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Abstract The yield of crops in both agrivoltaic (AV) and agroforestry (AF) systems is difficult to predict. The shade pattern of an AV system is not typical and is quite different from the one of AF systems. Most countries allow AV systems on croplands only if the crop productivity is maintained (e.g., in France) or slightly reduced, as in Japan and Germany, with 80% and 66% minimum relative yield (RY) required, respectively. I suggest using the Ground Coverage Ratio (GCR: ratio of area of photovoltaic panels to area of land) as an indicator of the crop potential productivity in AV systems. The GCR can easily be computed and controlled for all kinds of AV systems with panels that are either fixed (horizontal, tilted, or vertical) or mobile (on 1- or 2-axis trackers). Here, I provide a synthesis of published data for crop productivity under AV systems. Only publications that provided both the GCR of the system and the crop RYs were included. Measuring RYs requires a reliable non-AV control plot. Several publications were excluded because of doubts regarding the measurements' validity (e.g., systems that are too small, resulting in strong edge effects, or unreliable control plots). Despite the scattering of results, a clear pattern is evidenced: RYs decrease rapidly when GCRs increase. It appears that a GCR < 25% is required to ensure that most crop RYs stay > 80%. These results are consistent with a recent meta-analysis examining the impact of shade on crops. The use of the GCR criterion to validate AV projects is a simple and cost-effective alternative to the tricky control of crop yields in the fields.

Keywords Agrivoltaic policy · Shade sensitivity · Shade tolerance · Crop yield · Photovoltaic panels

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Introduction

There is a need to assess whether a photovoltaic project deserves to be considered an agrivoltaic (AV) system. While an AV system was originally defined simply as a dual system with both crop and electricity production on the same plot (Dupraz et al. 2011), several more detailed definitions were produced recently in various policies or labels in France (République Française 2023), Japan (Tajima and Iida 2021), Italy (Ministero della transizione ecologica 2022), and Germany (Deutsches Institut für Normung 2021). These definitions insist that the main condition for qualifying as an AV system is that the crop yield is maintained (if not improved) under the system. Some level of crop yield reduction, however, is tolerated in certain countries (Table 1). The main impact of

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Table 1 Regulatory requirements in the agrivoltaic policies of various countries (including maximum cropped area loss and minimum relative crop yields)

Country	Maximum lost areas[a]	Minimum relative crop yield	Minimum vertical clearance	Ground coverage ratio limit	Minimum relative electricity yield	Rate of agricultural subsidies	References
France	Not considered	100% (no reduction allowed)	Not considered	Not considered, but 50% indicated in the AFNOR label	Not considered	100% if GCR < = 30% No grants if GCR > 30%	French Law (République Française 2023) AFNOR label (AFNOR 2021)
Germany	Category 1 (overhead AV): 10% Category 2 (Interspace AV): 15%	66%	Category 1: 2.1 m Category 2 no clearance requested	Not considered	Not considered	85%	DIN Standard 91,434 (Deutsches Institut für Normung 2021)
Italy	30%	Not defined	1.3 m with animals 2.1 m with crops	40%	60%	Undecided	Ministero della transizione ecologica (2022)
Japan	Not considered	80%	Not considered	Not considered	Not considered	Unknown	Cited in Tajima and Iida (2021)
South Korea	Under discussion	Under discussion. 80% considered	Under discussion	Not considered	Not considered	Unknown	Kim et al. (2022)

[a]Lost areas are zones that cannot be cropped due to the AV system (lines of posts, electric systems, areas of support structures, e.g., guy cables, access tracks for maintenance)

photovoltaic (PV) panels on crops is their shadow, which reduces the available photosynthetically active radiation needed for photosynthesis. There is a debate about the shade ratio that is acceptable in AV systems. The shade ratio is difficult to measure, as it varies from hour to hour and from one day to the next, depending on the latitude, the design of the system, and the position within the system. In contrast, the design of the system (area of panels, elevation above ground, tilting angle, movement of the panels if any) is well known, stable, and easy to control. In this review, I explore whether the system's ground coverage ratio (GCR: ratio of area of photovoltaic panels to area of land) could be a good predictor of crop yields in AV systems. Indeed, the GCR might provide a simple measure of an AV project's validity, both at the project design and plant operation stages. To date, only Italy has included a limit for Ground Coverage Ratios in AV systems (Table 1), which is at 40%.

In this paper, after defining the GCR, the literature is searched to identify all relevant agrivoltaic studies, i.e., those that provide both the GCR and the relative yields of crops. After excluding some questionable values, the regression between GCR and relative crop yields was established and compared with the results of a meta-analysis examining the impact of shade on crops. This leads to the proposal of ways in which legislators can use these results in their drafting of forthcoming policies to regulate the developing field of agrivoltaics.

Materials and methods

Defining the ground coverage ratio of AV systems

The ground coverage ratio is defined as

$$\text{GCR} = \text{Area of solar panels}/\text{Area of the land used for the AV system} \quad (1)$$

The area of the land used for the AV system is the area below and between the solar panels. It also includes a border area around the system, whose width equals half the distance between the rows of panels.

For fixed panels, it can also be defined as the ratio of the panel width to the row-to-row pitch. The GCR can be easily computed for all kinds of agrivoltaic systems (i.e., with fixed or mobile panels, opaque or semi-transparent panels, vertical, horizontal, or tilted panels). With semitransparent panels, the ratio is adjusted as GCR_{st} to take into account the actual light transmission of the panels:

$$\text{GCR}_{st} = \left[\text{Area of solar panels}/\text{Area of the land used for the AV system}\right] * (1 - \text{Transmittance of the panels}) \quad (2)$$

For opaque panels, Transmittance = 0. For semi-transparent PV panels, values of transmittance are usually in the [0; 0.3] range.

While vertical panels inside the field ("intra panels") are fully included in the calculation, vertical panels used as hedges around the field ("limit panels") contribute only half of their area to the panel area used in the GCR calculation (the other half contributes to the GCR of the neighbouring field).

$$\text{Area of vertical panels} = \text{Area of vertical intra panels} + 1/2 \text{ Area of vertical limit panels} \quad (3)$$

The computation of the GCR does not change when bifacial panels are used, since these do not cast more shade on crops than monofacial panels (provided that the panels' actual transmissivity is used in the calculation).

