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Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes

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ABSTRACT

The need for new sources of renewable energies and the rising price of fossil fuels have induced the hope that agricultural crops may be a source of renewable energy for the future. We question in this paper the best strategies to convert solar radiation into both energy and food. The intrinsic efficiency of the photosynthetic process is quite low (around 3%) while commercially available monocristalline solar photovoltaic (PV) panels have an average yield of 15%. Therefore huge arrays of solar panels are now envisaged. Solar plants using PV panels will therefore compete with agriculture for land. In this paper, we suggest that a combination of solar panels and food crops on the same land unit may maximise the land use. We suggest to call this an agrivoltaic system. We used Land Equivalent Ratios to compare conventional options (separation of agriculture and energy harvesting) and two agrivoltaic systems with different densities of PV panels. We modelled the light transmission at the crop level by an array of solar panels and used a crop model to predict the productivity of the partially shaded crops. These preliminary results indicate that agrivoltaic systems may be very efficient: a 35–73% increase of global land productivity was predicted for the two densities of PV panels. Facilitation mechanisms similar to those evidenced in agroforestry systems may explain the advantage of such mixed systems. New solar plants may therefore combine electricity production with food production, especially in countries where cropping land is scarce. There is a need to validate the hypotheses included in our models and provide a proof of the concept by monitoring prototypes of agrivoltaic systems.

1. Introduction

Energy from biomass is claimed as being a possible substitute to fossil fuels for the future [1]. Biofuels are currently playing an increasing role in several countries such as Brazil or the USA. However, the land area that would be necessary for replacing fossil fuels with biofuels largely exceeds the cropland area of the planet. To move the 40 million cars of France only, about 40 million hectares of cereals (ethanol pathway) or oil crops (transesterification pathway) would be required, which is more than the actual cropped land area. Moreover, fuel markets of developed countries may compete with food markets of less developed countries and induce food shortages [2]. This was already observed in Mexico in 2008 when corn prices raised due to demand of the USA market for ethanol. Concerns over the impact of energy crops on the food availability are therefore shared worldwide [3]. Second generation energy crops will not change much the issue: although the yield of conversion from biomass to energy may be increased by 50% by new pathways of cracking the whole plant to energy, the needs for energy are so huge that the pressure on cropland will remain very high. Land constraints were not considered significant 10 years ago [4] because of the predicted surpluses in land and food in Europe, but the scene has changed since then [5].

Fossil fuels (petrol, gas, coal) are basically biofuels originating in the photosynthetic process, exactly as modern biofuels from biomass are. But fossil fuels result from the stockpiling of photosynthetic production for millions of years. The low efficiency of the photosynthetic process will not be able to cope with our current energy needs. The intrinsic efficiency of the photosynthetic process is quite low (around 3%) [6,7] and will remain the same with second generation energy crops.

Liquid biofuels target transportation needs. However, burning high quality molecules with a food value is questionable. With the best up to date technology, a hectare of cereals in Europe may allow a car to run for about 18000 km [8]. The transesterification pathway is more efficient (about 22 000 km). But the solar electricity pathway (solar panels producing electricity used to move electric cars) has an astonishing performance: about 3 250 000 km with

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a single hectare of solar panels on trackers, 147 times more than the transesterification pathway [8]. This is explained by the efficiency of solar panels combined with the efficiency of electric engines.

On the long term, it may therefore be questioned what the best option for producing energy from solar radiation is. Is it with liquid biofuels from cultivated crops or trees? Is it with electricity from solar photovoltaic (PV) plants? Commercial solar photovoltaic panels (PVPs) have today an average yield of 15% (monocrystalline PVPs, which are the most widely used). The latest releases in PVPs technology allow to reach 19% (monocrystalline with back contact modules, SunPower E19, SunPower, San Jose, California, USA). They are much more efficient for energy production than energy crops.

As we need both fuels and food, any optimisation of land use should consider the two types of products simultaneously. We intend here to compare two options for producing both fuels and food from a given land area:

1. Split the land area in two parts, one devoted to food production and the other to fuel production. This may be considered as the current dominant scheme of production separation [9].
2. Combine fuel and food production on the same land unit. We will explore this option in the case of mixing solar panels and food crops, as already suggested by [10]. Surprisingly, the idea of mixing solar panels and food crops was never explored since this premonitory paper. Some authors have explored the possibility to mix food and fuel production on the same land area by mixing crops for food and trees for fuel [11–13].

In this paper, we suggest to adopt the Land Equivalent Ratio approach to optimise the land use for producing both food and fuels. A similar approach was used for agroforestry systems which combine trees and food crops. Mixing trees and crops was suggested to increase the overall productivity of the land [14]. We intend in this paper to check if such an increase in productivity could also be expected from agrivoltaic systems combining solar PVPs and crops.

2. Designing innovative agrivoltaic systems

When designing agrivoltaic systems, a compromise should be looked for between electricity and crop production, between the solar panel component and the crop component. This compromise could be found by playing upon several characteristics of the solar panel component. Constant tilt arrays intercept less radiation than single-axis trackers, and much less than double-axis trackers [15]. The panel density may also be reduced to allow more irradiation to reach the crop layer. We decided to adopt constant tilt panels in this study.

