Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems. A meta-analysis.

Moritz Laub (ML) [a,b#], Lisa Pataczek (LP)[a#*], Arndt Feuerbacher (AF)[b], Sabine Zikeli (SZ)[a], Petra Högy (PH)[c]

[a]Center for Organic Farming, University of Hohenheim, Germany
[b]Agricultural and Food Policy Research Group, University of Hohenheim, Germany
[c] Plant Ecology and Ecotoxicology, University of Hohenheim, Germany
[#]Both authors equally contributed to this work
*Corresponding author: Lisa Pataczek, Center for Organic Farming, University of Hohenheim, Fruwirthstr. 14-16, 70599 Stuttgart. Email: lisa.pataczek@uni-hohenheim.de

Abstract:

Despite the large body of research studying crop growth parameters, there is still a lack of systematic assessments on how harvestable yields of different crop types respond to varying levels of shading. However, with the advent of agrivoltaic (AV) systems, a technology that combines energy and food production, and the new focus on agroforestry (AF), shade tolerance is becoming an important parameter for crop production systems. To address this research gap, a meta-analysis with data from two experimental approaches (intercropping and artificial shading with cloths, nets or solar panels) was performed to quantitatively assess the susceptibility of different temperate crop types to increasing levels of shading. Crop type specific yield response curves were estimated as a function of reduction in solar radiation (RSR), by estimating relative crop yields compared to the unshaded controls. Only studies that reported RSR and crop yield per area in temperate and subtropical areas were included. Using a random slope effect for each study, the specific variance components were accounted for. The results suggested a nonlinear relationship between achieved crop yields and RSR for all crop types. Most crops tolerate RSR up to 15%, showing a less than proportionate yield decline. However, significant differences between the response curves of different crop types existed: Berries, fruits and fruity vegetables benefited from shading up to RSR of 30%. Forages, leafy vegetables, tubers/root crops and C3 cereals showed initially less than proportionate crop yield loss. In contrast, maize and grain legumes experienced strong crop yield losses even at low RSR levels. The results provide first indicators for differences in crop type suitability to shading, and thus for AV and AF systems. Detailed yield response curves, as provided in this study, are valuable tools to optimize the output of annual crop components in AV and AF systems.

Keywords:

Crop specific meta-analysis; Shading; Agrivoltaics; Agroforestry; Shade sensitivity; Shade tolerance; Crop yield

1. Introduction

With its goal to reach net-zero greenhouse gas emissions by 2050 (European Commission 2018), the European Union (EU) has recently made another clear commitment towards renewable energies. A substantial increase in renewable energy investments, particularly in photovoltaics (PV), will be required to achieve this goal. Yet, one of the most cost-effective technologies, ground-mounted photovoltaic (GM-PV) systems, directly competes for land with agricultural production (Schindele et al. 2020). Agrivoltaic (AV) systems enable the combination of PV and agricultural production on the same area of land (Dinesh and Pearce 2016), e.g., by elevating the PV panels to heights greater than five meter (Fig. 1).

Fig. 1 Shaded winter wheat in an agrivoltaic system in Germany

This allows for all agricultural activities to be performed in AV systems, thus maintaining most of the crop growing area. While AV systems come at higher costs compared to GM-PV, they may still allow for reasonable agricultural yields (Schindele et al. 2020). However, apart from the additional income from the PV, the shade tolerance of the crop is essential to determine the economic outcome of AV (Feuerbacher et al. 2021). Defining and delimiting AV in comparison to GM-PV was one reason to establish the specification ("pre-standard") 91434 for AV systems in Germany (DIN SPEC 91434:2021-05). However, key figures of agricultural yields in these systems could not be standardized due to missing data of crop yield responses in AV and a lack of synthesized knowledge of crop yield responses in the shade in general. Although some crops can show yield reductions due to e.g., alteration of microclimatic conditions in shaded systems (Weselek et al. 2021), some crops can even adapt their morphology or physiology, leading to low or no yield losses (Arenas-Corraliza et al. 2019). Depending on the general climatic condition of the evaluated location, crops can benefit from shading in hot and dry areas (Barron-Gafford et al. 2019), leading to synergies known in intercropping systems, but without competition for nutrients and water. Also agroforestry (AF) systems have recently regained attention in the EU due to their potential to sequester carbon (Kim et al. 2016) and to increase both total system yields and ecosystem services (Kay et al. 2019). However, the economic performance of AF systems also depends on the degree of shade-induced yield changes (Kay et al. 2018). In order to develop improved AF and AV systems, to optimize crop rotations or to estimate the adoption potential of these systems at different spatial scales, it will be important to know, how different crop types react to varying levels of shade. To our knowledge, there is yet no systematic analysis of crop yield responses to shading. Recently, Weselek et al. (2019) conducted a literature review about the potential of AV systems including a qualitative assessment of crops potentially benefiting and suffering from shading. They concluded that fruits and vegetables will likely benefit from shading but found ambiguous results for cereals and potatoes. Their assessment was only qualitative neither allowing reliable estimations nor optimization of shade levels in AV and AF systems.

In the light of the above, this study's objective is to conduct a detailed and quantitative analysis of the response of different crop types to shading, for relevant crop types in temperate and subtropical regions, where radiation is potentially the main limiting factor. The focus is on differences in the yield response of different crop types to shade, as absolute yields depend on much more than just radiation. Many regions are facing either a strongly growing or already mature market of ground-based PV systems, which in combination with land scarcity makes them particularly relevant for the establishment of AV systems. In this regard, the present study may also serve as a basis for further developments of AV standards and legislation or AF certifications. Expanding the concept of Beck et al. (2012), who classified the yield response of crops into positive, negative and no change, we add a continuous scale for the level of shade to derive a prediction of crops' continuous responses to increasing levels of shading. We hypothesize that, across crop types, there are significant differences in yield responses to shading, which can be categorized as shade benefiting, shade tolerant and susceptible to shade. Shade benefiting crops are defined as crops experiencing a yield increase at low levels of shading with declining yield only at higher levels of shade. Shade tolerant crops experience a decline in yield that is less than proportional to the level of shading. Shade susceptible crops, on the other hand, are defined as crops that show a disproportionately large decline in yield with shading. This concept is used in the following as a basis to categorize the behavior of nine different crop types based on the results of the meta-analysis.

2. Material and Methods

2.1 Literature search

A systematic search in the scientific database SCOPUS was conducted with the terms ‘agrivoltaics’ (n = 17), ‘“agrivoltaic systems” AND crop AND yield’ (n = 10), ”solar panels” AND “crop yield”’ (n = 8), ‘shading AND “crop yield”’ (n = 278), and ‘shade AND yield’ limiting the results to the keywords including ‘shading’ OR ‘yield’ (n = 330). Additionally, references to other shading experiments within the results of the SCOPUS search (n = 15) and references mentioned in Weselek et al. (2019; n = 34) were collected. Excluding duplicates, a total of 613 studies were screened.

In order to assure representativity and relevance of studies, only publications presenting data from field or pot trials were included in the meta-analysis (Fig. 2). The criteria for exclusion of studies were as follows:

- Absence of yield assessment on a per area base (for fruits and vegetables yield per plant was considered representative in case of equal number of plants in shading/ non shading environments).
- Total absence of yield information.
- Shading not conducted throughout the full growing season. For perennial crops this was defined as the phase of fruit formation, for all other crops it was defined as four weeks after emergence until harvest.
- Exact shading period not mentioned.
- No exact data reported on the mean reduction in solar radiation (RSR), photosynthetically active radiation (PAR) or level of shading.
- Data from outside of temperate or subtropical regions (experimental sites between the Tropic of Capricorn and Cancer, 23°27’ North and South).
- Experiments from greenhouses as the system difference to AF and AV was considered too large.
- Minor crops (e.g., turmeric, pomegranate, stevia, medicinal herbs and winged bean), ornamental plants or plants not relevant for temperate regions (e.g., rice, cotton, jujube, coffee, cocoa, switchgrass and mung bean), or trees not used for agricultural production (e.g., common beech and common oak).
- Additional implementation of treatments other than shading, which were not applied to a corresponding control treatment (e.g., reduced irrigation).
- Studies only presenting modeled results.
- Literature reviews without own data.
- Experiments without an unshaded control treatment.

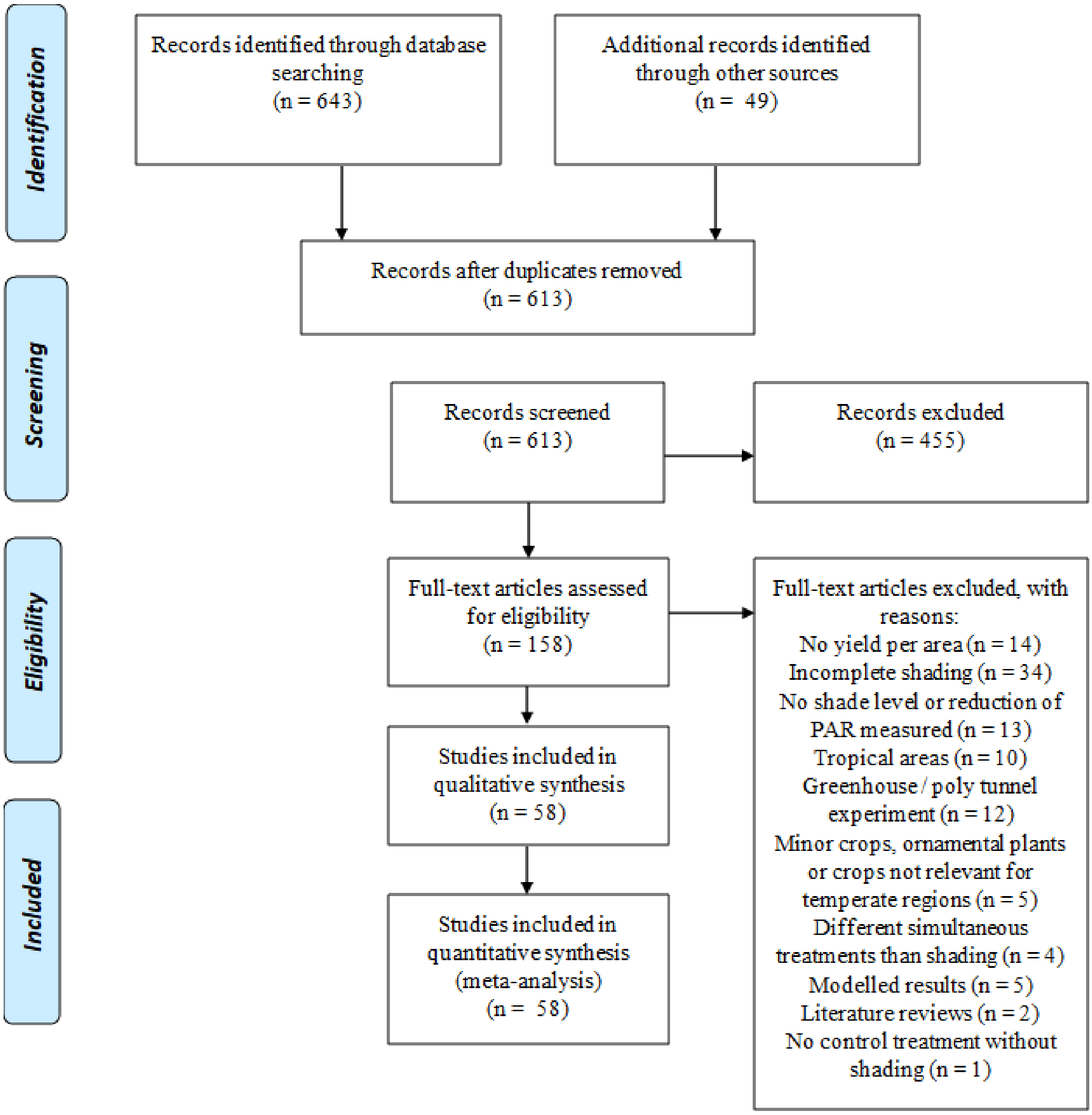

Fig. 2 Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Flow Chart describing the steps conducted in the search and selection of publications within this meta-analysis. Further details about the final 58 studies are presented in Table S 1.