When computing the relative crop yield, it is necessary to take into consideration two aspects:

- Any change in crop yield at the plot level (per cropped m^2), termed here Relative Plot Yield (RPY).
- Any additional reduction in yield at the field level due to lost areas, i.e., areas where no crop production can be obtained (lines of posts, electric systems, areas for support structures, e.g., guy cables, access tracks for maintenance). Taking lost areas into consideration allows one to compute the relative field yield (RFY, Eq. 3).

$$\text{RFY} = \text{Relative Plot Yield} * (1 - \text{Lost Area rate}) \quad (4)$$

with the Lost Area rate = Area unavailable for cropping / Total area of the AV system.

As an example, a system where the crop would produce a normal yield per m^2 (i.e., 100% of the control yield) on only 50% of the field area would have a relative field yield of 50%.

Shading ratios and ground coverage ratios

A number of papers have measured or modelled the shade pattern of various AV systems (Amaducci et al. 2018; Dupraz et al. 2011; Tahir and Butt 2022; Trommsdorff et al. 2021). This shade pattern is highly variable depending on the height of the panels, their orientation and tilting, and the season. The shading pattern can be averaged for periods of time such as one year, the crop's growing season, or specific phenological phases of those crops that are considered to be the most sensitive to shade. Depending on the AV system design, the shading pattern at the crop level may be very homogeneous or heterogeneous in both space and time. Many authors assume that the shade level under an AV system is close to the GCR of the system (e.g., Kim et al. 2021), but most field measurements show that the average shade level is usually slightly higher than the GCR.

The following factors increase the heterogeneity of the shading pattern at the crop level:

- A low elevation of the panels above the ground and/or a small distance between panels and crop canopy
- Clustered panels (panels arranged in lines or blocks)
- Opaque panels

Conversely, the following factors increase the homogeneity of the shading pattern at the crop level:

- A high elevation of the panels above the ground, resulting in a large distance between panels and crop canopy
- Diffuse positioning of the panels (in a quicunx, checkered, etc.)
- Semitransparent panels

For the same GCR, mobile panels on trackers (i.e., pure solar tracking) cast a heavier shade on crops than fixed panels. For the same GCR, fixed tilted or vertical panels aligned east–west cast a more heterogeneous shade than fixed tilted or vertical panels aligned north–south. Similar results have been obtained in agroforestry alley-cropping systems at latitudes higher than the tropics, where north–south tree lines cast a more homogeneous shade on crops than east–west tree lines (Dupraz et al. 2018).

A typical GCR for ground-mounted photovoltaic systems is 50–60%. Tonita et al. (2023) showed that at latitudes ranging from 17° N to 75° N, the efficiency of fixed-tilt arrays peaks for GCRs between 50 and 70%. Detailed measurements of the radiation available under the panels of several agrivoltaic power stations have been published. For example, at an experimental site in Lavalette, Montpellier (France), the annual shade was 28% under fixed panels with a 25% GCR and 56% under fixed panels with a 49% GCR (Dupraz et al. 2011; Marrou et al. 2013a). The shade cast by the mounting structure adds to the shade of the panels; this accounts for discrepancies in the results obtained on different sites using different technologies. The order of the difference between the shade ratio and the GCR is quite stable across various experimental sites. The additional shade due to the mounting structure decreases when the GCR increases, as more parts of the structure tend to be in the shade of the panels. The impact of various GCRs on the shading ratios can be summarized, as indicated in Table 2 for latitudes of 45° north or south. These values are supported by a number of papers that investigated both the system's averaged shade ratio and its GCR (Dupraz et al. 2011; Marrou et al. 2013a; Valle et al. 2017; Amaducci et al. 2018). However, the GCR is only relevant when the design of the system is optimal: fixed panels facing south (in the Northern Hemisphere) or mobile panels on 1-axis trackers with the rotation axis aligned north–south. If an AV facility has fixed panels facing north (in the Northern Hemisphere), the shade induced by the panels and the electricity production will be reduced for the same GCR value. This will never happen in real life for economic reasons, but some significant deviations from the optimum may occur, such as at the German facility of Heggelbach (Trommsdorff et al. 2021). At this site, fixed panels face the southwest (52° deviation from south to west) in an attempt to homogenize the shade at the crop level. This results in a decrease in the shade ratio by approximately 5% (Trommsdorff, pers. com.) and may explain why the yield results at Heggelbach are somewhat higher than those at other sites with the same GCR. The actual GCR of any AV facility could be easily fixed to account for this deviation from the optimal. This was not performed in this paper, as the orientation of the panels is almost never indicated in the reviewed publications.

Table 2 Approximate relationship between the GCR of 2 different AV systems with contrasting GCRs and the average annual shade ratio of the crop (assuming an optimal orientation of the panels)

	Ground coverage ratio	
	30%	60%
Type of panels	Average annual shade ratio	
Fixed, tilted, or vertical	35%	65%
Mobile solar tracking	40%	70%
Mobile crop adaptive tracking	20–40%	40–70%

Filtering experimental data to avoid bias

All available papers that presented both RPY values and the data needed to compute a GCR of the system were included in the present synthesis. However, some papers suffered from research limitations and thus produced unreliable results. These flaws also tend to occur in agroforestry systems research (Dupraz 1998). The reasons for excluding certain papers were as follows:

- Modelling results not validated by a field experiment (Amaducci et al. 2018; Campana et al. 2021; Dinesh and Pearce 2016; Dupraz et al. 2011; Malu et al. 2017; Mamun et al. 2023);
- A too-small system, whose limited size might have induced marked edge effects.

These edge effects also hinge on the distance between the panels and the top of the crop canopy. A small system is acceptable when there is also a small distance between the crop and the panels. This is usually the case with tall fruit trees. However, when the distance between the panels and the crop canopy is large (e.g., low annual crops under panels at a 4- to 6-m elevation), the edge effect will be significant. Small-sized systems harvest sun radiation on an area much larger than the actual size of the AV system since they shade the field located north of the system (in the northern hemisphere). This effect is negligible with large systems, but it can be a concern when the width of the system is narrow. On the winter solstice, the sun is at its lowest daily maximum elevation in the sky. Radiation will penetrate deeply under the AV system at noon. If the system is very narrow, the entire area under the system will receive full sun at noon on the winter solstice and possibly during long periods of the year around the winter solstice. Here is how to compute the minimum width (Wmin) that allows the system to obtain full sun on the winter solstice:

$$\text{Wmin} = (\text{Clearance height} - \text{canopy height}) * \text{Tangent}\ (90 - \text{latitude} + \text{sun declination}). \tag{5}$$

If we explore the 40–60° latitude, we obtain a Wmin/H ratio ranging from 2 to 8. A ratio of 5 was assumed to be a sensible minimum for the temperate zone. However, a more site-specific calculation should be performed at each experimental site. Sites at low latitudes may be narrower. If there are no winter crops, the calculation should be performed with the sun elevation during the crop growing season, and the bias is less important. It is therefore recommended to ensure that the width of the system is larger than 5× the clearance height of the system. This was particularly concerning for some very narrow experiments, such as those of Sekiyama and Nagashima (2019) on maize or at the Tanzania site of Randle-Boggis et al. (2023).