2.1. The solar panels component

With fixed solar panels of a given size, the optimisation of the system for energy collection results in a sloping angle (that faces South) and a spacing distance between panels (that may be expressed as the percent of ground covered by the vertical projection of the panels) [16]. At our 43.6° latitude North (Montpellier, France), the optimised system has a 33° slope and 63% ground projection, as predicted with the PVsyst software [17]. This can be defined as the reference energy production system. However, in that case, the sun radiation that is available below the panels may not be sufficient to ensure a profitable crop production. To achieve a profitable crop production, a reduced density (or a different sloping angle) of the panels may be required.

The same configuration with one axis trackers, with a twilit angle varying from 10° to 80° southward, would intercept 7% radiation more, resulting in less radiation available for crops (PVsyst software simulation). The only possibility to compromise would be to reduce the density of the trackers.

To allow an easy mechanical cultivation of the crops, solar panels should be lifted to an elevation that is compatible with modern machinery. A 4 m clearance was considered satisfactory. The cost of building a structure that would support either fixed panels or trackers at that height should be carefully evaluated. Supporting pillars must also be well spaced out to allow wide machines (such as harvesters) to pass between.

A yield set can relate the electricity production of the system (expressed in kWh ha^{-1}) and the crop yield (expressed in T ha^{-1}) for varying densities (and/or slopes) of the solar panels. The shape of this function is essential to optimise the systems [18]. An economically based joint production function can also be designed by taking into account the economic value of both productions. Basically, solar panels and crops will compete for radiation, and possibly for others resources such as water, as solar panels may reduce the available water quantity for crops due to increased runoff or shelter effects. However some facilitation processes (positive interactions between solar panels and crops) may also occur, such as the protection of the crops against high temperatures, or an increased water availability for the crops if the rainfall is concentrated and infiltrated on a limited cropped area. The height above ground level of the solar panels has no impact on the total quantity of radiation available at the soil level, but has a very large impact on the heterogeneity of radiation at ground level. The closer to the ground the panels are, the higher the heterogeneity is. Border effects will also be more pronounced if the panels are high above the ground, allowing radiation penetration below the panels from the sides of the arrays, and projecting shadows on the surrounding area.

2.2. The crop component

The main ecophysiological constraint for plant productivity under PV panels results from light reduction. Only scarce information is available on the tolerance to shade of most crop species. In ecology, "shade tolerance" is a plant trait that describes the ability to tolerate low light levels. In agronomy, heavy shade (less than 75% of the natural level of radiation) is usually reducing most plant characteristics. Very few screening studies of the tolerance of crops to shade are available, such as [19] for some specific garden plants of South China or [20] for varieties of *Parthenocissus* lianas. Recently Ref. [21] showed that for maize, plant height, stem diameter, leaf net photosynthetic rate, specific leaf weight, above ground dry matter accumulation, and the number of kernels per row were all significantly reduced under 50% shade, and that the varieties may be classified as shade-tolerant or shade-intolerant. Common beans are reputed to tolerate shade well, but Ref. [22] showed that shade also reduced significantly bean yield in a rubber agroforestry system. Similar results were also published on perennial crops such as alfalfa [23], but most commercials crops were never studied under shade. It is therefore extremely difficult to recommend some species for their adaptation to shade tolerance.

Moreover, interactions between radiation stress and other limiting factors for plant production may happen. Thermal stresses or photoinhibition processes sometimes limit plant productivity, and may increase in the future as a result of climate change. Ref. [24] showed that banana optimises light use at a significantly high shade level. The optimum shade level for photosynthetic productivity would be one at which the level of photosynthetic photon flux density is high enough to saturate CO_2 assimilation but low enough to induce shade acclimation and reduce photoinhibition. For banana, this saturation level was around 1000 μmol m^{-2} s^{-1}, a low light level typical of the tree-based intercropping systems in which banana is commonly grown in the tropics. Some shade protection of the crops may also reduce the occurrence of various stresses, such as water stress or nitrogen deficiency stress. Water availability limits many crop productions in the world. Shade will reduce transpiration needs, and possibly increase water efficiency. Reduced biomass in the shade may also reduce the need for nitrogen, and consequently mitigate nitrogen stresses. However, no experimental evidences of such facilitative interactions are available so far.

2.3. The Montpellier experimental agrivoltaic plant

This system was set up in the Spring of 2010 and will be used later for three years for the validation of the models developed in this paper. To our knowledge, it is the first ever reported realisation of such an agrivoltaic system.

The prototype has an area of 820 m^2 and is located in Montpellier, France (43°65N–3°87E). Rows of PVPs are 44.8 m long and mounted at a height of 4 m above ground. Supporting pillars are 6.4 m apart, both in North–South and East–West direction. Unit PVPs are monocrystalline modules (JT185Wc, Jetion Solar Holdings Limited, Jiangsu, China), considered as opaque, 1.58 m long and 0.808 m large. The experimental plot is rectangular, and the prototype is aligned with the border of the parcel, that is not exactly East–West. This results in a 14° aspect angle orientation of the panels towards East. The panels are tilted with 25° slope, spaced every 1.64 m (distance between the lower side of two consecutive panels) resulting in a 59% vertical projected cover of the ground. This design is very close to the optimum design (as achieved with a full South aspect) and results in a small 1.5% reduction of the maximum system performance as calculated with the Syst PV Software.