Data of eligible publications were systematized into a table, extracting all data available from either tables or figures. Data from figures were digitized using WebPlotDigitizer software version 4.4 (Rohatgi 2020). The yields were standardized to relative yield under shading defining the unshaded control as 100%. This was done because the focus of the study was the yield response to shading and to obtain a common scale across publications. This was assumed to be the best way to deal with the range of site conditions and crop types in the different studies, which included different climatic zones and soil conditions. If data from several years were available, all years were included as individual data points. Explanatory variables of interest were crop type and the reduction in solar radiation or light intensity, which was expressed differently in the different studies, e.g., reduction in photosynthetically active radiation (PAR) or level of shading (expressed in %). Intercropping trials mainly reported reductions in

PAR, whereas trials with artificial shading (e.g., cloths) stated shade levels. Due to the different ways that radiation and shading were represented, sometimes without stating the baseline level of radiation, we chose to use the relative reduction in solar radiation (RSR) compared to the control, as a standardized measure across different studies. This RSR was derived from the level of shading or manually computed from the radiation under shading and the control. To account for the possible effect of absolute radiation at each site in a comparable way across all included studies, we obtained the site locations and extracted the average annual radiation (global horizontal irradiation) for each site from the World Bank Global Solar Atlas (https://globalsolaratlas.info/). Other confounding variables with the potential to affect the yield, such as type of shading (nets, cloths, PV panels, etc.) and the type of experiment classified into pure shading experiments (with PV modules or other artificial shading, e.g., cloths or nets) and intercropping experiments (including agroforestry), were also included in the systematized table.

2.2 Data analysis

The 58 studies provided effects of shade on yield for 38 different crop species (Table S 1), providing a total of 428 data points (340 without the no shade/control data points). Data on the individual crops were aggregated to the following nine crop types based on crop physiology and data availability: Berries, fruits, fruity vegetables, leafy vegetables, C3 cereals, maize, tubers/root crops, grain legumes, as well as forages (including grasses, forage legumes and multispecies forage stands). The table with the full dataset of the analysis can be found in a repository (doi: 10.5281/zenodo.5716091).

The statistical analysis was conducted using SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) with the general linear mixed model package (GLIMMIX). We conducted the meta-analysis using crop type specific linear meta-regressions. Less than half of the studies had reported measures of uncertainty and thus a weighting of studies by the inverse of the variance, as it is common in meta-analysis, was not done. As shown by Möhring and Piepho (2009), variance weighting in a meta-analysis may improve model performance in some cases, but the choice of data to include has the strongest impact. Using all suitable observations without weighting was thus considered superior to only using half the dataset with weighting of studies. The response variable of the model was the crop yield relative to no shading, explanatory variables were RSR the quadratic term thereof, and the interaction of RSR with crop types. To test the hypothesis that the yield response curve would be different between different absolute levels of radiation, we furthermore tested for a significant interaction of RSR and its quadratic term with absolute radiation, obtained for each location, as well as for a three-way interaction of RSR with absolute radiation and crop type. Interactions of RSR with other confounding categorical variables, such as the type of shading (e.g., nets vs. cloths vs. PV panels, or the color of the nets) were also tested for significance, to be able to account for confounding effects, should they exist. Backwards elimination of fixed effects assured that only significant explanatory variables remained in the final model used to predict the response curves (Table 1). The backwards elimination was done in a stepwise manner, removing fixed effects one by one starting with the least significant term, removing individual independent variables only after all interactions containing them were removed. The response variable "relative crop yield" was further transformed using a decimal logarithm to assure normality and homogeneity of variance, which was visually inspected based on histograms and Quantile-Quantile-Plots of model residuals. By definition, a 0% RSR results in 100% yield (or log10(yield) =2) and to force the regressions through this point (0/100 or 0/2 in the log10 scale), the value 2 was subtracted from the decimal logarithm of the yield and the regression was then forced through the origin. To account for location specific deviations from the main effect, a random slope effect for RSR (both linear and quadratic) was added with an unstructured covariance matrix. A random intercept was intentionally not allowed to assure that all the random regressions are forced through the origin. As model output, the mean and the 95% confidence intervals (CI) of the yield of each crop type were estimated in 5% steps for 5 to 80% of RSR, using the estimate function of SAS. Additionally, 95% prediction intervals (PI) were estimated, accounting for the variance of random effects and the residual error term in addition to the variance components of fixed effects (for further details on how to do this, see Laub et al., 2018; equation 3). The estimated means, CI and PI were then transformed back to normal scale as: value = $10^{(2+x)}$. Graphs were produced with R version 4.0.2 (R Core Team 2020), using the ggplot2 package (Wickham 2016).

Table 1 Analysis of variance of fixed effects of the mixed linear model, applied within this study (Type III). Displayed are the initial full model and the final reduced model after removing the insignificant interactions, keeping only those with type. RSR= reduction in solar radiation

Model	Fixed effect	Num DF	Den DF	F-value	p-value
Initial full model	RSR	1	41.52	0.14	0.7088
	RSR^2	1	32.96	0.67	0.4192
	RSR x crop type	7	33.39	2.05	0.078
	RSR x experiment type	1	32.69	0.01	0.9109
	RSR x climatic zone	1	57.48	6.44	0.0139
	RSR x colored nets	2	59.69	0.64	0.5321
	RSR x shade type	3	38.7	2.16	0.1087
	RSR x annual radiation	1	45.17	0.17	0.6819
	RSR x annual radiation x crop type	8	32.09	1.23	0.3135
	RSR^2 x annual radiation	1	34.04	2.05	0.1609
Final reduced model	RSR	1	33.18	0	0.9713
	RSR^2	1	31.09	12.05	0.0015
	RSR x crop type	8	55.22	7.16	<.0001

3. Results

3.1 Different crop types show different reactions to shading

Despite a high scatter within the raw data, the loss of crop yield at higher levels of RSR is evident for all crop types (Fig. 3). However, the shape of the curves are profoundly different. The analysis of variance (Table 1) shows that the quadratic term of RSR is significant ($p \leq 0.005$) in explaining yield reduction for all crop types. However, there are highly significant differences ($p \leq 0.001$) between the crop types in the yields response to increasing levels of shading, corroborating the assumption of a varying behavior of different crop types to RSR. In contrast, there is no evidence of a significant difference in the response of yield to RSR between intercropping and shading-only experiments, or whether cloths, PV panels or nets were used for shading. Also the absolute level of radiation did not significantly affect the response curves.

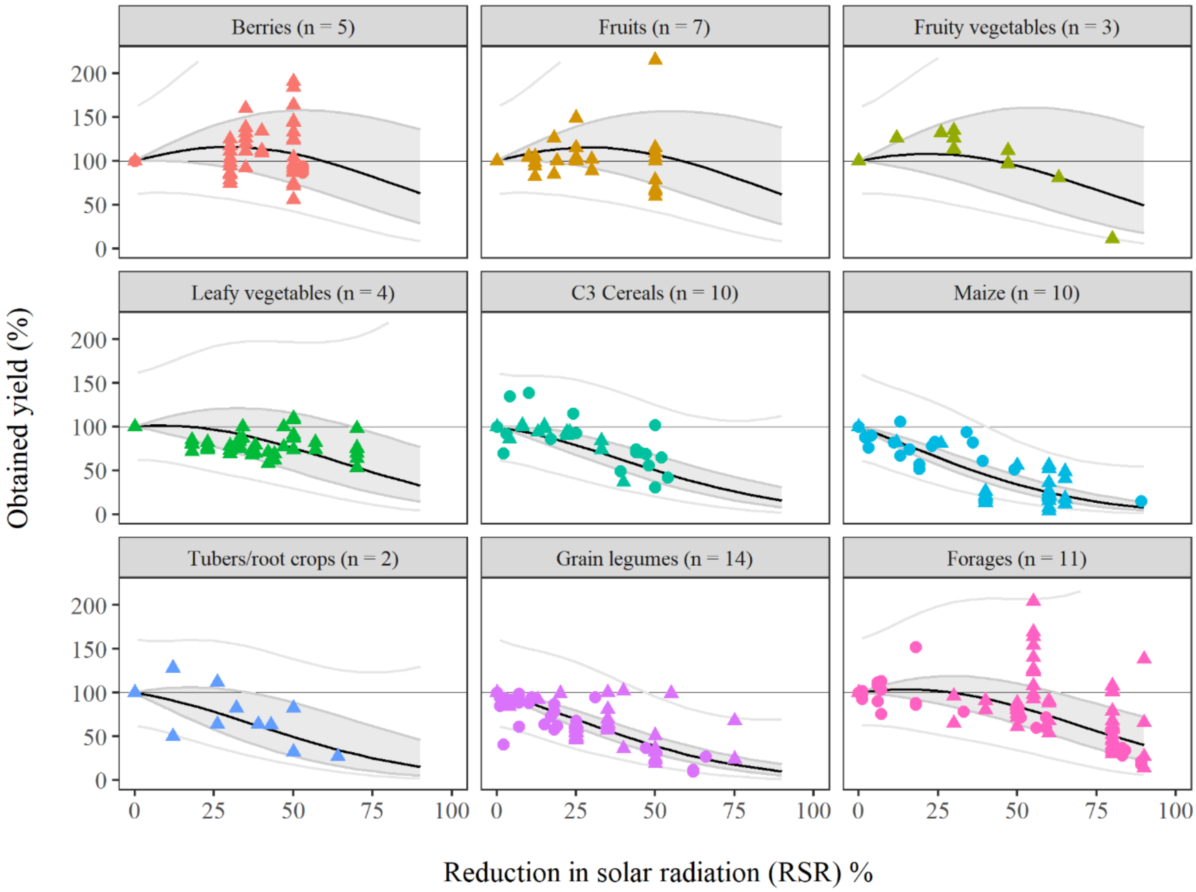

Fig. 3 Original data and derived crop type specific meta-regressions (black line) of obtained yield as function of reduction in solar radiation (RSR). The dark grey shaded band and light grey lines depict the 95% confidence intervals and prediction intervals, respectively. Triangles (Δ) represent data from normal shading experiments and circles (•) are from intercropping experiments. Two large values of the type ‘fruits’ (20,292 and 50,249) are not displayed for better visibility of all other points.

The strong difference in the estimated susceptibility of the different crop types is shown by the different shapes of the predicted response curves to RSR and in the difference in estimated means (Fig. 4). For a more detailed analysis where yield losses start, Fig. S 1 shows the estimated slope of yield reductions for varying levels of RSR across the nine crop types. The meta-regressions suggest that berries, fruits and fruity vegetables will likely experience increases in harvestable yield until RSR levels of about 30, 25 and 20%, respectively. To levels of at least 20% RSR, several other crop types show a yield decrease that is less than proportional to RSR. Those are in order of declining yield losses: forages, leafy vegetables and tubers/root crops. C3 cereals only have a less than proportional yield decline until 15% RSR. Grain legumes and maize are most susceptible to RSR and have a disproportionately large decline in yield right from 1% RSR. Due to the log transformation, uneven 95% confidence intervals (CI) around estimated means are predicted. Uncertainties in predicted crop yields depend strongly on the number of available measurements, how strong the response deviates from the general linear and the quadratic effect of RSR, as well as on the range of RSR for which observations are available. Therefore, berries and fruits, which have mostly positive responses in the experiments and no data points at very high levels of shading, as well as tubers/root crops and fruity vegetables, which have few observations overall, are subject to the highest level of uncertainty for yield prediction.