- Documented doubts about soil homogeneity across AV and control plots have arisen at sites including the world's first dynamic agrivoltaic farm in Tresserre, France, and in a vertical panel experiment with cereals described by Tiffon-Terrade et al. (2023).
- It is sometimes impossible to calculate a GCR value from published data (Barron-Gafford et al. 2019; Giuseppe et al. 2023; Thompson et al. 2020). Often, the experimental device consisted of isolated, small-sized panels, with only a limited number of yield measurements made under the panels or close to the panels.
- Concerning agrivoltaic greenhouses, some studies did not compare a standard greenhouse with a photovoltaic greenhouse (Cossu et al. 2014). Cossu et al. (2014) even added light under the PV panels to increase the very low irradiation in winter in a greenhouse with a GCR of approximately 50% (half the roof was covered with panels). Dramatic drops in crop yields were recorded but could not be included in this synthesis because the true control was missing. Similarly, other studies carried out in greenhouses did not provide average yields under PV panels but gradients and therefore could not be included (Kadowaki et al. 2012).
- Documented doubts about the weed/disease impact in both the AV system and the control. In an experiment in Montpellier, barley had much higher yields under the panels than in full sun (Dupraz et al. 2014 unpublished data). However, the key explanation was that the control plot was overrun with weeds, whereas the barley located under the panels was almost weed-free. We had no way to prove that the absence of weeds under the panels resulted from a positive impact of the panels, as there was no replication at different sites.
- Extremely low yields in the control, indicating that solar radiation was not a limiting factor. Such systems, which cannot provide farm revenue, are often designed by researchers to explore the limits of the system. Here, trials were excluded in which unirrigated maize provided approximately the same very low yield in AV and in full sun. Those yields were so low (less than 1 T of grain DM ha^{-1}) that they made no economic sense. Another set of data was excluded because it concerned pastures with an annual dry matter productivity lower than 3 T DM ha^{-1} $year^{-1}$ (Madej et al. 2022). In the area studied by these authors, pas-

tures usually have an annual productivity of 5–8 T of DM ha^{-1} $year^{-1}$.

- Some studies explore whether it might be possible to grow a crop in full summer under an AV system in instances where it is impossible to do so in full sun. A good example of this is the work of Dal Prà et al. (2023) on growing lettuce during the summer in Italy. The results are convincing, with a higher yield of fresh lettuce under the AV system. However, an increased RY for a short duration in summer may be compensated by low yields during the other growing seasons. The impact of an AV system should be assessed at least on a timescale of one year, including the full rotation of crops over the year.
- Measurements on perennial plants during a single year. For perennial plants, year-to-year depletion of carbon reserves due to shade is crucial, and several years of measurements are required to reach a solid conclusion. Moreover, yield measurements made on perennial plants after only 1 year of shade may not reflect the true impact of an AV system, especially if the system was constructed on a previously existing orchard that had been growing in full sun conditions for many years. Conversely, measurements made during a 1-year period but on perennial crops that have already been under the AV system for several years could be considered, given that the impact of the system on the plant reserves is probably stabilized.

Some papers show very high relative yields (>1). They were scrutinized to detect any possible flaws:

- The experiment on alfalfa by Edouard et al. (2023) recorded a 1.4-fold high relative yield for alfalfa under panels in 2021 at the Les Renardières site near Fontainebleau, France. Alfalfa is a perennial plant, and data including several consecutive years would be required. The available records for this site covered only two consecutive years (2020 and 2021), with a value of 0.79 for the first year. Nonetheless, the present paper includes the average RY value for these two consecutive years of measurements since that study met all the validity criteria.
- The yield of chiltepin pepper, jalapeno, and tomato was monitored under PV panels at the University of Arizona (Barron-Gafford et al. 2019), with extremely high values of relative yields for chiltepin (RPY close to 3) and tomato (RPY close to 2). These values were not included in Fig. 1 because it was not possible to compute a GCR for this experiment with isolated panels. Indeed, this was done under desert conditions, where growing crops in full sun is a challenge, even with irrigation. A control with standard removable shading nets would have been useful if this would have represented the standard method of cultivation in that area without PV panels. When the shade of panels allows crops to grow in very harsh environments, such as deserts where growing crops in full sun is impossible, infinite relative yields might be expected. However, such scenarios relate to places where agriculture is a challenge, so they differ from mainstream agriculture.
- The Tanzanian experiment by Randle-Boggis et al. (2023) displayed very high RPYs for beans, chard, and spinach but moderate RPYs for onion and sweet pepper. This is the only available study so far to have been conducted in a tropical country. The width of the system was small, inducing possible edge effects. For this reason, its results were not included in the present synthesis. More results from tropical countries are needed to assess whether tropical crops can be more successful than temperate crops under AV systems. As a consequence, the [GRC; RPY] relationship evidenced in this review paper is valid for temperate crops only.
- Finally, in their experiment on maize, Sekiyama and Nagashima (2019) observed surprisingly high RPY of maize in the shade of an AV system with a high GCR. These results were not included in this synthesis because the GCR could not be calculated and because the plots were so small that important edge effects may have affected the crop yield. These results are at odds with other reported results, which display significantly reduced yields in the shade of AV systems for maize (Kim et al. 2021; Ramos-Fuentes et al. 2023).

The final dataset used for assessing the GCR-RPY relationship

Thirty-five publications and two unpublished results were identified that presented measures of crop yields in AV systems as of May 2023. All papers reviewed included the relative plot yield, but only