We split the prototype in two parts differing in the density of solar panels: one part is at full density (FD) as described above and the second part is at half density (HD). By "full density" we mean optimal spacing for electricity production, calculated as explained above. The productivity of the plant under Standard Test Conditions (1000 W m^{-2}) would be 36 W m^{-2} in the HD part, and 72 W m^{-2} in the FD part. We also have the possibility to manually modify the tilt angle of the solar panels in the range 20–35°. This feature may be used later to allow more radiation to reach the crops at some sensitive phenological stages. Adaptive reconfiguration schemes to reduce the effect of shadows on solar panels by modifying the tilting angle have been proposed to increase the power output of the solar PV array [25], but we suggest that this could be done also to increase the crop production under the solar panels.

3. *Ex ante* modelling of agrivoltaic systems productivity

3.1. About the use of models

Models of radiation interception and electricity production by PVPs arrays are available and validated [26]. Models of crop productivity are also available and validated for many crops and soil conditions [27]. In this paper, we coupled the two types of models in order to simulate the functioning of an agrivoltaic system.

- We designed a radiation interception model that predicts the amount of radiation available at any location and height under the array, at the day time step required by crop models.
- We used a crop model that simulates the crop development in response to environmental and technical forcing variables.

We based our simulation on the actual Montpellier agrivoltaic prototype described above, with the two densities of solar panels. We will detail later the improvements of both types of models for tackling the specificity of agrivoltaic systems. Linking these two types of models may indicate: i) if the potential system productivity is attractive; ii) what parameters of the design of the system may be modified in an optimisation procedure.

3.2. The radiation interception model

We developed this model with the R software (Free Software Foundation Inc., www.fsf.org). It calculates the amount of daily radiation (direct and diffuse) reaching any point at ground level under the array. It is based on a ray tracing algorithm [28]: the sky hemisphere is approximated by a set of 1296 sample rays regularly distributed with a step of 5° azimuth and 5° elevation. The diffuse to direct ratio of radiation is calculated for each day according to the proportion between global radiation and extra terrestrial radiation [29]. The spatial repartition of diffuse radiation amongst the 1296 sample rays is performed for each day under the hypothesis of standard overcast sky conditions, SOC [30]. The spatial repartition of direct radiation amongst the sample rays is calculated for each day from the sun path at that latitude [29]. The agrivoltaic system is described by the following parameters: the number of PVPs strips, their length, height, inclination southward, spacing and the size of individual PVPs. The model determines for each sample ray if it is intercepted by any of the PVPs strips before reaching ground at a given point, and deduces the percentage of PAR (Photosynthetically Active Radiation, designates the spectral range of solar radiation from 400 to 700 nm) received at that point for each day of the year. Results are summarized on radiation maps at ground or crop level. The model can also integrate the relative available radiation at different time spans (year, month) and provide the corresponding maps.

PVPs arrays are not infinite in horizontal directions. Borders effects may be very important on radiation availability under the panels, especially if the panels stay high above the ground. We therefore developed a model that is able to predict the radiation availability as influenced by borders effects. Light availability outside the array is also predicted, as influenced by the shadow of the solar panels. If a simulation without border effects is required, we simulate a scene with a large number of panels strip and we only visualize the map corresponding to the area at the centre of the scene.

The gradient of irradiation near the array sides may be sharp, from almost 100% radiation available some tenths of metres away down to less than 40% irradiation under the array. This gradient should be taken into consideration for modelling the productivity of crops, and for designing any experimental procedure for monitoring crop growth and productivity. The radiation predictions allow to locate crop monitoring zones in homogeneous and representative locations for light availability.

Results of the predictions of radiation availability under the two densities of panels are shown in Fig. 1. Border effects are strong, and very important in the South and North directions. Away from the sides, irradiation can be considered as homogenous in the East West direction, but heterogeneous along the North–South direction. This heterogeneity depends on the elevation of the panels above the ground (Fig. 2). The higher the panels are, the more homogeneous the daily irradiation at ground level is. Some crops such as maize reach a height of 2 m or more. For such crops, the heterogeneity of the irradiation will increase during the growing season, as the distance from the top of the crop to the panels will diminish.

The limited variations (Fig. 3) of irradiation along the East–West axis (when side effects are removed) suggest that we may use a simpler model predicting only the North–South irradiation gradient. The North–South variability of irradiation results from two different patterns (Fig. 4): inside the array, the pattern results