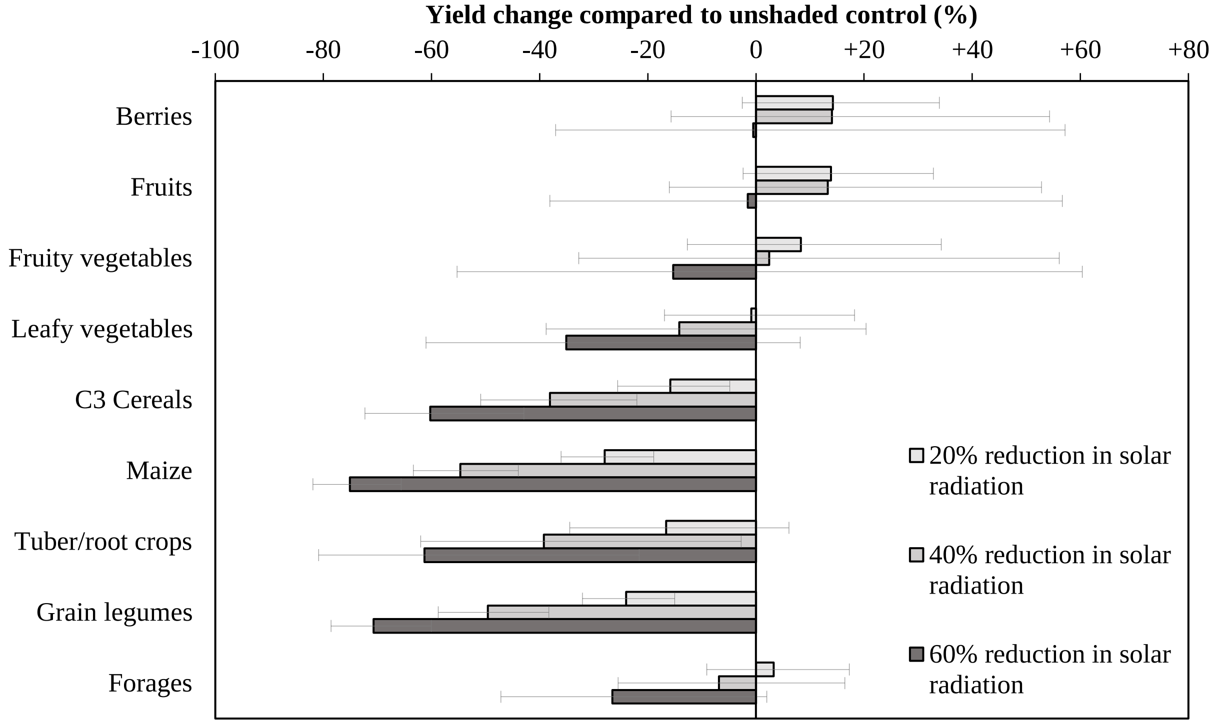

Fig. 4 Yield responses of different crop types to varying levels of reduction in solar radiation (RSR). Displayed are the least square means. Error bars delimit the 95% confidence intervals of the true mean. Within the same level of RSR, crop types with non-overlapping confidence intervals are significantly different ($p<0.05$).

3.2 Estimated crop yield changes due to moderate levels of shade

The predicted crop yields for different crop types in 5% steps of RSR reduction, including 95% CI, are provided the supplement (Table S 2). For maize, which is the crop type with the strongest and disproportionately largest yield loss in response to RSR, the estimated yield at 40% RSR is 45% (95% CI 37 to 56%). Also, grain legumes have disproportionately large losses of seed yield in response to RSR. Estimated yields at 40% RSR are 50% (CI 41 to 61%). In contrast to these crops, berries, fruits and fruity vegetables benefit at 20% of RSR (114, 114 and 108%, respectively) as well as at 40% RSR (114, 113 and 102% estimated yield, for berries, fruits and fruity vegetables, respectively; CI at 40% RSR: 84 to 154%, 84 to 152% and 67 to 156%). Forages are also estimated to be only little susceptible to RSR with an estimated yield of 103% at 20% RSR and 93% at 40% RSR (CI at 40% RSR: 75 to 117%). For leafy vegetables the estimate for 40% RSR is 86% (CI 61 to 120%).

4. Discussion

4.1 The shape of the yield response curve distinguishes beneficial and tolerable shade levels

The results of this meta-analysis shows a fact that may be exploited in optimizing both AF and AV systems: The relationship between RSR and crop yield is not simply proportional for any of the crop types. While maize and grain legumes are expected to react most strongly to RSR, all crop types are estimated to have at least a short initial range of less than proportional yield reduction in response to RSR. Therefore, low levels of shading appear tolerable for most crops. However, losses can become disproportionately large already at RSR greater than 10% for C3 cereals, and shortly thereafter for tubers/root crops. While the maximum obtainable yield predicted from the regression may be used to estimate the optimal levels of shading for each crop type, tolerable levels of shading for dual land use systems, could be with RSR levels that still allow for less than proportionate yield losses. Yet, how much yield loss is tolerable in AV and AF, strongly depends on the value obtained by the second land use activity (Kay et al. 2019). As the large prediction intervals suggest, absolute yields will be site dependent and influenced by factors such as soil fertility. The results thus allow to assess the relative shade tolerance of different cop types compared to one another, rather than to predict exact changes in yield. Consequently, the results help to identify crop types particularly suitable for the partial shade of AV and AF systems. At an estimated level of 20 to 40% shade, berries, fruits and fruity vegetables will likely benefit and the yield of forages suffer little. Leafy vegetables and tubers/root crops on the other hand are expected to suffer moderate yield losses. In contrast, maize and grain legumes seem less suitable for AV systems, at least compared to other crop types. Although growing C3 cereals in AV systems might lead to yield losses, cultivation may still be feasible, since several studies showed an increase in protein concentration in wheat grains under shaded cultivation conditions (Artru et al. 2017; Qiao et al. 2020), or rather a positive correlation between shade intensity and protein content in % in grains (Qiao et al. 2019).

Despite the differences between the response of different crop types to RSR, as shown by the highly significant ($p \leq 0.001$) interaction term between RSR and crop type, our statistical model estimates the difference in the reaction to RSR between different crop types mostly based on independent experiments, which has limited statistical power. Few studies tested more than one crop type in the same location, so in order to better understand the impact of soil type and climate we recommend to include various crop types at the same location for future studies. Future research on effects of shading on crop yield should especially focus on the crop types that were subject to the highest uncertainty, such as tubers/root crops and fruit vegetables.

4.2 Shade susceptibility changes dynamically with the level of solar radiation

The yield response curves show that a simple classification such as shade benefiting or susceptible (e.g., Beck et al. 2012) is very limited for optimizing the level of shade in AV and AF systems. Instead, a detailed analysis of the yield response curves should be carried out. All crops show susceptibility, at least with higher level of shading, and most show at least some tolerance towards low levels of shading. Depending on whether the goal of an AV and AF system is to maximize crop yields from ground component or returns from both the ground and the elevated component (which is yields from trees in AF and electricity from photovoltaic modules in AV), the optimal level of shading may vary substantially. In case of AV, it was shown that this also depends on the absolute changes in agricultural contribution margins and the relative price level of agricultural and energy outputs (Feuerbacher et al. 2021). Thus, crop types cannot generally be classified by their specific response curves as either shade benefiting, tolerant or susceptible. Depending on the level of shading, a crop-type may exhibit different response patterns as illustrated in Fig. 5. The "shade benefit" area shows situations, in which a crop type has higher yield due to shading compared to the unshaded control. Shade tolerance is the area of less than proportionate yield losses. Finally, susceptibility is the area below the linear interpolation of the points (0% RSR/ 100% yield) and (100% RSR/ 0% yield). Determining through which of those areas the crop type specific curves pass (Fig. 5) helps to identify suitable shade levels for each crop type. According to this classification, forages are shade benefiting until 25% RSR, and shade tolerant thereafter, while C3 cereals are not shade benefiting, but shade tolerant until 50% RSR and shade susceptible with RSR > 50%. A detailed classification of crop types by average shade tolerance at different levels of RSR compared to non-shading is shown in the supplement (Table S 2). The optimal level of shade is shown by the maximum predicted yield for each crop type (Fig. 3), which - depending on the crop value - may be more relevant than the average shade tolerance. For example, while berries at 40% RSR are still expected to benefit from shade compared to no shading, their highest yield is expected at around 30% RSR.

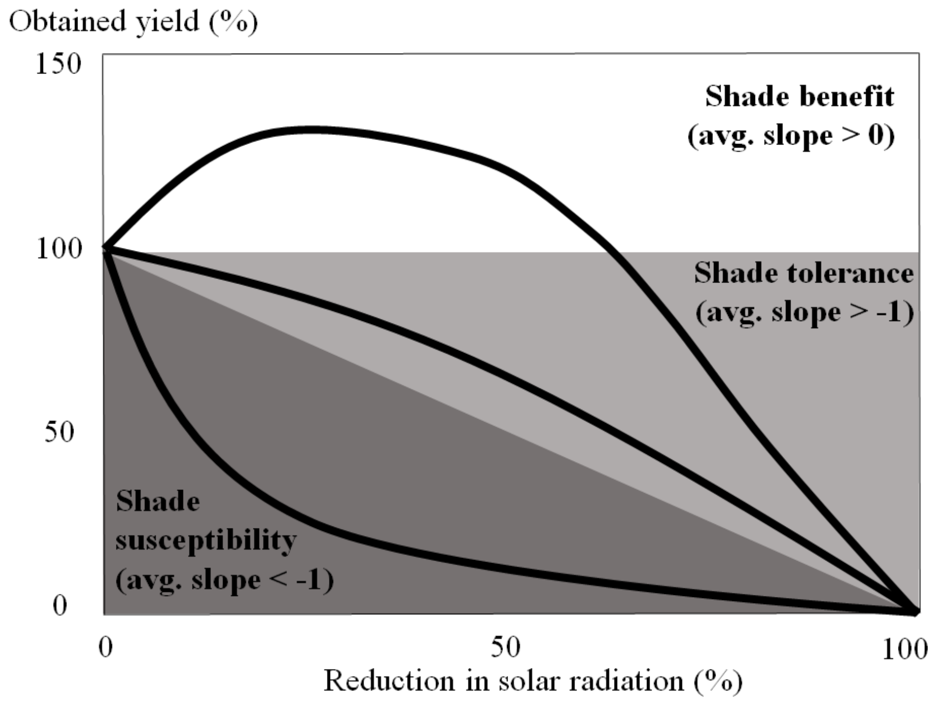

Fig. 5 A conceptual model showing shade sensitivity passing through areas of benefit, tolerance and susceptibility. Some crops are initially in the area of shade benefit (white area) and most are at least shortly in the area of shade tolerance (light grey shade), where their yield loss is less than proportionate.

4.3 What enables the shade tolerance of some crop types?

According to the results of this meta-analysis, maize is expected to be most susceptible to shading among all crop types studied. This is likely because maize is a C_4 plant, which can make use of high levels of solar radiation, but is sensitive to light restrictions (Gao et al. 2020). Shaded maize leaves show a reduced photosynthetic efficiency (Collison et al. 2020) and compete directly with cob development in terms of assimilate allocation (Chen et al. 2020). This results in reduced seed yield and harvest index. Similarly, grain legumes are estimated to be almost as susceptible as maize. In contrast, berries and fruits and fruity vegetables prove to be shade benefiting, while most of the other crops showed some shade tolerance and therefore seem to be suitable choices for crops grown in AV systems. The mechanisms that cause positive to tolerant responses are manifold, but can be related to morphological or physiological changes of a crop (Evans and Poorter 2001; Gratani 2014). Lettuce, for example, increases total and specific leaf area under shaded conditions, improving light interception (Marrou et al. 2013b; Valle et al. 2017). Though, if the total number of leaves per plant decreases interception (Marrou et al. 2013b; Valle et al. 2017), the effect on harvestable yield can be rather low. Overall, this may explain low yield losses of leafy vegetables under shading, lettuce in particular, with regard to the results of our meta-analysis.