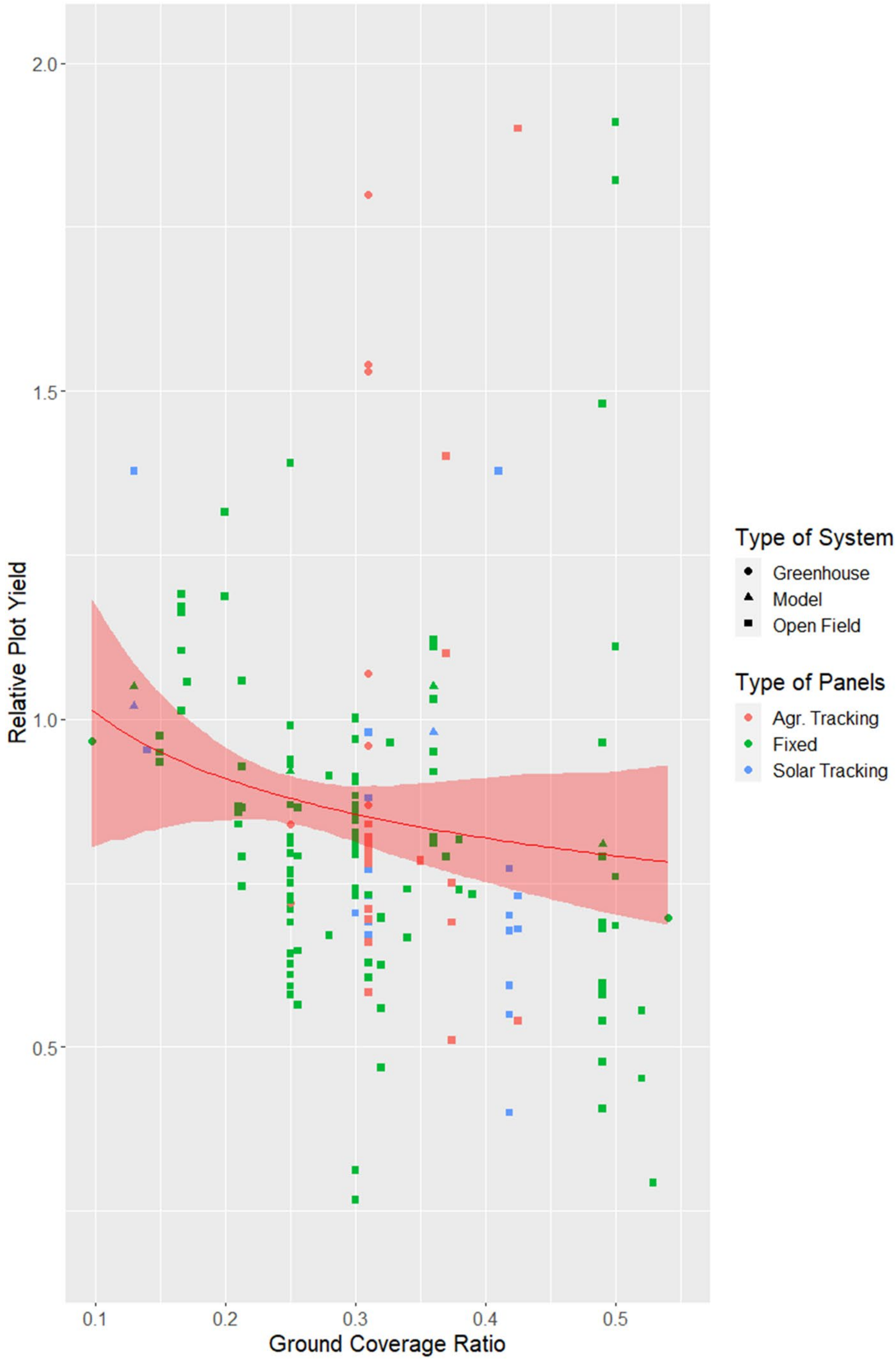

Fig. 1 Decrease in the relative plot yield in agrivoltaics as a function of the system's ground coverage ratio (including all available data). Adjustment: $RPY = aGCR^b$ with $a = 0.7128$ and $b = -0.1515$

a few mentioned the relative field yield. Unfortunately, no published results could be found for AV systems with vertical panels for inclusion in this synthesis. Some preliminary results by Tiffon-Terrade et al. (2023) on vertical panels could not be included, as there were serious concerns about soil heterogeneity in the experiment. Most publications included several [GCR; RPY] data points corresponding to different crops and/or different years, resulting in a total of 167 points on the global synthesis graph. After filtering data with the previous methodological conditions, 129 [GCR; RPY] points

Table 3 Publications included in the final analysis of the relationship between the GCRs and RPYs (sorted by date of publication)

Reference (sorted by year of publication)	Country	Crop	Year of experiment	GCR	Panel Type and Movement
Marrou (2012) Ph. D. thesis	France	Durum wheat; Beans; Cucumber	2010	0.25; 0.49	Fixed
Marrou et al. (2013b)	France	Lettuce	2010;2011	0.49; 0.25	Fixed
Dupraz (2014, unpub. data)	France	Durum wheat	2014	0.25; 0.49	Fixed
Valle et al. (2017)	France	Lettuce	2015	0.25; 0.31	Fixed; ST; AT
Aroca-Delgado et al. (2019)	Spain	Tomato	2010–2012	0.09	Fixed
Thompson et al. (2020)	Italy	Basil; Spinach	2016; 2019	0.43	Fixed, tinted, semi-transparent
Andrew et al. (2021)	USA	Grass	2019–2020	0.28	Fixed
Trommsdorff et al. (2021) Weselek et al. (2021)	Germany	Potato; Wheat; Celeriac; Clover grass	2017;2018	0.36	Fixed
Al-agele et al. (2021)	USA	Tomato	2019	0.52	Fixed
Gonocruz et al. (2021)	Japan	Rice	2014 to 2017	0.21; 0.3; 0.39;0.34	Fixed
Hudelson and Lieth (2020)	USA	Kale; Chard; Broccoli; Peppers; Tomato; Spinach	2018	0.42	ST
Kim et al. (2021)	South Korea	Sesame; Mung bean; Red bean; Maize; Soybean	2020	0.21;0.26;0.32	Fixed
Potenza et al. (2022)	Italy	Soybean	2021	0.14	ST
Lee et al. (2022)	South Korea	Potato; Sesame; Soybean; Rice	2021	0.25 to 0.3	Fixed; ST
Jiang et al. (2022)	China	Kiwifruit	2018–2020	0.15; 0.25; 0.31	Fixed, semi-transparent
Jo et al. (2022)	South Korea	Rice; Rye; Soybean; Adzuki bean; Silage maize; Garlic; Onion	2018–2020	0.30	Fixed
Juillion et al. (2022)	France	Apple	2022	0.43	ST, AT
Kumpanalaisatit et al. (2022)	Thailand	Bok Choi	2018	0.53	Fixed
Edouard et al. (2023)	France	Alfalfa	2020;2021	0.37	Fixed; AT
Ramos-Fuentes et al. (2023)	France	Maize	2019–2021	0.25; 0.31; 049	Fixed; ST; AT

Caption for the movement of the panels: ST = Solar tracking; AT = Agronomical tracking (adaptive tracking to favour the crops during some stages)

from 21 publications (Table 3) were included in the final synthesis. The data were collected in nine countries (China, France, Germany, Italy, Japan, Spain, South Korea, Thailand, and the USA), and 27 different crops were documented. They include both open-air and greenhouse agrivoltaics.