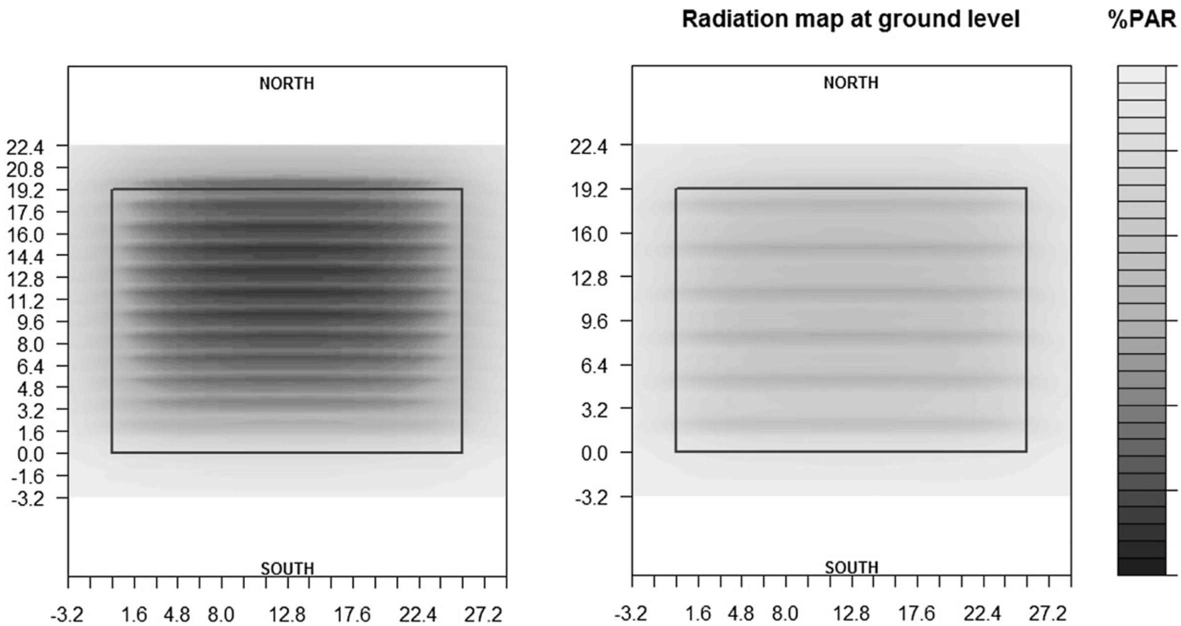

Fig. 1. Predicted relative yearly irradiation at ground level at 43° latitude North under two agrivoltaic arrays differing by the PVPs density (Right: Full density; Left: Half density). The panels are at 4 m elevation above ground. The sides of the array are indicated by the black square. The axes are labelled in metres.

from the projection of the shade from the closest arrays of PVPs. At the South side of the array, this pattern is altered by the sun penetration from the South under the panels, and at the North by the projection of the shades outside the array. For any agronomical experimentation, the zones under the two last rows of PVPs at the South side should be avoided if a homogeneous irradiation is preferred.

We linked the crop model with irradiation predictions not influenced by side effects. In that case, light distribution under the agrivoltaic array is constant in the East–West direction, and reproduces the same spatial pattern across each strip of panels, along the North–South axis.

3.3. The STICS crop model

We used the generic STICS crop model [31] to predict the crop behaviour under the agrivoltaic array. STICS has been used and validated in a large number of situations (e.g. [32–34] and was coupled to some models [35]. This is the first time that STICS is used to predict the productivity of crops in the shade of PVPs. We choose durum wheat as a test crop for this study, as this is the main field crop in the Montpellier area. To account for the heterogeneity of light availability along the North–South direction, STICS was used to predict the crop behaviour at 5 different locations with regular spacing along this axis. The crop model was calibrated with data collected on a nearby experiment in 2007 and 2008 [36]. All calculations used the soil and climate conditions of the Restinclières farm, located at 15 km North of Montpellier, France (43°42N–3°51E).

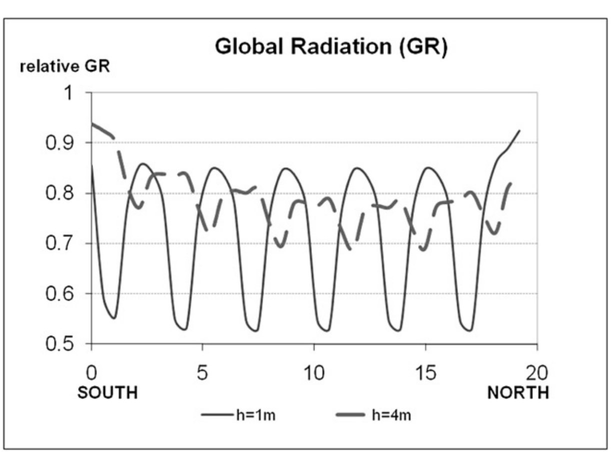

Fig. 2. Effects of the elevation of the panels above the ground (1 m versus 4 m) on the heterogeneity of light distribution at ground level in an agrivoltaic system at half density of panels.

4. The performance of agrivoltaic systems as predicted by the models

4.1. Radiation availability for the crop under agrivoltaic systems

The average simulated radiation during the wheat cropping season (November to June) was 43% and 71% of the incident radiation under FD and HD of PVPs respectively. These values were slightly lower than the values for the whole year (Table 1). The radiation availability varied consistently depending on the day of the year and the position under the array (Table 1). At the winter solstice the radiation pattern is homogeneous and the level of relative irradiation is at the lowest. At the equinoxes the daily relative irradiation varies a lot according to the position under the panels.