For fruity vegetables, the low initial crop yield reduction due to RSR may be due to a change in the different components making up per area yield, or by changes in leaf area and photosynthetic activity. For example, bell pepper (*Capsicum annuum)* showed a tendency to reduce the number of fruits per plant at 26% RSR or higher, but single fruits were heavier and larger, compensating the lower quantity of fruits in terms of total yield (Rylski and Spigelman 1986). Also, total leaf area increases with increasing shade level (Rylski and Spigelman 1986), and net photosynthesis is found highest (Kabir et al. 2020) or unaffected (Díaz-Pérez 2013) at 30% RSR. Another important measure of horticulture and fruit production is yield quality and marketable yield. However, due to the diversity of crop types and studies, this is not covered in this meta-analysis. Shading of bell pepper e.g., results in a higher share of marketable yield due to the reduction of sun damage of the fruits (Rylski and Spigelman 1986; Díaz-Pérez 2014; Kabir et al. 2020). Thus, the benefit of shading for fruit vegetables might be even greater than the predicted yield indicates.

Beneficial side effects of shading for fruit production, such as increase in fruit numbers for blueberries, are also reported by Retamales et al. (2008). In their study, leaf size as well as shoot and internode length increased under shaded conditions, which they accounted to reduced stress conditions in the trial (in subtropical Chile). Rotundo et al. (1998) reported a prolongation of the harvesting period, when shading blackberry in a trial in Italy, resulting in an increase of cumulated berry yield. Additionally, the shading nets reduced leaf gas exchange, but increased the chlorophyll content, representing an adaptation mechanism to environments with RSR.

Also forages show adaptation mechanisms to RSR, which resulted in no effect on dry matter yield at 30% RSR (Mercier et al. 2020) and 45% RSR (Pang et al. 2019) or, depending on the crop species, even a slight increase of dry matter yield at 45% RSR (Pang et al. 2019). Varella et al. (2011) showed that alfalfa, a forage legume, can maintain an adequate photosynthetic activity even under dense shading conditions, suggesting that the light saturation point is reached, which is in general ranging between 25-60% of maximum sunlight for C_3 plants (Pang et al. 2019; Carrier et al. 2019). On the contrary, excess light above the saturation point could increase dark respiration rates and decrease photosynthetic efficiency of unshaded plants (Pang et al. 2019). This may explain the estimated yield increase in our study under 20% RSR, or rather the less pronounced effects on yield in comparison to other crop types.

Nevertheless, morphological changes due to RSR can result in yield reductions. For example, grain legumes showed a strong yield reduction due to RSR in our meta-analysis, which can be traced back to typical shade avoidance responses like e.g., internode length and stem elongation (Liu et al. 2017; Wu et al. 2017), resulting in plant lodging (Liu et al. 2015). Also, a reduced leaf area index was observed, which negatively affected soybean yield (Su et al. 2014). One potential confounder between crop classes response to shading should be investigated in more detail: the yield of grain legumes, maize and other cereals is commonly reported on a dry matter base, whereas in case of fruits, berries and fruity vegetables it is predominantly reported as fresh biomass. The comparison between these two reporting methods could thus be biased since the main driver of fresh biomass yield will be the soil as well as the plant water content. Under shading, evapotranspiration can be reduced due to a lower climatic demand and e.g., also changes in soil coverage (Marrou et al. 2013a). This condition can favor water flows to harvestable crop yield components and could be therefore an explanation for this clear visible trend, differentiating crop yield losses between crops based on dry matter yield and crops based on fresh biomass yield. For example, Artru et al. (2018) could show that the water content of sugar beet increased significantly under continuous shading in one experimental year, but root dry matter decreased at the same time. Although this had no effect on the sugar content itself, total sugar yield on a per area base was reduced due to decreased root yield under continuous shade. Thus, we strongly advice to also report dry matter yield for shading experiments with fruits and vegetables.

4.4 Implications and limitations of this study

With RSR data ranging to at least 50% RSR, this meta-analysis includes a sufficient range to assess the suitability of crops in AV and AF systems. Particularly AV systems rarely exceed a RSR of 50%: AV with fixed solar panels, referred to as ‘half-density’, typically range between 28% to 50% RSR (Dupraz et al. 2011; Elamri et al. 2018; Majumdar and Pasqualetti 2018; Marrou et al. 2013; Valle et al.,2017). AV with solar tracking range between 15% to 36% RSR (Amaducci et al. 2018; Elamri et al. 2018; Valle et al. 2017), whereas the RSR is rather depending on total panel area than on the tracking system (Amaducci et al. 2018). In contrast, PV systems optimized for electricity production, which is often indicated as ‘full density’ in the literature, are assumed to reduce radiation by about 50% and more (Dupraz et al. 2011). In AF systems, the levels of shading are similar as in typical AV (most in this study were in the range of 20-40%) but several studies reported levels above 80% RSR. Estimating the shade effect on crop yields for very high levels of RSR (>75%) are associated with high uncertainty as it would require extrapolations beyond the range of data availability. Moreover, our statistical model was not forced through the point of 0% crop yield at 100% RSR, which further adds uncertainty to very high RSR levels. However, with very high levels of shade in AF systems, are usually only present when trees are not pruned and in systems where the component below the tree is of subordinate importance.

This study is only a first attempt to establish differences in the shade tolerance between different crop types, based on the data availability until now. As the field of AV is still young, only four of the studies, which fulfilled our general inclusion criteria, used PV panels for shading. Yet, in the absence of a significant effect of shade type (Table 1), it is not evident that plants under AV should behave considerably different from other types of shading, as there was even not difference found between cloths, or nets and intercropping/AF systems. This could be due to purposeful selection of crops and trees with different root systems to reduce nutrient competition (Isaac and Borden 2019). Overall, the uncertainty of yield responses was quite high, as credibility intervals of many crop types pass through all different areas of shade tolerances (Fig. 3). Hence the presented results are more suitable to establish the differences between crop types than for site-specific yield predictions, e.g. they show that berries, fruits and fruit vegetables are much more likely to benefit from shading in AV systems at typical ranges of 20 to 40% RSR than maize or C3 cereals. Leafy vegetables, forages and tubers/root crops appear partly suitable, as they were still estimated to be in the range of less than proportionate losses. These findings are in alignment with the meta-analysis by Slattery et al. (2013), who found that shading increases plant energy conversion efficiency for many crops. They argued that this will likely counteract yield depressions, but for a yield increase, indirect benefits of shading are needed, such as higher water use efficiency and/or lower transpiration. The presented results could serve as an important data input for estimating the cost-effectiveness and adoption potential of dual land-use systems, for example by using them in the FEADPLUS framework (Feuerbacher et al. 2021): while the uncertainties at a plot scale (PI) are large, the overall trend represented by the CI is the more valid estimator at country or continental scales, where site specific positive and negative deviations should balance each other out. The results may also contribute to standardization and policy processes, in which the eligibility for policy support of AV systems with different levels of shading has to be determined. However, due to the large uncertainty, more trials will be needed for both AV and AF systems to corroborate or falsify the crop type suitability and improve the crop type specific meta-regressions. In some cases, AV systems are defined according to the level of yield reductions, e.g., in Japan, among other criteria, shading-induced yield losses in AV systems may not exceed 20% (Japanese Ministry of Agriculture 2016). In this context, the results of our analysis may help policymakers and relevant stakeholders to better understand the relationship between shading and yield loss and to define "acceptable" yield reductions of AV systems, or alternatively, maximum levels of RSR across different AV system designs combined with different crop types. Such considerations are very important in AV systems, to assure that economic crop yields under AV stay high enough to avoid unwanted side effects such as farmers abandoning the crop land below the AV system (Feuerbacher et al. 2021). We suggest that in any such analysis, yield response curves should be used instead of only assessing one level of shading.

The normalization of both shading and yield within this study enabled to predict crop type-based yield response curves, but comes with limitations. Due to a scarcity of studies on individual crops, the aggregation to crop types was necessary, but this masks heterogeneity between different crops in the same crop type classification. Also, the number of studies for different crop types ranged between two and eleven, which increases uncertainty for crop types with few data. By aggregating crops it was assumed, that there would be significant differences in the response of one aggregated crop type compared to another. However, if aggregated crop types are heterogeneous, this leads to a higher uncertainty for the predictions of that crop type compared to others. This was visible when comparing the relatively homogeneous C3 crops and maize to forages and fruits, the latter comprising both temperate and subtropical fruit trees. Another potential limitation is that absolute radiation was only approximated based on global radiation for each study location, as this variable was not available in many of the studies. However, that absolute radiation was not found a significant covariate to predict response curves, may be either due to the coarse resolution of global datasets but could also be due to the fact that the cropping season mostly corresponds to a time where light is abundant and other factors may be more important. This meta-analyses cannot directly capture other stresses, such as water stress, where shading may provide additional benefits, such as reduced evapotranspiration. Dynamic crop growth models (e.g., Amaducci et al., 2018) may help to provide improved recommendations, once enough calibrations and data are available. Further field experiments are needed especially for different AV (e.g., top-mounted AV panels with or without tracking or vertically mounted panels) or AF designs to provide the input to calibrate these data hungry model and further optimize systems. These may differ in their impacts on other factors than solar radiation, e.g., soil water distribution or air humidity.

To date the literature of the shading effect measured in AV experiments is still scarce. So far, there are only few studies on crop growth beneath AV systems, and they are limited to top-mounted solar panels (n=4 in our meta-analysis). We therefore included studies that had shading from various treatments. The type of shading (nets, cloths, PV modules or intercropping) was not a significant covariate in the final model. This could be an indication that AV systems should not have fundamentally different results, because the insignificant difference between cloths and intercropping should be a stronger one than between cloths and AV. Future research will need to make further tests if the effect of shading by AV is really not different from shading by other sources, such as nets, once more AV experiments become available.

Synthesized knowledge on the effect of shading on crop yields is still rare. We therefore hope that the dataset collected within this study may serve as a basis for future meta-analyses within the growing field of AV shading experiments. The dataset is therefore published in the zenodo repository (10.5281/zenodo.5716091). Overall, this study provides promising initial evidence about which crops are most likely to benefit from shading within AV systems. Moreover, our conceptual model and recommendations can be used as a basis to guide further research efforts on the effects of shading on crop yields.

5. Conclusion

We presented the results of a meta-regression by a mixed effects model, to estimate the susceptibility of different crop types to shading. The results suggested that berries, fruits and fruity vegetables show initial benefits up to 40% shade. Forages, leafy vegetables and tubers/root crops start with a less than proportionate loss of yield at low levels of shade, whereas maize and grain legumes are very susceptible to shading. From our analysis, it becomes clear that no crop type has an exactly proportional decrease of yield due to increased level of shading. To optimize shade systems, e.g., for the design of AV and AF systems, it is thus important to know the shape of the yield response curve and, depending on the objective, to identify the optimal level of shading for maximum yield or at where yield loss is still less than proportionate. Estimating the response curves of crop yield to shading is therefore very relevant and of significantly higher information content than classifying crops into categories of shade sensitivity. Results such as the ones of this study will be an essential input to better estimate the potential of AV systems in achieving a transition to renewable energies and of AF systems to sequester carbon and optimize agronomic output per unit of land and thus to design adequate policies supporting the adoption of these new technologies. However, especially for AV systems, more data and further experiments on new AV designs, e.g., dynamic systems, are needed to improve prediction of yield loss beneath AV and to adapt dynamic crop growth models.

Acknowledgements

We want to thank Prof. Dr. Hans-Peter Piepho for his kind advice in creating the meta-analysis.

Declarations:

Funding

This study was funded by the German Federal Ministry of Education and Research (BMBF), grant number 033L098G.

Conflict of interest/Competing interests

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics approval

Not applicable

Consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The datasets generated and analyzed during the current study are available in the Zenodo repository (https://doi.org/10.5281/zenodo.5716091).

Authors' contributions

PH and SZ acquired the funding for the work. LP screened the literature for relevant references. LP and ML digitized the dataset. ML conducted the statistical analysis and produced all graphs. ML together with LP wrote the first manuscript draft. AF gave intensive feedback on the first draft. All authors contributed to developing the final manuscript.