It could be argued that these different [GCR; RPY] points do not have the same significance nor should carry the same weight. Indeed, it is inaccurate to give the same weight to one measurement done on an annual crop with a 3-month cycle (such as lettuce) and another that comprises 4 years of production on a perennial plant (such as an apple orchard). One solution to this problem might have been to weight each point by the number of growing seasons included in the data. The preferred solution, however, was to translate all the values obtained into annual measurements, including those made with perennials, which provided a satisfactory way of giving more weight to data collected over longer periods of time. For example, Juillion et al. (2022) provided 4 years of relative apple yields. These 4 different values were included in the synthesis instead of using the cumulated 4-year value and weighting it by a factor of 4.

The list of the 33 publications is available as supplementary material and includes the 21 publications used in the regression analysis and the 12 publications that were not included, with details about the reasons for rejection.

Results: dropping RPYs with increasing GCRs

Most papers provided only the relative plot yield and gave no values for the relative field yield. The relationship between the GCR and the RPY was analysed. For the sake of transparency, two figures are presented for the GCR-RPY relationship. Figure 1 shows points for all 33 papers under consideration, including numerical simulation model results and questionable field results that did not meet the validity requirements. Figure 2 only includes validated results. Most (but not all) values for RPYs above 1 included in Fig. 1 did not meet the validity criteria and were therefore excluded from the final analysis.

Figure 1 displays some very high RPYs (i.e., above 1), including high GCR values. It is interesting that most of these were produced by studies that did not comply with this review's safety criteria. As a consequence, these data are not included in the final dataset (Fig. 2).

The RPY of crops decreased steadily with GCR (Fig. 2). A system with a GCR of 50% (typical ground-mounted photovoltaic system) will allow a 60% average relative plot yield only. A system with half as many panels (GCR = 25%) will allow an average relative plot yield of 80%. Pending more results from vertical systems, this decreasing RPY with increasing GCR seems to be shared by all other types of AV systems, including both fixed and mobile panels.

High RPYs were also documented in pastures (Madej et al. 2022), but with very low absolute yields. When absolute yields are this low, radiation, logically, may no longer be a limiting factor. It could be argued that in extreme environments or for some severe drought/heat events (such as those expected as a consequence of climate change), the positive impact of AV systems on low yields could be attractive—even for very low yields such as those documented by Madej et al. (2022). However, this positive impact should be assessed in a stochastic way, asking oneself: What is the frequency of such events? During years with no extreme stress events, the competition for light dominates, which may largely offset any advantage obtained during dry and hot years. Similarly, when crops grow on very poor soils and sites with very low potential yields, light may not be a limiting factor and RPY may be high, but such limited yields would not allow farmers to make a living.

It could also be stressed that some crops are deemed to be particularly well adapted to shade and could therefore reach high relative yields in the shade of panels—for example, red berries (Fernandez and Pritts 1996). Such fruit crops export low amounts of dry matter per hectare (usually less than 2 T ha^{-1} $year^{-1}$) and may therefore be compatible with low levels of radiation. However, the results by Jiang et al. (2022) on kiwi fruit did not confirm a high shade tolerance in this species, which displayed reduced RPY for GCR values > 0.25. Unfortunately, no published data are available as yet in agrivoltaic systems for berry fruits such as raspberries, strawberries, and blueberries, but preliminary data on raspberries grown in AV by Duchemin et al. (2023) display a 20–32% yield reduction in AV compared with raspberries protected by plastic umbrellas, while the fruit taste quality is maintained.

In addition, some high RPYs were recorded in several agrivoltaic greenhouses in France with cucumber, eggplant, and tomato crops as a consequence of more foliar diseases in the control greenhouse than in the AV greenhouse (Sun'Agri project steering committee, pers. com). However, nothing could prove that this effect was due to the PV panels, since there were no replications. Such outbreaks of diseases in a greenhouse may depend on many different stochastic processes to the extent that these values could not be included in this synthesis, pending their publication and validation.

For perennial crops, the impact of shade may be delayed to the following years, and a solid assessment requires at least 3 to 4 consecutive years of monitoring. This is especially required with fruit trees that exhibit alternate bearing in production. This synthesis