The time pattern of light reduction at a given point under the PV array depends on its distance to the closest PVP (Fig. 5). In the FD system, patterns are quite similar along the year: less than 45% of light is available until spring equinox (March), whereas available light varies between 45% and 65% from March until the end of the wheat cycle (June), both right below PV arrays, and at the centre of alleys.

In the HD system, on the contrary, light patterns are more contrasted and not always easy to predict: in April, plants located in the middle of alleys receive 83% of light, whereas, plant under the

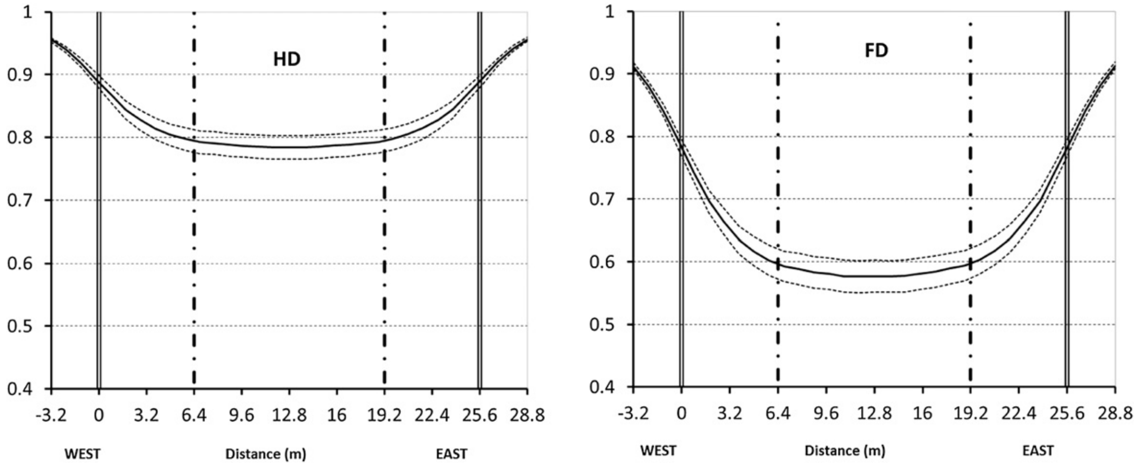

Fig. 3. West–East gradient of irradiation under agrivoltaic arrays at half (HD) and full (FD) density of panels expressed as the relative annual radiation available at ground level. The black line represents the mean of relative radiation along the East–West direction, and dot lines delimitate 95% confidence intervals across the North–South axis. The vertical double straight lines indicate the limits of the array. The vertical dot lines indicate the limits of the area where plants will be monitored (measurement areas).

PV rank receive only 63% of light. In June, the trend is totally different, with a light availability lower than 60% in the alleys and higher than 85% under the PVPs. Such low values may be limiting for wheat development during these periods.

This suggests that phenological development, biomass accumulation and yield elaboration will be affected differently in crops depending on their position under the PVPs.

4.2. Crop production under two densities of photovoltaic panels

The STICS crop model predicts that durum wheat yields are reduced in the shade of PVPs. However, the results are contrasted between the two densities of panels. At FD, durum wheat dry matter (DM) and yield (Y) were reduced by 29% and 19% respectively. At HD wheat production was almost unaffected: only −11% for DM and −8% for Y. Relative DM could be reasonably predicted from the relative radiation received between crop sowing and maturity and a common equation could be fit to both systems ($R^2 = 0.95$). Relative Y was best predicted with the relative radiation received between the maximum leaf area (LAI) stage and the flowering date. Both separated and common equations can be fitted with a very high r^2 coefficient ($r^2 = 0.91$, 0.83, 0.67, for HD and FD together, HD alone and FD alone respectively).

These results are coherent with Ref. [37] who identified the pre-anthesis period as the highest sensitive stage for yield elaboration in durum wheat. Y was less affected by light reduction than DM accumulation, indicating that biomass allocation within the plant is different under dense shade. The wheat crop responded to the radiation reduction through compensation mechanisms as every point are located above the 1:1 line in the relative DM/relative radiation graph (Fig. 6). Compensation mechanisms may include the dynamics of leaf expansion.

It is important to note that a 57% (resp. 29%) reduction in light availability results in only a 19% (resp. 8%) reduction in wheat yield. As a consequence, the model predicts that the light efficiency of wheat crop is increased under the shade of PVPs.

4.3. The agrivoltaic Land Equivalent Ratio

Land Equivalent Ratios (LERs) are indicators of the productivity of the land used to assess the value of mixed cropping systems [38–40]. They allow to compare the productivity of mixtures of crops on the same land area versus monocultures [41], and are used