References

Amaducci S, Yin X, Colauzzi M (2018) Agrivoltaic systems to optimise land use for electric energy production. Appl Energy 220:545–561. https://doi.org/10.1016/j.apenergy.2018.03.081

Arenas-Corraliza MG, Rolo V, López-Díaz ML, Moreno G (2019) Wheat and barley can increase grain yield in shade through acclimation of physiological and morphological traits in Mediterranean conditions. Sci Rep 9:. https://doi.org/10.1038/s41598-019-46027-9

Artru S, Garré S, Dupraz C, et al (2017) Impact of spatio-temporal shade dynamics on wheat growth and yield, perspectives for temperate agroforestry. Eur J Agron 82:60–70. https://doi.org/10.1016/j.eja.2016.10.004

Artru S, Lassois L, Vancutsem F, et al (2018) Sugar beet development under dynamic shade environments in temperate conditions. Eur J Agron 97:38–47. https://doi.org/10.1016/j.eja.2018.04.011

Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, et al (2019) Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat Sustain 2:848–855. https://doi.org/10.1038/s41893-019-0364-5

Beck M, Bopp G, Goetzberger A, et al (2012) Combining PV and Food Crops to Agrophotovoltaic – Optimization of Orientation and Harvest. In: Proceedings of the 27th European Photovoltaic Solar Energy Conference and Exhibition. pp 4096–4100

Carrier M, Rhéaume Gonzalez F-A, Cogliastro A, et al (2019) Light availability, weed cover and crop yields in second generation of temperate tree-based intercropping systems. F Crop Res 239:30–37. https://doi.org/10.1016/j.fcr.2019.05.004

Chen G, Chen H, Shi K, et al (2020) Heterogeneous light conditions reduce the assimilate translocation towards maize ears. Plants 9:1–15. https://doi.org/10.3390/plants9080987

Collison RF, Raven EC, Pignon CP, Long SP (2020) Light, Not Age, Underlies the Maladaptation of Maize and Miscanthus Photosynthesis to Self-Shading. Front Plant Sci 11:1–10. https://doi.org/10.3389/fpls.2020.00783

Díaz-Pérez JC (2013) Bell Pepper (Capsicum annum L.) Crop as Affected by Shade Level: Microenvironment, Plant Growth, Leaf Gas Exchange, and Leaf Mineral Nutrient Concentration. HortScience 48:175–182. https://doi.org/10.21273/HORTSCI.48.2.175

Díaz-Pérez JC (2014) Bell Pepper (Capsicum annum L.) Crop as Affected by Shade Level: Fruit Yield, Quality, and Postharvest Attributes, and Incidence of Phytophthora Blight (caused by Phytophthora capsici Leon.). HortScience 49:891–900. https://doi.org/10.21273/HORTSCI.49.7.891

Dinesh H, Pearce JM (2016) The potential of agrivoltaic systems. Renew Sustain Energy Rev 54:299–308. https://doi.org/10.1016/j.rser.2015.10.024

Dupraz C, Marrou H, Talbot G, et al (2011) Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. Renew Energy 36:2725–2732. https://doi.org/10.1016/j.renene.2011.03.005

Elamri Y, Cheviron B, Lopez J-M, et al (2018) Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. Agric Water Manag 208:440–453. https://doi.org/10.1016/j.agwat.2018.07.001

European Commission (2018) A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. Com(2018) 773 114

Evans JR, Poorter H (2001) Photosynthetic acclimation of plants to growth irradiance: the relative importance of specific leaf area and nitrogen partitioning in maximizing carbon gain. Plant Cell Environ 24:755–767. https://doi.org/10.1046/j.1365-3040.2001.00724.x

Feuerbacher A, Laub M, Högy P, et al (2021) An analytical framework to estimate the economics and adoption potential of dual land-use systems: The case of agrivoltaics. Agric Syst 192:103193. https://doi.org/10.1016/j.agsy.2021.103193

Gao J, Liu Z, Zhao B, et al (2020) Shade stress decreased maize grain yield, dry matter, and nitrogen accumulation. Agron J 112:2768–2776. https://doi.org/10.1002/agj2.20140

Gratani L (2014) Plant Phenotypic Plasticity in Response to Environmental Factors. Adv Bot 2014:1–17. https://doi.org/10.1155/2014/208747

Isaac ME, Borden KA (2019) Nutrient acquisition strategies in agroforestry systems. Plant Soil 444:1–19. https://doi.org/10.1007/s11104-019-04232-5

Japanese Ministry of Agriculture F and F (2016) “About the handling under the farmland conversion permission system for solar power generation facilities, etc. that continue farming with pillars” (directly translated from Japanese with google translate)

Kabir MY, Díaz-Pérez JC, Nambeesan SU (2020) Effect of shade levels on plant growth, physiology, and fruit yield in bell pepper (Capsicum annuum L.). Acta Hortic 311–318. https://doi.org/10.17660/ActaHortic.2020.1268.42

Kay S, Crous-Duran J, García de Jalón S, et al (2018) Landscape-scale modelling of agroforestry ecosystems services in Swiss orchards: a methodological approach. Landsc Ecol 33:1633–1644. https://doi.org/10.1007/s10980-018-0691-3

Kay S, Graves A, Palma JHN, et al (2019) Agroforestry is paying off – Economic evaluation of ecosystem services in European landscapes with and without agroforestry systems. Ecosyst Serv 36:100896. https://doi.org/10.1016/j.ecoser.2019.100896

Kim D-G, Kirschbaum MUF, Beedy TL (2016) Carbon sequestration and net emissions of CH4 and N2O under agroforestry: Synthesizing available data and suggestions for future studies. Agric Ecosyst Environ 226:65–78. https://doi.org/10.1016/j.agee.2016.04.011

Laub M, Blagodatsky S, Lang R, et al (2018) A mixed model for landscape soil organic carbon prediction across continuous profile depth in the mountainous subtropics. Geoderma 330:177–192. https://doi.org/10.1016/j.geoderma.2018.05.020

Liu W, Zou J, Zhang J, et al (2015) Evaluation of Soybean (Glycine max) Stem Vining in Maize-Soybean Relay Strip Intercropping System. Plant Prod Sci 18:69–75. https://doi.org/10.1626/pps.18.69

Liu X, Rahman T, Song C, et al (2017) Changes in light environment, morphology, growth and yield of soybean in maize-soybean intercropping systems. F Crop Res 200:38–46. https://doi.org/10.1016/j.fcr.2016.10.003

Majumdar D, Pasqualetti MJ (2018) Dual use of agricultural land: Introducing ‘agrivoltaics’ in Phoenix Metropolitan Statistical Area, USA. Landsc Urban Plan 170:150–168. https://doi.org/10.1016/j.landurbplan.2017.10.011

Marrou H, Dufour L, Wery J (2013a) How does a shelter of solar panels influence water flows in a soil-crop system? Eur J Agron 50:38–51. https://doi.org/10.1016/j.eja.2013.05.004

Marrou H, Wery J, Dufour L, Dupraz C (2013b) Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. Eur J Agron 44:54–66. https://doi.org/10.1016/j.eja.2012.08.003

Mercier KM, Teutsch CD, Fike JH, et al (2020) Impact of increasing shade levels on the dry-matter yield and botanical composition of multispecies forage stands. Grass Forage Sci 75:291–302. https://doi.org/10.1111/gfs.12489

Möhring J, Piepho H-P (2009) Comparison of Weighting in Two-Stage Analysis of Plant Breeding Trials. Crop Sci 49:1977–1988. https://doi.org/10.2135/cropsci2009.02.0083

Pang K, Van Sambeek JW, Navarrete-Tindall NE, et al (2019) Responses of legumes and grasses to non-, moderate, and dense shade in Missouri, USA. I. Forage yield and its species-level plasticity. Agrofor Syst 93:11–24. https://doi.org/10.1007/s10457-017-0067-8

Qiao X, Chen X, Lei J, et al (2020) Apricot-based agroforestry system in Southern Xinjiang Province of China: influence on yield and quality of intercropping wheat. Agrofor Syst 94:477–485. https://doi.org/10.1007/s10457-019-00412-5

Qiao X, Sai L, Chen X, et al (2019) Impact of fruit-tree shade intensity on the growth, yield, and quality of intercropped wheat. PLoS One 14:e0203238. https://doi.org/10.1371/journal.pone.0203238

R Core Team (2020) R: A Language and Environment for Statistical Computing

Retamales JB, Montecino JM, Lobos GA, Rojas LA (2008) Colored shading nets increase yields and profitability of highbush blueberries. Acta Hortic 193–197. https://doi.org/10.17660/ActaHortic.2008.770.22

Rohatgi A (2020) Webplotdigitizer: Version 4.4

Rotundo A, Forlani M, Di Vaio C (1998) Influence of shading net on vegetative and productive characteristics, gas exchange and chlorophyll content of the leaves in two blackberry (Rubus Ulmifolius Schott.) cultivars. Acta Hortic 333–340. https://doi.org/10.17660/ActaHortic.1998.457.42

Rylski I, Spigelman M (1986) Effect of shading on plant development, yield and fruit quality of sweet pepper grown under conditions of high temperature and radlation. Sci Hortic (Amsterdam) 29:31–35. https://doi.org/10.1016/0304-4238(86)90028-2

Schindele S, Trommsdorff M, Schlaak A, et al (2020) Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. Appl Energy 265:114737. https://doi.org/10.1016/j.apenergy.2020.114737

Slattery RA, Ainsworth EA, Ort DR (2013) A meta-analysis of responses of canopy photosynthetic conversion efficiency to environmental factors reveals major causes of yield gap. J Exp Bot 64:3723–3733. https://doi.org/10.1093/jxb/ert207

Su BY, Song YX, Song C, et al (2014) Growth and photosynthetic responses of soybean seedlings to maize shading in relay intercropping system in Southwest China. Photosynthetica 52:332–340. https://doi.org/10.1007/s11099-014-0036-7

Valle B, Simonneau T, Sourd F, et al (2017) Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. Appl Energy 206:1495–1507. https://doi.org/10.1016/j.apenergy.2017.09.113

Varella AC, Moot DJ, Pollock KM, et al (2011) Do light and alfalfa responses to cloth and slatted shade represent those measured under an agroforestry system? Agrofor Syst 81:157–173. https://doi.org/10.1007/s10457-010-9319-6

Weselek A, Bauerle A, Hartung J, et al (2021) Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. Agron Sustain Dev 41:59. https://doi.org/10.1007/s13593-021-00714-y

Weselek A, Ehmann A, Zikeli S, et al (2019) Agrophotovoltaic systems: applications, challenges, and opportunities. A review. Agron Sustain Dev 39:1–20. https://doi.org/10.1007/s13593-019-0581-3

Wickham H (2016) ggplot2 - Elegant Graphics for Data Analysis. Springer International Publishing, Cham

References of the meta-analysis

Abbasi Surki A, Nazari M, Fallah S, et al (2020) The competitive effect of almond trees on light and nutrients absorption, crop growth rate, and the yield in almond–cereal agroforestry systems in semi-arid regions. Agrofor Syst 94:1111–1122. doi:10.1007/s10457-019-00469-2

Abeysinghe SK, Greer DH, Rogiers SY (2016) The interaction of temperature and light on yield and berry composition of Vitis vinifera “Shiraz” under field conditions. Acta Hortic 1115:119–125. doi:10.17660/ActaHortic.2016.1115.18

Amarante CVT, Steffens CA, Argenta LC (2012) Radiation, yield, and fruit quality of “Gala” apples grown under white hail protection nets. Acta Hortic 934:1067–1074. doi:10.17660/ActaHortic.2012.934.143

Artru S, Lassois L, Vancutsem F, et al (2018) Sugar beet development under dynamic shade environments in temperate conditions. Eur J Agron 97:38–47. doi:10.1016/j.eja.2018.04.011

