled tracking (CT) mode was conceived to reduce the impact of PVPs on the crop by increasing available radiation at plant level. Not surprisingly, CT mode, corresponding to limited periods of solar tracking around midday, also resulted in less electric production than regular, solar tracking (ST) throughout the day. The increase in dry mass provided by CT compared to the ST mode was limited to the gain in transmitted radiation at plant level and was largely counterbalanced by a large decrease in photovoltaic production. As a consequence, the LERs of CT systems were less than 1.25, much lower than ST. The ST system was clearly the most interesting one when looking at the global productivity of the land. However, the CT mode allowed for maintenance of crop yield at levels close to that of control (FS) conditions (71% in the spring and 82% in summer) which may help solve food safety issues. Considering that the more shaded the plant was, the higher its use of transmitted radiation was, control laws of solar trackers could be optimized with longer periods of shading than the 4 h a day of regular tracking experimented in this work in the CT mode. These control laws might be overridden by instant control laws during rainfall events depending on the wind direction ensuring a homogeneous distribution of rainwater. By increasing the maximum tilt angle of PVPs (currently 50%), it would be possible to remove the water collected by the panels and easier homogenize the water supply at the crop level. However, this would be require new technical developments.

Agrivoltaic systems should also be compared in terms of gross margins. Currently, the mean price of one lettuce plant is 0.55 €, resulting in 4.4–7.7 € per square meter, with planting density ranging from 8 to 14 plant per m^2. PV production in agrivoltaic systems ranged from 6.5 to 18 kW h m^2 with an average 0.13 € purchasing price per kW h, resulting in 0.85–2.34 € per square meter. This simple comparison of purchasing prices, without taking into account any other expenses, shows that the crop yield represents a minimum of 65% of the total, economic production of the land, attesting an important role for agricultural production in agrivoltaic systems. Thus, in spite of its intermediate LER compared to regular tracking (ST), the CT mode which favours biomass production could represent a real economic gain when cultivating a crop with strong added-value.

In the future, our research program aims at providing optimized controlling laws depending on the physiological stage of the crop, the climate and the land status (free/occupied) to increase the total productivity of agrivoltaic systems even more over the whole year. We focused on the dry mass of plants harvested on the same date without discussing the shading effect in terms of growth delay. At least for crops with undetermined growth such as lettuce, a similar yield to control can be reached in agrivoltaic systems a few days later, increasing the period where the land is occupied by a crop. Recent progress in the photovoltaic industry could also improve agrivoltaic systems, with the development of semi-transparent modules [31,32] or bifacial solar panels [33]. Agrivoltaic systems aim at limiting the impacts of photovoltaic structure on standard farming processes such as planting and harvesting by raising PVPs at 4–5 m allowing the use of tractors. Experiments have been carried out with prototypes compatible with market garden crops. Other precautions should be taken for other crop systems that require specific practices or equipment (straddle tractors, aerial spraying).

Different species (lettuces, durum wheat, cucumber) were tested under fixed panels for various cropping seasons in a Mediterranean climate [18]. The different varieties tested responded differently to the same level of shade created by fixed panels. This study only focused on lettuce crops. The shade responses of different crops such as other vegetables, orchards and grapevine under dynamic systems should be studied in the future. Different results can be supposed for more complex crops such as crops which produce tubers like potatoes. Carbon allocation between shoot and root might be altered for shaded plants potentially impacting the size, number and weight of tubers. For crops sensitive to sunburn as apples and other fruit species, cullage could be avoided by shading plants during periods of high temperature and excess solar radiation [34]. The shade provided by PVPs could also be interesting in vineyards preventing increase in sugar (thus alcohol) content [35].

One of the concerns of agrivoltaic spread is soil artificialization, directly threatening arable land and thus food safety. Agrivoltaic systems were originally conceived to produce electricity as an added value, without weakening crop production. It is of the highest importance that these systems should avoid potential deviation such as the agricultural production shutdown in order to exclusively produce electricity. A suggested solution in Japan relies on the annual reporting of amounts of cultivation to ensure continuous farming, coupled with a low reduction of production amount (20%) after the PV installation.

Further investigations should help to find species and varieties adapted to these modified microclimates and to determine the best conditions for plant growth in terms of duration and timing of shading periods by moving PVPs.

5. Conclusions

This study showed that very high productivity per land area unit could be reached using dynamic instead of stationary photovoltaic panels in agrivoltaic systems while maintaining a biomass production of lettuce at levels close to or even similar to that in full-sun conditions. This was mainly due to the physiological acclimation of the plants to the transient shading conditions in agrivoltaic systems, resulting in a higher use efficiency of transmitted radiation by the crop. A controlled tracking mode was analysed which increased radiation transmitted at plant level and favoured crop growth but at the expense of electric production. We conclude that optimized controlled tracking scenarios can now be derived as a function of the gross margin of crop production in order to satisfy agricultural objectives while increasing land use efficiency with associated, photovoltaic production.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2017.09.113.

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