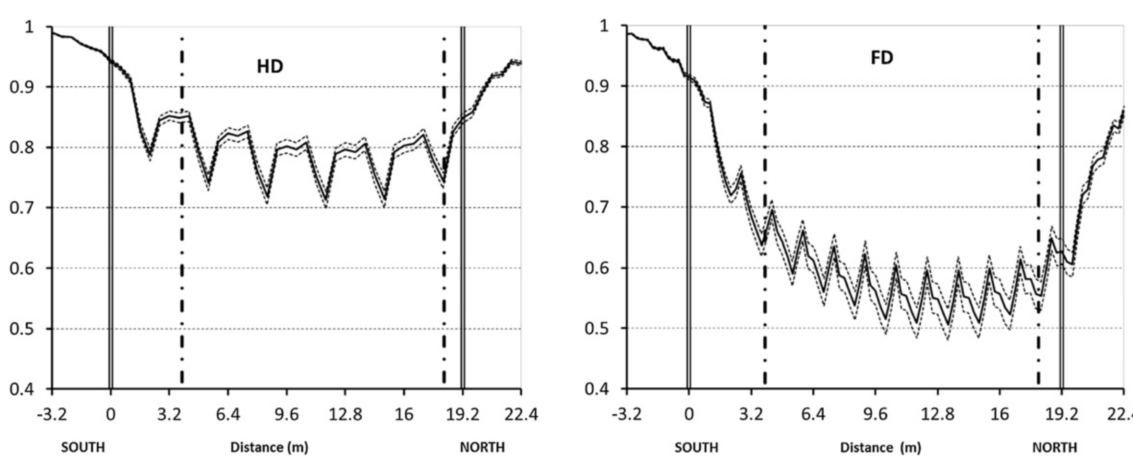

Fig. 4. South–North gradients of irradiation under agrivoltaic arrays at half (HD) and full (FD) density of panels expressed as the relative annual radiation available at ground level. The black line represents the mean of relative radiation along the North–South direction, and dot lines delimitate 95% confidence intervals across the East–West axis. The vertical double straight lines indicate the limits of the array. The vertical dot lines indicate the limits of the area where plants are monitored (measurements area).

Table 1
Variability of the relative irradiation calculated every 10 cm along the North–South axis under the solar panels at the solstices, equinoxes, and for the year (at 43° latitude North).

	Full density				Half density			
	Min	Average	Max	Range of variation	Min	Average	Max	Range of variation
Spring equinox	15.5	37.4	64.6	48.8	23.2	68.7	93.4	70.2
Summer solstice	38.8	54.1	68.3	29.5	49.2	75.4	90.0	40.8
Autumn equinox	20.4	38.9	67.3	46.9	29.3	69.6	92.5	63.2
Winter solstice	49.3	51.1	53.9	4.6	72.0	74.4	76.7	4.7
Annual	15.2	44.9	76.3		23.2	72.0	93.7	

for both mixtures of annual crops or mixtures of trees and crops [39,42]. The concept of the Land Equivalent Ratio can be extended to any system that mixes two (or more) types of production on the same land unit, and we propose here to apply this concept to the suggested new agrivoltaic systems. The LER of an agrivoltaic system is defined as:

$$\mathrm{LER} = \left(Y_{\mathrm{cropin\ AV}} / Y_{\mathrm{monocrop}}\right) + \left(Y_{\mathrm{electrictyAV}} / Y_{\mathrm{electricityPV}}\right)$$

where the monocropping system refers to the sole cropping of the crop; PV refers to a standard PV plant, and AV refers to the mixed agrivoltaic system. In our situation (FD and HD systems) we consider that 90% of the area under the array is cultivated, accounting for the proportion of the surface that is occupied by pillars. In the FD part, the relative electricity productivity equals 1, as FD is configured according to standards for PV plants, and we consider that there is no difference of productivity between panels at ground levels or at 4 m ground. However, the panels at 4 m height may benefit from a best ventilation by the wind or a reduced dust deposition, that could increase the productivity of the panels, resulting in a relative productivity higher than 1 [43]. In the HD part, the relative productivity is estimated to 0.52: the density of the panels is divided by 2 compared to the standard, which should lead to a relative yield equal to 0.5. However, the reduction of the near mask by neighbour panels entails an increase of 2% of the potential productivity, which entitles us to estimate that the relative yield of HD equals to $0.5 + 0.02 = 0.52$.

If LER $>$ 1, the AV system is more effective than the pattern of separate crops and PV arrays for the same land area. Usually, mixed cropping systems have LERs between 1.0 and 1.3, while agroforestry systems have LERs between 1.1 and 1.5. A LER of 1.4 means that, by adopting a mixed system, the production of a 100 ha farm will be as high as the production of a 140 ha farm with separate productions. Such large increases of productivity are very attractive and explain the current trend in investigating mixed systems. They are explained by a better use of resources by the mixed system, resulting from complementarity in resource needs, but also from facilitation processes when one component benefits from the other. In mixed cropping systems, a typical facilitation mechanism is the provision of fixed Nitrogen by a legume species to a non-fixing species.

The predicted Land Equivalent Ratios (LERs) of agrivoltaic systems are impressive (Table 2). Such high values of LERs were never reported nor predicted for any mixed systems of crop intercropping or agroforestry associations. A 1.7 LER value would mean that a 100 ha farm would produce as much electricity and food crops as a 170 ha farm with separate productions.

The STICS predictions are more reliable for dry matter accumulation than for yield prediction. Yield prediction results from the calculation of a harvest index (ratio of harvested organ biomass to the total biomass of the crop) that is applied to the Dry Matter predictions. We therefore suggest to retain provisionally as conservative estimates of the relative productivity of agrivoltaic systems the LERs based on Dry Matter accumulation.