Bing L, De-Ning Q, Xiao-Mei Z (2015) The shoot dry matter accumulation and vertical distribution of soybean yield or yield components in response to light enrichment and shading. Emirates J Food Agric 27:258–265. doi:10.9755/ejfa.v27i3.18889

Burner DM, Belesky DP (2008) Relative effects of irrigation and intense shade on productivity of alley-cropped tall fescue herbage. Agrofor Syst 73:127–139. doi:10.1007/s10457-008-9118-5

Carrier M, Rhéaume Gonzalez FA, Cogliastro A, et al (2019) Light availability, weed cover and crop yields in second generation of temperate tree-based intercropping systems. F Crop Res 239:30–37. doi:10.1016/j.fcr.2019.05.004

Chen T, Song Z, Zhang M, et al (2016) Effects of shading and plant density on ear development and plant productivity of spring maize in Northeast China. Chinese J Appl Ecol 27:3237－3246. doi:10.13287 /j.1001-9332.201610.028

Díaz-Pérez JC (2014) Bell Pepper (Capsicum annum L.) Crop as Affected by Shade Level: Fruit Yield, Quality, and Postharvest Attributes, and Incidence of Phytophthora Blight (caused by Phytophthora capsici Leon.). HortScience 49:891–900. doi:10.21273/HORTSCI.49.7.891

Ding S, Su P (2010) Effects of tree shading on maize crop within a poplar-maize compound system in Hexi Corridor oasis, northwestern China. Agrofor Syst 80:117–129. doi:10.1007/s10457-010-9287-x

Djordjevic B, Šavikin K, Djurovic D, et al (2014) Biological and nutritional properties of blackcurrant berries (Ribes nigrum L.) under conditions of shading nets. J Sci Food Agric 95:2416–2423. doi:10.1002/jsfa.6962

Do Amarante CVT, Steffens CA, Argenta LC (2011) Yield and fruit quality of “Gala” and “Fuji” apple trees protected by white anti-hail net. Sci Hortic (Amsterdam) 129:79–85. doi:10.1016/j.scienta.2011.03.010

Du S, Bai G, Liang Y (2011) Effects of soil moisture content and light intensity on the plant growth and leaf physiological characteristics of squash. Chinese J Appl Ecol 22:1101–1106

Ehret M, Graß R, Wachendorf M (2015) The effect of shade and shade material on white clover/perennial ryegrass mixtures for temperate agroforestry systems. Agrofor Syst 89:557–570. doi:10.1007/s10457-015-9791-0

El-Naby SKMA, Esmail AMAM, Baiea MHM, et al (2020) Mitigation of heat stress effects by using shade net on Washington navel orange trees grown in Al-Nubaria Region, Egypt. Acta Sci Pol Hortorum Cultus 19:15–24. doi:10.24326/asphc.2020.3.2

Elamri Y, Cheviron B, Lopez J-M, et al (2018) Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. Agric Water Manag 208:440–453. doi:10.1016/j.agwat.2018.07.001

Gao J, Shi JG, Dong ST, et al (2017a) Effect of different light intensities on root characteristics and grain yield of summer maize (Zea Mays L.). Sci Agric Sin 50:2104–2113. doi:10.3864/j.issn.0578-1752.2017.11.016

Gao J, Zhao B, Dong S, et al (2017b) Response of summer maize photosynthate accumulation and distribution to shading stress assessed by using13CO2 stable isotope tracer in the field. Front Plant Sci 8:. doi:10.3389/fpls.2017.01821

Gao L, Xu H, Bi H, et al (2013) Intercropping Competition between Apple Trees and Crops in Agroforestry Systems on the Loess Plateau of China. PLoS One 8:. doi:10.1371/journal.pone.0070739

García-Sánchez F, Simón I, Lidón V, et al (2015) Shade screen increases the vegetative growth but not the production in “Fino 49” lemon trees grafted on Citrus macrophylla and Citrus aurantium L. Sci Hortic (Amsterdam) 194:175–180. doi:10.1016/j.scienta.2015.08.005

Ghassemi-Golezani K, Bakhshi J, Dalil B (2015) Rate and duration of seed filling and yield of soybean affected by water and radiation deficits. Acta Agric Slov 105:225–232. doi:10.14720/aas.2015.105.2.05

Gholamhoseini M, Ebrahimian E, Habibzadeh F, et al (2018) Interactions of shading conditions and irrigation regimes on photosynthetic traits and seed yield of soybean (Glycine max L.). Legum Res 41:230–238. doi:10.18805/LR-359

Hadi H, Ghassemi-Golezani K, Khoei FR, et al (2006) Response of common bean (Phaseolus vulgaris L.) to different levels of shade. J Agron 5:595–599. doi:10.3923/ja.2006.595.599

Huang XH, Gao J, Ren BZ, et al (2019) Effects of phytase Q9 on yield formation of summer maize shading in the field. Sci Agric Sin 52:3309–3322. doi:10.3864/j.issn.0578-1752.2019.19.003

Hussain S, Pang T, Iqbal N, et al (2020) Acclimation strategy and plasticity of different soybean genotypes in intercropping. Funct Plant Biol 47:639–650. doi:10.1071/FP19161

Iglesias I, Alegre S (2006) The effect of anti-hail nets on fruit protection, radiation, temperature, quality and probability of Mondial Gala apples. J Appl Hortic 08:91–100. doi:10.37855/jah.2006.v08i02.22

Inurreta-Aguirre HD, Lauri PÉ, Dupraz C, Gosme M (2018) Yield components and phenology of durum wheat in a Mediterranean alley-cropping system. Agrofor Syst 92:961–974. doi:10.1007/s10457-018-0201-2

Jumrani K, Bhatia VS (2020) Influence of different light intensities on specific leaf weight, stomatal density photosynthesis and seed yield in soybean. Plant Physiol Reports 25:277–283. doi:10.1007/s40502-020-00508-6

Kyriazopoulos AP, Abraham EM, Parissi ZM, et al (2013) Forage production and nutritive value of Dactylis glomerata and Trifolium subterraneum mixtures under different shading treatments. Grass Forage Sci 68:72–82. doi:10.1111/j.1365-2494.2012.00870.x

Li F, Meng P, Fu D, Wang B (2008) Light distribution, photosynthetic rate and yield in a Paulownia-wheat intercropping system in China. Agrofor Syst 74:163–172. doi:10.1007/s10457-008-9122-9

Li H, Jiang D, Wollenweber B, et al (2010) Effects of shading on morphology, physiology and grain yield of winter wheat. Eur J Agron 33:267–275. doi:10.1016/j.eja.2010.07.002

Lin CH, McGraw RL, George MF, Garrett HE (1998) Shade effects on forage crops with potential in temperate agroforestry practices. Agrofor Syst 44:109–119. doi:10.1023/a:1006205116354

Liu X, Rahman T, Song C, et al (2017) Changes in light environment, morphology, growth and yield of soybean in maize-soybean intercropping systems. F Crop Res 200:38–46. doi:10.1016/j.fcr.2016.10.003

Lopez G, Boini A, Manfrini L, et al (2018) Effect of shading and water stress on light interception, physiology and yield of apple trees. Agric Water Manag 210:140–148. doi:10.1016/j.agwat.2018.08.015

Makus DJ (2010) Weed control and canopy light management in blackberries. Int J Fruit Sci 10:177–186. doi:10.1080/15538362.2010.492335

Marrou H, Wery J, Dufour L, Dupraz C (2013b) Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. Eur J Agron 44:54–66. doi:10.1016/j.eja.2012.08.003

Mauro RP, Sortino O, Dipasquale M, Mauromicale G (2014) Phenological and growth response of legume cover crops to shading. J Agric Sci 152:917–931. doi:10.1017/S0021859613000592

Mauromicale G, Occhipinti A, Mauro RP (2010) Selection of shade-adapted subterranean clover species for cover cropping in orchards. Agron Sustain Dev 30:473–480. doi:10.1051/agro/2009035

Mu H, Jiang D, Wollenweber B, et al (2010) Long-term low radiation decreases leaf photosynthesis, photochemical efficiency and grain yield in winter wheat. J Agron Crop Sci 196:38–47. doi:10.1111/j.1439-037X.2009.00394.x

Pang K, Van Sambeek JW, Navarrete-Tindall NE, et al (2019) Responses of legumes and grasses to non-, moderate, and dense shade in Missouri, USA. I. Forage yield and its species-level plasticity. Agrofor Syst 93:11–24. doi:10.1007/s10457-017-0067-8

Peng X, Zhang Y, Cai Y, et al (2009) Photosynthesis, growth and yield of soybean and maize in a tree-based agroforestry intercropping system on the Loess Plateau. Agrofor Syst 76:569–577. doi:10.1007/s10457-009-9227-9

Querné A, Battie-laclau P, Dufour L, et al (2017) Effects of walnut trees on biological nitrogen fixation and yield of intercropped alfalfa in a Mediterranean agroforestry system. Eur J Agron 84:35–46. doi:10.1016/j.eja.2016.12.001

Retamales JB, Montecino JM, Lobos GA, Rojas LA (2008) Colored shading nets increase yields and profitability of highbush blueberries. Acta Hortic 193–197. doi:10.17660/ActaHortic.2008.770.22

Reynolds PE, Simpson JA, Thevathasan N V., Gordon AM (2007) Effects of tree competition on corn and soybean photosynthesis, growth, and yield in a temperate tree-based agroforestry intercropping system in southern Ontario, Canada. Ecol Eng 29:362–371. doi:10.1016/j.ecoleng.2006.09.024

Rotundo A, Forlani M, Di Vaio C (1998) Influence of shading net on vegetative and productive characteristics, gas exchange and chlorophyll content of the leaves in two blackberry (rubus ulmifolius schott.) cultivars. Acta Hortic. 457:333–340

Rylski I, Spigelman M (1986) Effect of shading on plant development, yield and fruit quality of sweet pepper grown under conditions of high temperature and radlation. Sci Hortic (Amsterdam) 29:31–35. doi:10.1016/0304-4238(86)90028-2

Schulz VS, Munz S, Stolzenburg K, et al (2018) Biomass and biogas yield of maize (Zea mays l.) grown under artificial shading. Agric 8:. doi:10.3390/agriculture8110178

Schulz VS, Munz S, Stolzenburg K, et al (2019) Impact of different shading levels on growth, yield and quality of potato (Solanum tuberosum L.). Agronomy 9:. doi:10.3390/agronomy9060330

Sharma RR, Patel VB, Krishna H (2006) Relationship between light, fruit and leaf mineral content with albinism incidence in strawberry (Fragaria x ananassa Duch.). Sci Hortic (Amsterdam)

109:66–70. doi:10.1016/j.scienta.2006.03.009

Sudmeyer RA, Speijers J (2007) Influence of windbreak orientation, shade and rainfall interception on wheat and lupin growth in the absence of below-ground competition. Agrofor Syst 71:201–214. doi:10.1007/s10457-007-9070-9

Thompson EP, Bombelli EL, Shubham S, et al (2020) Tinted Semi-Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland. Adv Energy Mater 10:1–9. doi:10.1002/aenm.202001189

Tsubo M, Walker S (2004) Shade effects on Phaseolus vulgaris L. intercropped with Zea mays L. under well-watered conditions. J Agron Crop Sci 190:168–176. doi:10.1111/j.1439-037X.2004.00089.x

Valle B, Simonneau T, Sourd F, et al (2017) Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. Appl Energy 206:1495–1507. doi:10.1016/j.apenergy.2017.09.113

Varella AC, Moot DJ, Pollock KM, et al (2011) Do light and alfalfa responses to cloth and slatted shade represent those measured under an agroforestry system? Agrofor Syst 81:157–173. doi:10.1007/s10457-010-9319-6

Verghis TI, McKenzie BA, Hill GD (1999) Effect of light and soil moisture on yield, yield components, and abortion of reproductive structures of chickpea (Cicerarietinum), in Canterbury, New Zealand. New Zeal J Crop Hortic Sci 27:153–161. doi:10.1080/01140671.1999.9514091

Zhang W, Wang BJ, Gan YW, et al (2019) Different tree age affects light competition and yield in wheat grown as a companion crop in jujube-wheat agroforestry. Agrofor Syst 93:653–664. doi:10.1007/s10457-017-0160-z

Zhao Y, Qiao J, Feng Y, et al (2019) The optimal size of a Paulownia-crop agroforestry system for maximal economic return in North China Plain. Agric For Meteorol 269–270:1–9. doi:10.1016/j.agrformet.2019.01.043

Zheng Y, Hu H, Wu R, et al (2013) Combined effects of elevated O3 and reduced solar irradiance on growth and yield of field-grown winter wheat. Shengtai Xuebao/ Acta Ecol Sin 33:532–541. doi:10.5846/stxb2011

Supplementary material

Contrasting yield responses at varying levels of shade suggest different suitability of crops for agrivoltaics. A meta-analysis.