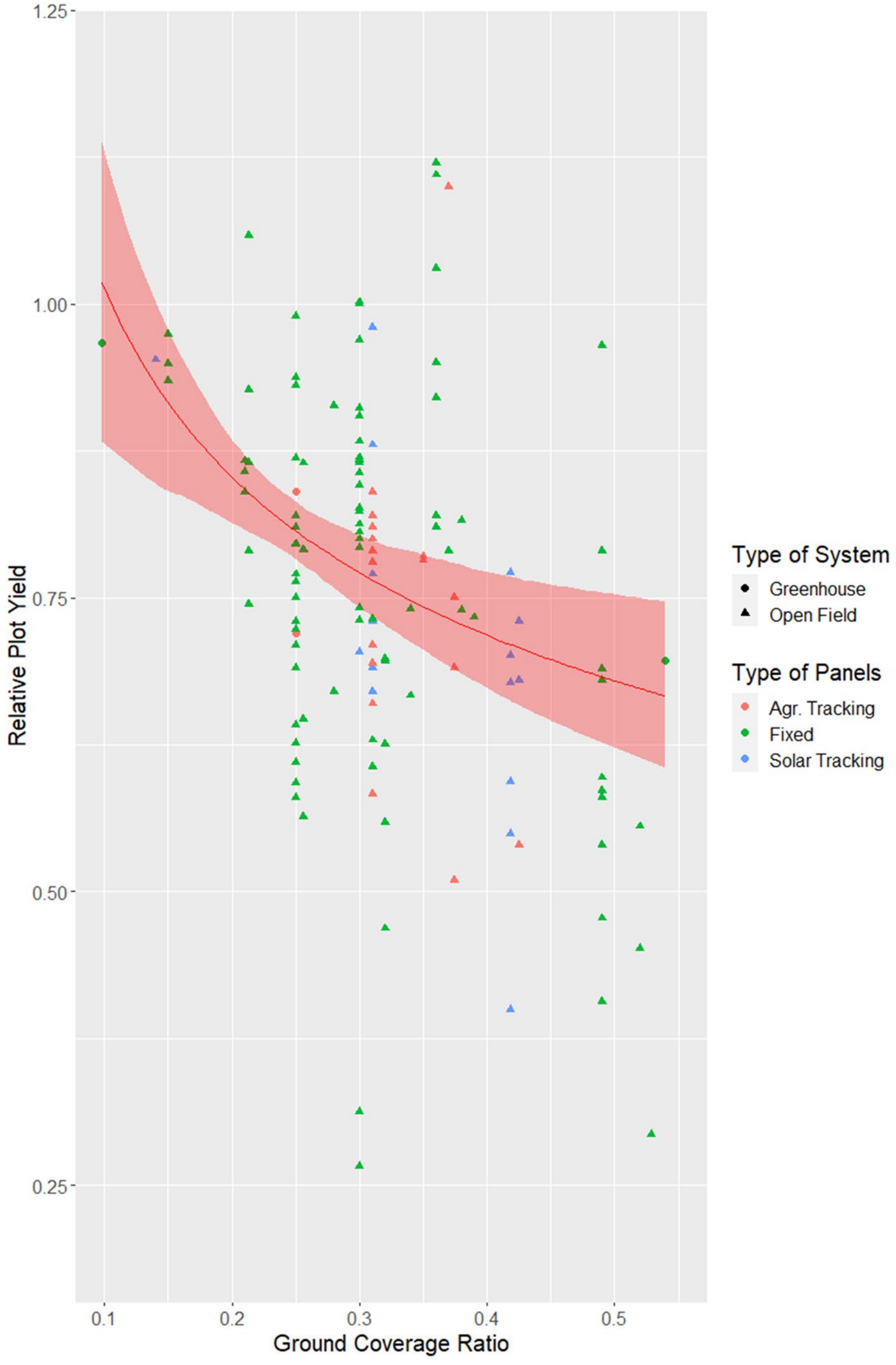

Fig. 2 Decrease in the relative plot yield in agrivoltaics as a function of the system's ground coverage ratio (comprising only the data that complied with the methodological criteria). Adjustment: $RPY = aGCR^{b}$ with $a = 0.5717$ and $b = -0.2486$

only includes results from apple trees with 4 years of yield measurements (Juillion et al. 2022), kiwifruits with 3 years of measurements (Jiang et al. 2022) and vineyards for one year but after 4 years under the AV system (Nidoleres farm, Tresserre, France; com. pers. Chambre Agriculture des Pyrénées-Orientales, Sun'Agri3 project). It is often suggested that perennial plants such as fruit trees may cope better with shade than annual crops, but this was not striking in the available data.

Many tropical shade-tolerant crops are often grown in agroforestry systems, such as coffee, cocoa, tea, and vanilla. These have not been included in any AV experiment so far. They would offer a new avenue for AV, given that they may tolerate shade better than temperate annual crops do.

Finally, the agronomic tracking of mobile panels (when panels do not shade the crops during some shade-sensitive stages) should result in higher RPYs for the same GCR. The limited number of datasets for mobile-panel systems with agronomical tracking (AT) did not allow us to compare the response curve of RPYs to GCR for agronomical tracking versus pure solar tracking versus fixed panels. Pending more data, a simple calculation may help to anticipate this impact. Assuming that no shade is cast on crops during 2 months per year, mobile AT may reduce the annual shade on crops by 10%, which would induce an increase in the RPYs by 8%, if one extrapolates the derivative of the GCR-RPY curve around the GCR = 0.3 point (Fig. 2).

Comparison with published meta-analyses of crop shading experiments

Two review papers recently synthesized the impact of shade on crops under various conditions (Aroca-Delgado et al. 2018; Laub et al. 2022). Most of the experiments cited in these papers used various shade nets that provided a homogeneous shade pattern, which is quite different from the shade strips cast by an agrivoltaic system. This means that one should refrain from directly extrapolating such results to agrivoltaic systems. However, it is interesting to compare the results of the more recent study (Laub et al. 2022) to our conclusions. While 58 papers were included in Laub et al.'s meta-analysis, only 2 of these came from AV studies—these 2 papers are also included in our review (Fig. 3). Therefore, the two datasets are almost independent.

Table 4 shows the results of Laub et al. (2022), transposed to AV systems by assuming that a GCR of 45% corresponds to a shade ratio of 50%, and a GCR of 20% corresponds to a shade ratio of 25%

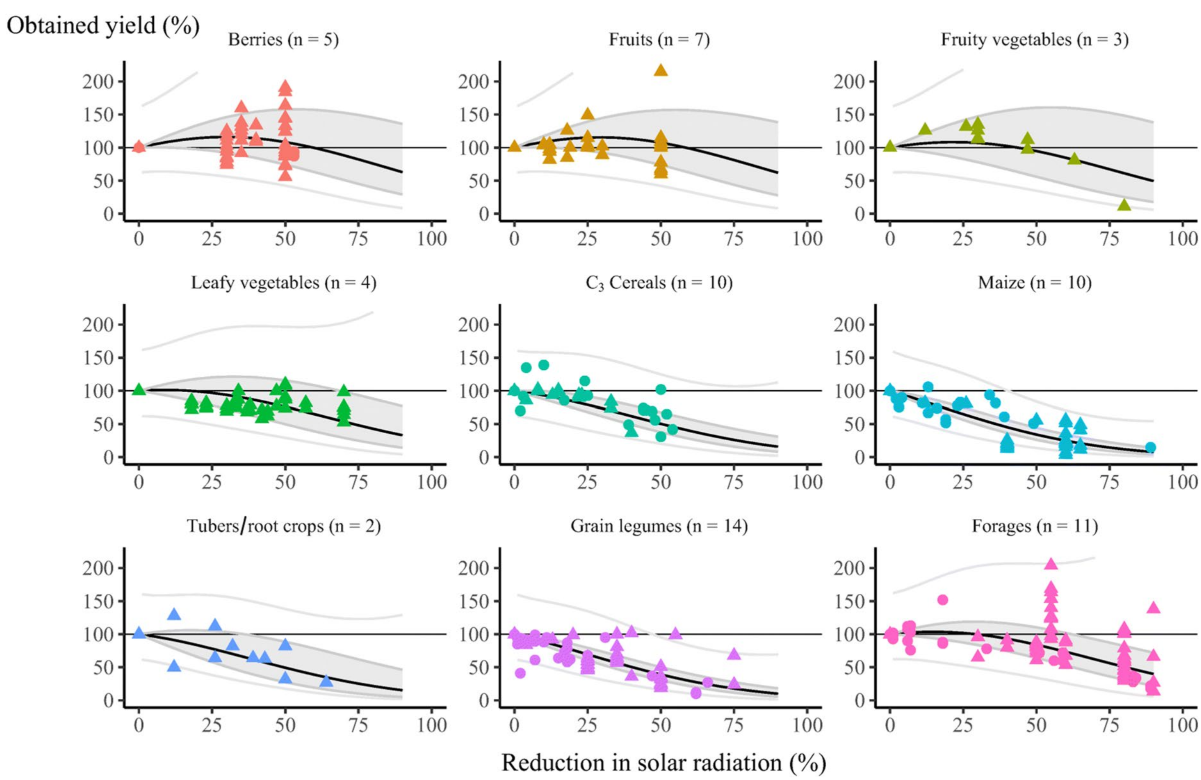

Fig. 3 Impact of shading on the relative yield of various types of crops (Laub et al. 2022)