The increased capture of radiation for production uses by the agrivoltaic system is impressive. In a monoculture wheat crop, the radiation that basks the land unit between wheat harvest (beginning of July) and wheat sowing (beginning of November) is not used for production. Conversely, in a conventional photovoltaic array, the radiation that is not captured by the panels is not used for production. This happens for most of the radiation before 9 am and after 3 pm in the day, which represents significant energy during the summer.

A system that would combine a winter crop and a summer crop in the same year would probably result in lower LERs, as the radiation use by the monocrop system would be higher. A system that would combine only a summer crop would also result in lower LERs, as the competition for radiation would be rather fierce, and the winter radiation not captured by the panels would not be used by the crops. Finally, if the winter radiation was too low under the FD array, it may not be possible to maintain a winter crop. In that case, the LERs should be recalculated by excluding the winter crop from the AV system. This would also diminish the actual LER of the system. Therefore, our estimates of LERs are probably close to the maximum LERs that can be obtained.

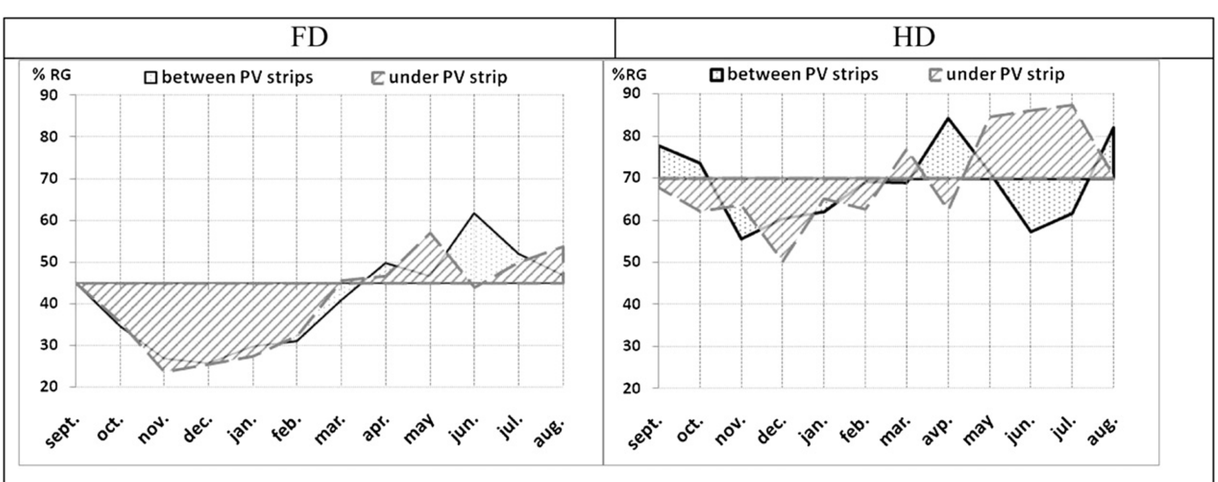

Fig. 5. Relative light transmission variation during the year at two positions under a photovoltaic array at full (right) and half density (left) of panels.

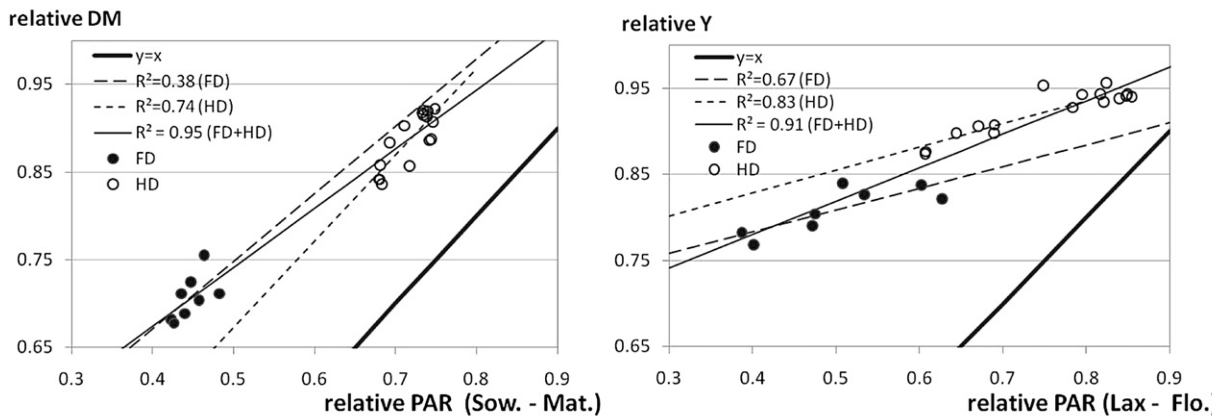

Fig. 6. Best integrated radiation predictors of the relative yields and dry matter of durum wheat as predicted by the STICS crop model under an agrivoltaic system. For the biomass (Dry Matter, DM, left), the radiation is integrated over the whole cycle of the crop from sowing (sow) to maturity (mat). For yield, the radiation is integrated for 3 weeks before flowering stage from the lax (maximum leaf area) to the flowering (flo) stages.