Moritz Laub (ML) [a,b#], Lisa Pataczek (LP)[a#*], Arndt Feuerbacher (AF)[b], Sabine Zikeli (SZ)[a], Petra Högy (PH)[c]

[a]Center for Organic Farming, University of Hohenheim, Germany
[b]Agricultural and Food Policy Research Group, University of Hohenheim, Germany
[c] Plant Ecology and Ecotoxicology, University of Hohenheim, Germany
[#]Both authors equally contributed to this work

*Corresponding author: Lisa Pataczek, Center for Organic Farming, University of Hohenheim, Fruwirthstr. 14-16, 70599 Stuttgart. E-mail: lisa.pataczek@uni-hohenheim.de

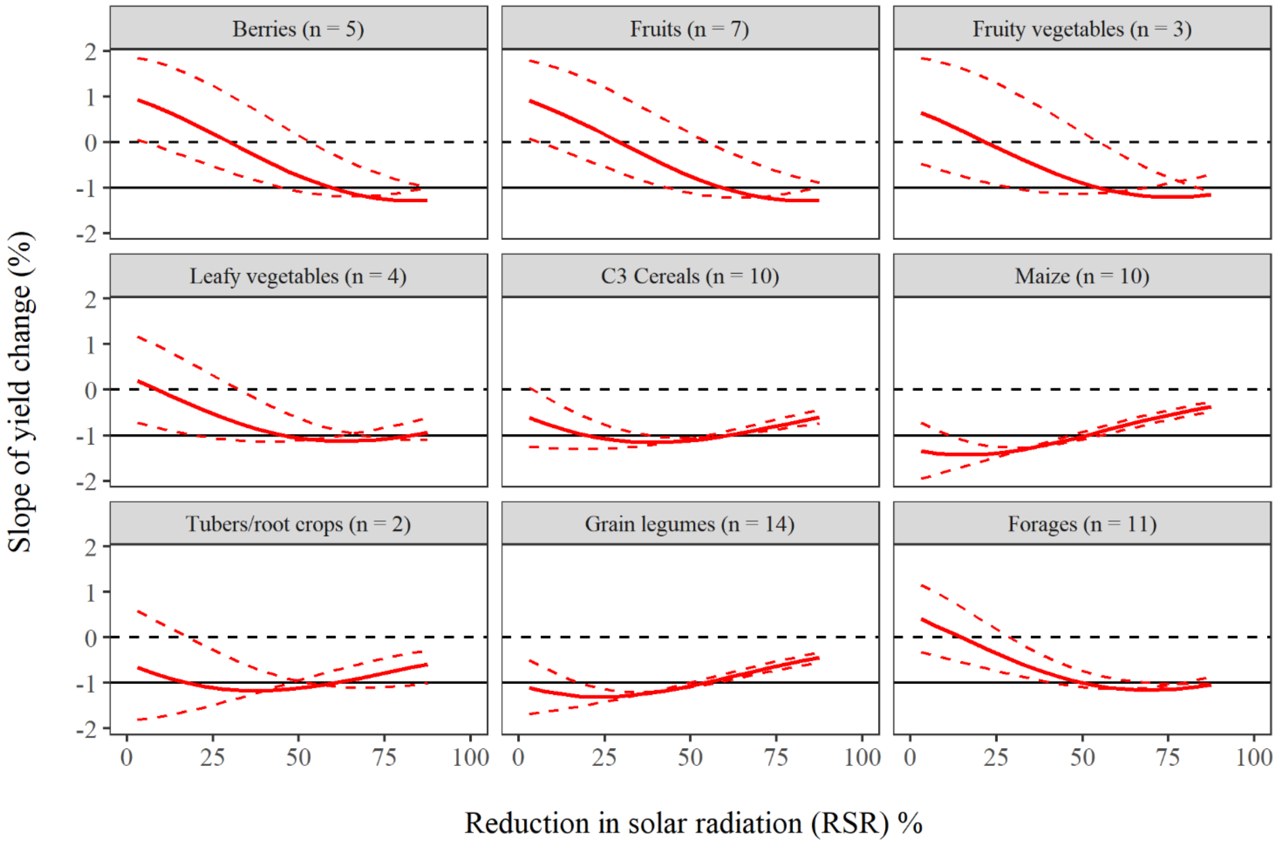

Fig. S 1 Estimated slope of yield change of different crop types to varying levels of reduction in solar radiation (RSR). If the slope is greater than 0, an increase in yield is expected, if the slope is between 0 and -1, the decrease in yield is less than the decrease in solar radiation. For slopes < -1 the decline in yield is stronger than the RSR. The red line indicates the slope of the estimated mean, the slopes of the lower and upper confidence intervals are indicated by the dashed red lines.

Table S 1 All 58 publications included in the analysis, including their properties with regards to the crops grown, classified crop type, experiment and shade type, climatic zone and global horizontal irradiation (GHI) in kWh m^{-2} per year.

Reference	Crop	Crop type	Experiment type	Shade type	Climatic zone	GHI	DOI
Abbasi Surki et al., 2020	Wheat, Barley	C3 cereals	Intercrop.	-	Subtrop.	2117.5	10.1007/s10457-019-00469-2
Abeysinghe et al., 2016	Grapevines	Fruits	Artificial	cloth	Subtrop.	1812.4	10.17660/ActaHortic.2016.1115.18
Amarante et al., 2012	Apple	Fruits	Artificial	nets	Subtrop.	1734.1	10.17660/ActaHortic.2012.934.143
Artru et al., 2018	Sugar Beet	Tubers/ root crops	Artificial	cloth	Temp.	1090.9	10.1016/j.eja.2018.04.011
Bing et al., 2015	Soybean	Grain legumes	Artificial	cloth	Temp.	1381.9	10.9755/ejfa.v27i3.18889
Burner & Belesky, 2008	Tall fescue	Forages	Intercrop.	-	Subtrop.	1636.1	10.1007/s10457-008-9118-5
Carrier et. al., 2019	Soybean, Maize, Wheat, Forage	Grain legumes, Maize, C3 cereals, Forages	Intercrop.	-	Temp.	1306.7 - 1367.8	10.1016/j.fcr.2019.05.004
Chen et al., 2016	Maize	Maize	Artificial	-	Subtrop.	1423.2	10.13287/j.1001-9332.201610.028
Díaz-Pérez, 2014	Bell pepper	Fruity vegetables	Artificial Shading	nets	Subtrop.	1774.6	10.21273/HORTSCI.49.7.891
Ding & Su, 2010	Maize	Maize	Intercrop.	.	Temp.	1673.8	10.1007/s10457-010-9287-x
Djordjevic et al., 2014	Blackcurrant	Berries	Artificial	nets	Temp.	1345.5	10.1002/jsfa.6962
Do Amarante et al., 2011	Apple	Fruits	Artificial	nets	Subtrop.	1986.1	10.1016/j.scienta.2011.03.010
Du et al., 2011	Squash	Fruity vegetables	Artificial	-	Temp.	1315	-
Ehret et al., 2015	Perennial grass, white clover	Forages	Artificial	cloth	Temp.	1051.7	10.1007/s10457-015-9791-0
Elamri et al., 2018	Lettuce	Leafy vegetables	Artificial	PV panels	Temp.	1530.9	10.1016/j.agwat.2018.07.001
El-Naby et al., 2020	Navel orange	Fruits	Artificial	nets	Subtrop.	2049.3	10.24326/asphc.2020.3.2
Gao et al., 2013	Soybean, Peanut	Grain legumes	Intercrop.	-	Temp.	1505.4	10.1371/journal.pone.0070739
Gao et al., 2017b	Maize	Maize	Artificial	cloth	Temp.	1437.3	10.3389/fpls.2017.01821
Gao et al., 2017a	Maize	Maize	Artificial	cloth	Temp.	1435.6	10.3864/j.issn.0578-1752.2017.11.016
García-Sánchez et al., 2015	Lemon/ Sour orange	Fruits	Artificial	cloth	Subtrop.	1787.2	10.1016/j.scienta.2015.08.005
Ghassem-Golezani et al., 2015	Soybean	Grain legumes	Artificial	nets	Subtrop.	1826	10.14720/aas.2015.105.2.05
Gholamhoseini et al., 2018	Soybean	Grain legumes	Artificial	nets	Subtrop.	1903.5	10.18805/LR-359

Hadi et al., 2006	Common bean	Grain legumes	Artificial	nets	Subtrop.	1826	10.3923/ja.2006.595.599
Huang et al., 2019	Maize	Maize	Artificial	.	Subtrop.	1435.6	10.3864/j.issn.0578-1752.2019.19.003
Hussain et al., 2020	Soybean	Grain legumes	Artificial	nets	Subtrop.	868.3	10.1071/FP19161
Iglesias & Alegre, 2006	Apple	Fruits	Artificial	nets	Temp.	1683.7	10.37855/jah.2006.v08i02.22
Inurreta-Aguirre et al., 2018	Durum wheat	C3 cereals	Intercrop.	-	Temp.	1523.2	10.1007/s10457-018-0201-2
Jumrani & Bhatia, 2020	Soybean	Grain legumes	Artificial	nets + cloth	Subtrop.	1907	10.1007/s40502-020-00508-6
Kyriazopoulos et al., 2013	Trifolium subterraneum	Forages	Artificial	cloth	Temp.	1594.9	10.1111/j.1365-2494.2012.00870.x
Li et al., 2008	Wheat	C3 cereals	Intercrop.	-	Subtrop.	1342.8	10.1007/s10457-008-9122-9
Li et al., 2010	Wheat	C3 cereals	Artificial	cloth	Subtrop.	1307.5	10.1016/j.eja.2010.07.002
Lin et al., 1998	Forage grasses	Forages	Artificial	cloth	Temp.	1560.6	10.1023/A:1006205116354
Liu et al., 2017	Soybean	Grain legumes	Intercrop.	-	Temp.	1368.5	10.1016/j.fcr.2016.10.003
Lopez et. al. 2018	Apple	Fruits	Artificial	nets	Temp.	1422.8	10.1016/j.agwat.2018.08.015
Makus, 2010	Blackberries	Berries	Artificial	cloth	Subtrop.	1825.9	10.1080/15538362.2010.492335
Marrou et al., 2013b	Lettuce	Leafy vegetables	Artificial	PV panels	Temp.	1530.9	10.1016/j.eja.2012.08.003
Mauro et al., 2014	Legume cover crops	Forages	Artificial	nets	Temp.	1765.3	10.1017/S0021859613000592
Mauromicale et al., 2010	Clover	Forages	Artificial	nets	Temp.	1769.2	10.1051/agro/2009035
Mu et al., 2010	Winter wheat	C3 cereals	Artificial	cloth	Subtrop.	1295.8	10.1111/j.1439-037X.2009.00394.x
Pang et al., 2017	Forage legume	Forages	Artificial	cloth	Subtrop.	1561	10.1007/s10457-017-0067-8
Peng et al., 2009	Maize	Grain legumes	Intercrop.	-	Temp.	1304	10.1007/s10457-009-9227-9
Querné et al., 2017	Alfalfa	Forages	Intercrop.	-	Temp.	1523.2	10.1016/j.eja.2016.12.001
Retamales et al., 2008	Blueberry	Berries	Artificial	nets	Temp.	1814.3	10.17660/ActaHortic.2008.770.22
Reynolds et al., 2007	Maize, Soybean	Maize, Grain legumes	Intercrop.	-	Temp.	1371.5	10.1016/j.ecoleng.2006.09.024
Rotundo et al., 1998	Blackberries	Berries	Artificial	nets	Temp.	1570.8	10.17660/ActaHortic.1998.457.42
Rylski & Spigelman, 1986	Sweet pepper	Fruity vegetables	Artificial	cloth	Subtrop.	2075.9	10.1016/0304-4238(86)90028-2
Schulz et al., 2018	Maize	Maize	Artificial	nets	Temp.	1184.1	10.3390/agriculture8110178
Schulz et al., 2019	Potato	Tubers/ root crops	Artificial	nets	Temp.	1184.1	10.3390/agronomy9060330
Sharma & Patel, Hare Krishna, 2006	Strawberry	Berries	Intercrop.	.	Subtrop.	1763.3	10.1016/j.scienta.2006.03.009
Sudmeyer & Speijers, 2007	Wheat/ Lupin	C3 cereals, Grain legumes	Artificial	nets + cloth	Subtrop.	1901.5	10.1007/s10457-007-9070-9