Table 4 Changes in the RPY of agrivoltaic crops as deduced from Laub et al. (2022) synthesis for 25% and 50% shade ratios

Crops	n	25% shade (proxy for GCR = 20%)	50% shade (proxy for GCR = 45%)
Berries	5	+ 15%	0%
Fruits	7	+ 10%	0%
Fruity vegetables	3	+ 5%	− 5%
Leafy vegetables	4	0%	− 25%
C3 Cereals	10	− 20%	− 45%
Maize	10	− 40%	− 60%
Root crops	2	− 25%	− 50%
Grain legumes	14	− 30%	− 60%
Forages	11	0%	− 20%
Weighted (by n) Average	66	− 14%	− 35%

The RPY change values were deduced from the fitted curves

(see Table 2). With 50% shade, most annual crops experience a significant drop (35%) in their production (and even a 50% relative yield drop for grain legumes, tuber crops, maize, and cereals), while perennial crops (forages, berries, and fruit trees) and some vegetables are less sensitive. With 25% shade, the average decrease in yield was 14% (Table 4).

The two approaches are consistent. However, some outstanding high relative yields were recorded for some (non-agrivoltaic) shading experiments with berries, fruit trees, and forages in Laub et al. (2022). These results need to be confirmed in agrivoltaic studies. Protection against climatic hazards such as frost, heat, and drought may explain such results, which are actively sought in "positive" agrivoltaic systems. Published evidence is still lacking, but many research projects are now addressing these issues for vineyards and fruit trees.

The shade of AV systems is very different from the shade provided by the shade nets that were used in most of the experiments synthesized by Laub et al. While shade nets provide a homogenous shade all day long, agrivoltaic systems impose on the plants sharp transitions from full direct sunlight to full shade several times per day. It was evidenced by Way and Pearcy (2012) that delays of 10–60 min may occur for stomata to fully reopen following a transition from shade to sun. Therefore, the performance of crops under AV systems may be lower than the performance of crops under shade nets for the same average shade level. The results of Laub et al. should therefore be considered optimistic when extrapolated to AV systems.

In AV, the yield of the crop is also reduced by the land area that is no longer cropped (the "lost area"): lines of posts, areas with cables, electric installations, areas needed for guy cables and anchors, and maintenance roads. A fair estimate of that lost area is approximately 10% of the land, but it may vary in the [5%; 30%] range, depending on the type of structure. When including this aspect, the relative field yield (RFY) of agrivoltaic crops is lower than the RPY (Table 5).

The Italian and German policies are the only ones so far to indicate a maximum "lost area" ratio in AV systems: 30% in Italy (Ministero della transizione ecologica 2022) and 10 to 15% in Germany (Deutsches Institut für Normung 2021). The highest values of these ranges would seriously impact the RFYs. It appears that to maintain an 80% relative field yield (as in the Japanese regulation), the GCR of AV systems with 10% lost areas should

Table 5 Relative field yields (RFY) of agrivoltaic systems, including the impact of 10% "lost area" in the system

GCR	Relative field yield (RFY)		
	Average (%)	Shade intolerant species[a] (%)	Shade tolerant species[b] (%)
25% (Typical AV system)	− 22	− 37	− 5
50% (Standard ground mounted PV system)	− 42	− 60	− 20

[a]According to Laub et al. (2022), shade-intolerant species are cereals, maize, root crops, and grain legumes.

[b]According to Laub et al. (2022), shade-tolerant species are berries, fruits, fruity vegetables, and forages.

not exceed 20%. This is less than the values recommended by Akiro Nagashima in his book *Solar Sharing* (Nagashima 2020) and widely applied in Japan today, where most AV systems have a 30% GCR.

Discussion: advantages of using the GCR in AV policies and labels

Policies usually refer to the field yield as they compare AV with standard cultivation, but this is not always clear in their current formulation. For example, when the German policy allows a maximum of 10% lost area and requires at least 66% of RY, is this 66% value the RPY or the RFY? It should be the RFY, and the RPY should then be at least 0.73 when the lost area is 10%. This should be made clear in all AV policies. In Japan, where an 80% RFY is required by the legislation and where the lost area is often 25%, since post lines are close to each other (Fig. 4), the RPY should be at least 1.07, which means that to meet the policy requirements, the crop yield per m^2 should be higher in the AV system than it is in standard agriculture.

Most AV policies so far require that the crop yield be maintained or slightly decreased and demand that project managers measure the crop yields year after year, both under the AV system and in a close control "full sun" area. This criterion, however, is difficult to measure and control for the following reasons:

1. The need for a fair control plot in full sun, with fair management. It is quite easy to "prove" that the crop yield under an AV system is acceptable by neglecting the full-sun crop control, thus reducing the latter's yield. Reliable crop control would normally also require a prior check of soil homogeneity. Many experiments run by seasoned scientists failed to prove this homogeneity, with a potential negative impact on the results when homogeneity is wrongly assumed.
2. The need for costly and labour-intensive crop yield measurements (i.e., sampling, separate harvesting, field and lab measures) that are not easily performed by farmers.
3. Year-to-year variability: depending on the climate, the relative crop yields do fluctuate. Therefore, only pluri-annual assessments of crop yields would be sensible. This would require a lot of time and money, year after year.

The Italian regulation insists on crop yield monitoring as necessary to define "advanced" AV

	
Lizuka, Sosa, Chiba, Japan Wheat crop Distance between post lines: 4 m Cropped area: 75% GCR: 33%	Sasaya, Nihonmatzu, Fukushima, Japan Wheat crop Distance between post lines: 2 m Cropped area: 50% GCR: 25%

Fig. 4 Two examples of AV sites in Japan where the 80% minimum relative field yield of the crops is almost impossible to achieve, since the uncropped area is already between 25% (left) and 50% (right) of the plot area (GCR provided by Tajima M., pers. com.)

systems that may be eligible for financial support through grants. This shows how this measurement may be crucial for projects. In some cases, developers refuse to set up a full sun control, arguing that the crop would not grow without the shade of the panels. This may be true in desert climates for plants such as lettuce or red kiwis. In that case, the control treatment should be the usual way of growing this particular crop, using shade structures or shaded greenhouses.