5. Discussion

Predicted LERs of AV systems are surprisingly high, suggesting that it may be very efficient to produce electricity and to harvest food crops on the same land unit. Such predictions call for the validation of the concept by the experimental monitoring of actual AV arrays.

5.1. About the domain of validity of the crop model

The STICS model predicted an increased maximum Leaf Area Index (LAI) in the shade: +16% and +9% for FD and HD respectively. This result is in contradiction with the few published papers (e.g. [37]) and our observations under artificial shade. It may indicate a limit of the STICS model to simulate the crops behaviour under dense shade. This is likely to induce an over-estimation of the calculated LERs. Two explanations may be suggested. First, the crop temperature calculation may not be correct in the shade of PVPs as the model predicts no significant reduction of leaves temperature in the shade, which is counter-intuitive. Second, the leaf area calculation is probably too sensitive to the reduction of the calculated nitrogen stress in the shade. To be on the safe side, we used the crop model again and forced some variables to their values in the reference simulation in full sun conditions. This was achieved by forcing the following variables: final harvest index, daily LAI increment and light use efficiency. This allowed us to calculate corrected LERs values that are not biased by such possible model inaccuracies. Corrected LERs for Dry Matter were 1.19 for HD and 1.43 for FD PV arrays (instead of 1.32 and 1.64 respectively with the straight model). This drop in LER predictions is probably pessimistic, as key processes of beneficial interactions between solar panels and crops are not taken into account by using the model in this way.

5.2. About the optimisation of the system

Goetzberger and Zastrow [10] suggested that in an AV system, two-thirds of the radiation were still available for other uses (at 48° latitude), when the arrangement of the solar panels is optimised for electricity production. However, present day PVPs arrays with fixed solar panels allow less than 50% of the radiation to reach the ground. The value for our prototype at FD is only 45% of the annual radiation available for the crops. Therefore the conclusions by Goetzberger and Zastrow were far too optimistic (they also predicted that solar panels would be commercially profitable from 1986 on). Solar panels slope and spacing are often optimised for collecting radiation close to the winter solstice (Fig. 5) which leaves a lot of radiation available for the crops in spring and summer. This is quite favourable, as this is the main growing season for most crops, including irrigated crops. We suggest here that the solar panels may need to be adjusted to optimise the system. Although higher LERs were calculated for the FD array, further studies are required to decide if the economical optimum is also towards high densities of PVPs.

5.3. About adjustments in the solar panels to reduce light deficit risks for the crops at some stages

Photovoltaic arrays are often optimised for collecting radiation close to the winter solstice. There is a risk of very low levels of irradiation for a winter crop during the early stages such as germination and emergence. However this may be compensated by side effects: in winter, light penetrates largely under the array from the sides, if the size of the array is not too large. This may help winter crops to germinate and start their growing cycle. However, if required, it could be a smart idea to modify the panel slope at some period of the year to help crops to face some specific phenological stages sensitive to light deficits. This is the case for the pre-anthesis period in cereals [36] (in April at our site) or for the germination of small seeds crops such as rapeseed (in September at our site). Therefore, a cheap and simple mechanical device that would allow to modify manually the slope of the panels would be required. Further modelling studies will indicate possible optimised temporal schemes of panel slope along the cropping season. The

Table 2
LERs of two different agrivoltaic systems as predicted by modelling.

	Solar panel	Crop	Crop	LER based on yield	LER based on dry matter
	Relative yield	Relative yield	Relative dry matter		
Monosystem	1	1	1	–	–
FD agrivoltaic system	1	0.73	0.64	1.73	1.64
HD agrivoltaic system	0.52	0.83	0.80	1.35	1.32

optimisation procedure will have to balance between electricity production (negatively affected by panel movements to provide radiation to the crops) and food crop production (if positively affected).

6. Conclusion

We evaluated in this paper a new combined system of PVPs and crops that we suggest to call an agrivoltaic system. *Ex ante* simulations based on the linkage of a radiation interception model by PVPs and a crop model show that AV systems may be highly productive, with increases of the overall land productivity as high as 60–70%. However, concerns about the validity of the crop model were raised, and should be explored in the future. Other microclimatic effects of PVPs on crops should also be investigated: rain redistribution under the panels, wind mitigation or acceleration, crop and soil temperature changes. The validity of the results for various latitudes should also be explored. Conversely, some effects of crop cultivation on the PVPs may also be anticipated such as dust deposition after soil tillage or humidity impact on PV cells if irrigation is required for the crops. In the context of climatic change, crops may also be protected by the PVPs against hail and excess of temperature, and this may prove more and more important in the future. Finally, some improvement of the concept may also be envisaged: the tilting of the panel may be adjusted at some period of the year to stimulate the crop productivity; semi-transparent PVPs could increase the light transmission to the crop [44]; PVPs with mirror backsides might also increase the light availability for the crops by multiple reflection of the incoming light not captured by the solar panels. The optimisation of an AV system should look for a compromise between electricity production and crop production and need some adjustments of the design of the PVP component, which was not envisaged by promoters of the idea in the early 80s [10].

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