Thompson et al., 2020	Spinach/ Basil	Leafy vegetables	Artificial	PV panels	Temp.	1422.8	10.1002/aenm.202001189
Tsubo & Walker, 2004	Common bean	Grain legumes	Intercrop.	-	Temp.	2137	10.1111/j.1439-037X.2004.00089.x
Valle et al. 2017	Salad	Leafy vegetables	Artificial	PV panels	Temp.	1533.4	10.1016/j.apenergy.2017.09.113
Varella et al., 2010	Alfalfa	Forages	Intercrop.	-	Temp.	1396.6	10.1007/s10457-010-9319-6
Verghis et al., 1999	Chickpea	Grain legumes	Artificial	cloth	Temp.	1394.5	10.1080/01140671.1999.9514091
Zhang et al., 2019	Wheat	C3 cereals	Intercrop.	.	Temp.	1450.4	10.1007/s10457-017-0160-z
Zhao et. al., 2019	Maize/ Wheat	Maize/ C3 cereals	Intercrop.	.	Subtrop.	1339.2	10.1016/j.agrformet.2019.01.043
Zheng et al., 2013	Wheat	C3 cereals	Artificial	.	Subtrop.	1294.8	10.5846/stxb201111151731

Table S 2 Predictions for yield at different levels of reduction in solar radiation (RSR) for temperate and subtropical areas including 95% confidence intervals (CI). The response to shading compared to no shading is classified as benefiting (B), tolerant (T) and susceptible (S).

Crop type	RSR	Prediction	(95% CI)	Shade response	RSR	Prediction	(95% CI)	Shade response
Berries	5	104.7	(100.3 - 109.3)	B	50	108.3	(74.3 - 157.9)	B
Fruits	5	104.6	(100.4 - 109)	B	50	107.4	(73.6 - 156.7)	B
Forages	5	102.1	(98.4 - 105.9)	B	50	84.1	(64.1 - 110.4)	T
Maize	5	93.3	(90.2 - 96.5)	S	50	34.2	(26.3 - 44.4)	S
Grain legumes	5	94.6	(91.6 - 97.6)	S	50	39.1	(30.4 - 50.2)	S
Tubers/root crops	5	96.8	(91 - 103)	T	50	49.3	(27.5 - 88.6)	S
Fruity vegetables	5	103.3	(97.7 - 109.2)	B	50	94.7	(55.9 - 160.5)	T
Leafy vegetables	5	101	(96.4 - 105.9)	B	50	75.9	(49.8 - 115.7)	T
C3 Cereals	5	97	(93.8 - 100.3)	T	50	50.4	(37.7 - 67.5)	T
Berries	10	108.7	(100 - 118.1)	B	55	104.2	(68.8 - 158.1)	B
Fruits	10	108.5	(100.2 - 117.5)	B	55	103.3	(67.9 - 157.2)	B
Forages	10	103.3	(96.4 - 110.8)	B	55	78.9	(58.5 - 106.4)	T
Maize	10	86.3	(80.9 - 92.1)	S	55	29.3	(21.9 - 39.2)	S
Grain legumes	10	88.6	(83.4 - 94.2)	S	55	33.9	(25.7 - 44.9)	S
Tubers/root crops	10	92.9	(82.2 - 105)	T	55	43.9	(23 - 83.7)	S
Fruity vegetables	10	105.8	(94.8 - 118.1)	B	55	89.9	(50.3 - 161)	T
Leafy vegetables	10	101.3	(92.4 - 111)	B	55	70.5	(44.3 - 112.3)	T
C3 Cereals	10	93.3	(87.4 - 99.6)	T	55	45	(32.5 - 62.2)	S
Berries	15	111.9	(99.1 - 126.4)	B	60	99.5	(63 - 157.2)	T
Fruits	15	111.6	(99.3 - 125.5)	B	60	98.5	(61.9 - 156.7)	T
Forages	15	103.7	(93.9 - 114.6)	B	60	73.4	(52.8 - 102)	T
Maize	15	79.2	(72.2 - 86.9)	S	60	24.9	(18.1 - 34.4)	S
Grain legumes	15	82.4	(75.5 - 90)	S	60	29.2	(21.4 - 40)	S
Tubers/root crops	15	88.4	(73.7 - 106.1)	T	60	38.7	(19.1 - 78.4)	S
Fruity vegetables	15	107.5	(91.3 - 126.5)	B	60	84.7	(44.7 - 160.4)	T
Leafy vegetables	15	100.6	(87.9 - 115.1)	B	60	64.9	(39 - 108.2)	T
C3 Cereals	15	89	(80.9 - 97.8)	T	60	39.8	(27.7 - 57.1)	S
Berries	20	114.3	(97.5 - 133.9)	B	65	94.1	(57 - 155.4)	T
Fruits	20	113.9	(97.6 - 132.8)	B	65	93.1	(55.8 - 155.3)	T
Forages	20	103.3	(90.9 - 117.3)	B	65	67.7	(47.2 - 97.3)	T
Maize	20	72	(64 - 81.1)	S	65	21	(14.7 - 30)	S
Grain legumes	20	76	(67.9 - 85)	S	65	25	(17.7 - 35.4)	S
Tubers/root crops	20	83.4	(65.6 - 106.1)	T	65	33.9	(15.7 - 72.9)	S

Fruity vegetables	20	108.3	(87.3 - 134.3)	B	65	79.1	(39.4 - 158.7)	T
Leafy vegetables	20	99.1	(83.1 - 118.2)	T	65	59.3	(33.9 - 103.6)	T
C3 Cereals	20	84.2	(74.4 - 95.2)	T	65	34.8	(23.3 - 52.1)	S
Berries	25	115.7	(95.2 - 140.6)	B	70	88.3	(51.1 - 152.8)	T
Fruits	25	115.2	(95.2 - 139.3)	B	70	87.3	(49.7 - 153.2)	T
Forages	25	101.9	(87.5 - 118.8)	B	70	62	(41.6 - 92.4)	T
Maize	25	65	(56.3 - 75)	S	70	17.6	(11.8 - 26.1)	S
Grain legumes	25	69.5	(60.7 - 79.5)	S	70	21.2	(14.4 - 31.2)	S
Tubers/root crops	25	78.1	(57.9 - 105.2)	T	70	29.4	(12.8 - 67.4)	S
Fruity vegetables	25	108.2	(82.8 - 141.2)	B	70	73.2	(34.3 - 156.1)	T
Leafy vegetables	25	96.8	(77.9 - 120.3)	T	70	53.7	(29.2 - 98.6)	T
C3 Cereals	25	78.9	(67.9 - 91.7)	T	70	30.3	(19.4 - 47.3)	T
Berries	30	116.1	(92.2 - 146.3)	B	75	82.2	(45.2 - 149.4)	T
Fruits	30	115.5	(92.2 - 144.8)	B	75	81.1	(43.8 - 150.4)	T
Forages	30	99.7	(83.6 - 119.1)	T	75	56.2	(36.2 - 87.3)	T
Maize	30	58.1	(49.2 - 68.6)	S	75	14.6	(9.4 - 22.6)	S
Grain legumes	30	63	(53.8 - 73.7)	S	75	17.8	(11.5 - 27.4)	S
Tubers/root crops	30	72.4	(50.7 - 103.4)	T	75	25.2	(10.3 - 61.9)	T
Fruity vegetables	30	107.1	(77.9 - 147.2)	B	75	67.2	(29.6 - 152.7)	T
Leafy vegetables	30	93.8	(72.5 - 121.4)	T	75	48.2	(24.9 - 93.4)	T
C3 Cereals	30	73.4	(61.5 - 87.6)	T	75	26.1	(15.9 - 42.8)	T
Berries	35	115.6	(88.5 - 150.8)	B	80	75.8	(39.5 - 145.4)	T
Fruits	35	114.9	(88.4 - 149.3)	B	80	74.8	(38.1 - 146.9)	T
Forages	35	96.8	(79.2 - 118.3)	T	80	50.6	(31.1 - 82.2)	T
Maize	35	51.5	(42.6 - 62.3)	S	80	12	(7.4 - 19.4)	S
Grain legumes	35	56.6	(47.3 - 67.7)	S	80	14.8	(9.2 - 24)	S
Tubers/root crops	35	66.6	(44.1 - 100.7)	T	80	21.5	(8.2 - 56.5)	T
Fruity vegetables	35	105.2	(72.7 - 152.2)	B	80	61.2	(25.2 - 148.5)	T
Leafy vegetables	35	90.1	(66.9 - 121.4)	T	80	42.9	(20.9 - 88)	T
C3 Cereals	35	67.7	(55.2 - 83)	T	80	22.3	(12.9 - 38.6)	T
Berries	40	114.1	(84.3 - 154.3)	B	85	69.3	(34.1 - 140.9)	T
Fruits	40	113.3	(84 - 152.8)	B	85	68.3	(32.7 - 142.9)	T
Forages	40	93.2	(74.5 - 116.5)	T	85	45.1	(26.4 - 77.1)	T
Maize	40	45.3	(36.6 - 56.1)	S	85	9.8	(5.7 - 16.7)	S
Grain legumes	40	50.4	(41.2 - 61.7)	S	85	12.2	(7.2 - 20.9)	S
Tubers/root crops	40	60.8	(38 - 97.3)	T	85	18.2	(6.5 - 51.3)	T
Fruity vegetables	40	102.5	(67.2 - 156.1)	B	85	55.2	(21.2 - 143.6)	T
Leafy vegetables	40	85.8	(61.2 - 120.4)	T	85	37.9	(17.4 - 82.4)	T
C3 Cereals	40	61.9	(49.1 - 78)	T	85	18.9	(10.3 - 34.6)	T
Berries	45	111.6	(79.5 - 156.6)	B	90	62.9	(29.1 - 135.9)	T
Fruits	45	110.8	(79 - 155.3)	B	90	61.9	(27.7 - 138.4)	T
Forages	45	88.9	(69.4 - 113.8)	T	90	39.9	(22.1 - 72.1)	T
Maize	45	39.5	(31.2 - 50.1)	S	90	7.9	(4.4 - 14.3)	S
Grain legumes	45	44.6	(35.6 - 55.8)	S	90	10	(5.5 - 18.2)	S
Tubers/root crops	45	55	(32.4 - 93.2)	S	90	15.3	(5 - 46.3)	T
Fruity vegetables	45	98.9	(61.6 - 158.9)	T	90	49.4	(17.7 - 138.2)	T
Leafy vegetables	45	81.1	(55.5 - 118.5)	T	90	33.2	(14.3 - 76.9)	T
C3 Cereals	45	56.1	(43.3 - 72.8)	T	90	15.9	(8.2 - 31)	T