Conversely, the GCR of any AV facility is easy to measure, and it cannot be modified or misreported easily. If an AV power station has a low GCR that warrants sustained yields of crops, the control becomes easy: it is enough to check that the AV field is cropped. This could even be done remotely, since it is very easy to use aerial pictures, now commonly used by governmental agencies to check crops. An alternate option is to install a few video cameras in each agrivoltaic plant. Cameras can document a system's lost area more precisely than aerial pictures because panels mask part of the cropped area.

Some PV developers argue that with some specialty crops (e.g., berries, fruit trees, and vineyards), a high GCR is compatible with high relative yields (Macdonald et al. 2023). High GCRs are also required to protect crops efficiently against climate hazards. While this may be true, such systems with a high GCR will not allow the farmer to replace the fruit crops with species that require more light. This would in fact reduce the farmer's options to change crop rotation in the future.

The issue of the relative crop yield in AV systems is also of importance for European farmers in relation to the Common Agriculture Policy (CAP) payments. Indeed, should these payments decrease proportionally as productivity decreases? This question is crucial for farmers. Germany has decided that crops in AV would receive a lump 85% of the CAP payments. In France, 100% of the CAP payments are being considered for future regulations, but this may be questioned if the relative yields are significantly decreased. Ensuring that AV systems do yield as much as standard fields would greatly simplify the policy controls, including for the European Common Agricultural Policy.

In Japan, the situation is even worse. The law requires an 80% minimum RFY of the crop, which is very difficult to achieve. Most systems in Japan have low distances between posts—two such systems are illustrated in Fig. 4.

As a consequence, new AV projects in Japan are no longer bankable. The banks refuse to finance new projects, in fear that the control of the RFY will induce a cut on the Feed In Tariffs for electricity that are crucial for the economic profitability of the projects. Most Japanese AV sites have a 30% GCR, which is not compatible with an 80% RFY.

Agrivoltaic labels such as the French AFNOR (AFNOR 2021) or the German DIN SPEC 91434 (Deutsches Institut für Normung 2021) were recently published. The current French AFNOR label for cropped AV indicates 50% as a recommended maximum value for the GCR of AV systems (criterion n°2.A). This value is in fact the value for ground-mounted PV systems, and it is totally incompatible with sustained yields of the crops, as evidenced by our synthesis. The German DIN label does not provide any maximum value for the GCR of AV systems. Our recommendation is that AV systems do not exceed 25% GCRs, which is approximately half the value of the standard GCR in common ground-mounted PV power stations.

Crops need light, and this synthesis shows that common ground-mounted PV projects (with GCRs > = 50%) are not compatible with a satisfactory crop yield. Some authors have extrapolated limited data sets of crop yield under AV systems and reached overoptimistic conclusions, such as Sarr et al. (2023) or Moreda et al. (2021). The latter, for example, assumed that maize would maintain its yield under PV panels, following the experiment by Sekiyama and Nagashima (2019). Unfortunately, further experiments on maize (Kim et al. 2021; Ramos-Fuentes et al. 2023) have not provided consistent results and instead suggest that maize may not thrive under PV panels. Similarly, in their recent synthesis on the potential of AV for the European Union, Chatzipanagi et al. (2023) referred to a very limited number of studies to assess the impact of panels on crop yields, and unfortunately, they relied on those few studies that predict surprisingly high yields under panels (Hudelson and Lieth 2020; Sekiyama and Nagashima 2019; Trommsdorff et al. 2021; Weselek et al. 2021). Some of these experiments were performed on a small scale, with potentially marked edge effects that may have led to an overestimation of crop yields.

Our synthesis is less biased, hopefully, since it includes most of the experiments that have been published to date and thus shows more solid and reliable trends. With 25% shade (i.e., with a GCR close to 20%), most crops behave well, and the average plot scale yield reduction is approximately 23%. With 60% shade (i.e., a GCR close to 50%), most crops see their productivity drop, with an average plot scale yield reduction of 55%.

Some recent experiments have shown that using panels for climate mitigation may be favourable to crops. This is especially true with perennial crops such as fruit trees and vineyards in dry and hot climates. In that case, climate protection could be positive, even with high GCRs. However, more data are needed to support this point. A balance needs to be struck between yield reduction due to shade and crop protection thanks to the panels during extreme weather events. If the GCR is too low, the protection may not be adequate. The optimal GCR will depend on the frequency of weather events when panel protection is positive. This is a clear illustration of the competition/facilitation in mixed systems documented by Vandermeer (1989). With climate change, the occurrence of negative events will increase, which might lead to systems with a higher GCR becoming acceptable.

In an AV system, the income from electricity exceeds by a factor of 10–50 the income from agricultural crops. Usually, the land owner will receive a payment for lending the site, and this payment may be much more than the expected agricultural income. It is very tempting for the land owner to give up agriculture (including to stop renting the land to a farmer if they are not a farmer themselves) and become an annuitant. This will especially be the case if high GCRs prevent acceptable crop yields. For this reason, our recommendation is that sustainable AV systems should have limited GCRs, which will ensure that cropping remains attractive, including if the farmer needs to change the crop rotation. Values of GCRs up to 25% are recommended for AV systems with fixed or mobile panels with solar tracking. For mobile panels with agronomical tracking, higher GCRs could be accepted, up to 35%, but with contractual commitments to provide more light to crops during light-demanding phenological stages, which may require further controls. Achieving business models that are profitable for electricity companies with such low values of GCRs is the key challenge for the future of agrivoltaic systems.

Conclusion

The ground coverage ratio of any agrivoltaic (AV) system is fixed and easy to calculate. Our synthesis indicates that the GCR is a simple predictor of the relative plot yield in AV and that GCRs > 0.25 are not advisable in AV systems if yield is to be maintained. Using the GCR may be useful to easily distinguish between agrivoltaic projects and ground-mounted photovoltaic projects. This would avoid the difficult control of AV systems through field measurements of crop yields. The GCR and the rate of lost area in the system may be combined to predict the relative field yield, which is essential to qualify a project as agrivoltaics. More data are needed to check whether the relationship between the GCR and the relative plot yield differs in different AV systems (i.e., open air vs greenhouse; fixed vs mobile panels; opaque vs semi-transparent panels). Other structural criteria may also be used to qualify an AV project, such as a minimum elevation of the panels above ground. Indeed, clearance should be high enough to provide a more homogeneous irradiation of the crops, allow for the passage of agricultural machinery, and provide flexibility for any future crop rotations.

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Declarations

Competing interests The authors declare no competing interests.

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