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META-ANALYSIS

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

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Abstract

Despite the large body of research surrounding 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 systems, a technology that combines energy and food production, shade tolerance of cropping systems is becoming increasingly important. 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. The aim was to quantitatively assess the susceptibility of different temperate crop types to increasing levels of shading. Crop type specific yield response curves were developed as a function of reduction in solar radiation, estimating relative crop yields compared to the unshaded controls. Only studies that reported reduction in solar radiation and crop yield per area in temperate and subtropical areas were included. The results suggested a nonlinear relationship between achieved crop yields and reduction in solar radiation for all crop types. Most crops tolerate reduced solar radiation up to 15%, showing a less than proportional yield decline. However, significant differences between the response curves of the following crop types existed: Berries, fruits and fruity vegetables benefited from reduction in solar radiation up to 30%. Forages, leafy vegetables, tubers/root crops, and C_3 cereals initially showed less than proportional crop yield loss. In contrast, maize and grain legumes experienced strong crop yield losses even at low shade levels. The results provide a set of initial indicators that may be used in assessing the suitability of crop types for shade systems, and thus for agrivoltaic or other dual land-use systems. Detailed yield response curves, as provided by this study, are valuable tools in optimizing the output of annual crop components in these systems.

Keywords Crop specific meta-analysis · Shading · Agrivoltaics · Shade sensitivity · Shade tolerance · Crop yield

1 Introduction

With the European Union's (EU) goal to reach net-zero greenhouse gas emissions by 2050 (European Commission 2018), the 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 5 m (Figure 1).

This elevation 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). 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

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Fig. 1 Shaded winter wheat in an agrivoltaic system in Germany (Photograph by Lisa Pataczek).

GM-PV was one reason to establish the specification ("prestandard") 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 to shade in general. Although some crops show yield reductions due to light reduction (Weselek et al. 2021), several crops can 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 location, crops can benefit from shading in hot and dry areas (Barron-Gafford et al. 2019). In order to develop improved 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. However, to our knowledge, thus far there is no systematic analysis of crop yield responses to shading. Recently, Weselek et al. (2019) conducted a literature review regarding the potential of AV systems including a qualitative assessment of crops potentially benefiting or 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 allowing neither reliable estimations nor to determine the optimal level of shade in AV systems.

In light of the above, this study's objective is to conduct a detailed and quantitative analysis of the response to shading for relevant crop types in temperate and subtropical regions. The intention is to better understand the agronomic effects of AV in Europe. The focus is on the differences in yield responses of different crop types to shade, as absolute yields depend on much more than just radiation. In many regions in Europe, either a rapidly growing or already mature market for ground-based PV systems exists. However, due to land scarcity, public opposition to ground mounted PV rises. To solve this problem, the establishment of AV might offer a solution for these regions reducing the competition between food and fuel. In this regard, the present study may serve as a basis for further developments of AV standards and legislation. 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 prevalent 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 derived from 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.

To assure representativeness and relevance of the studies chosen, only publications presenting data from field or pot trials were included in the meta-analysis (Figure 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.

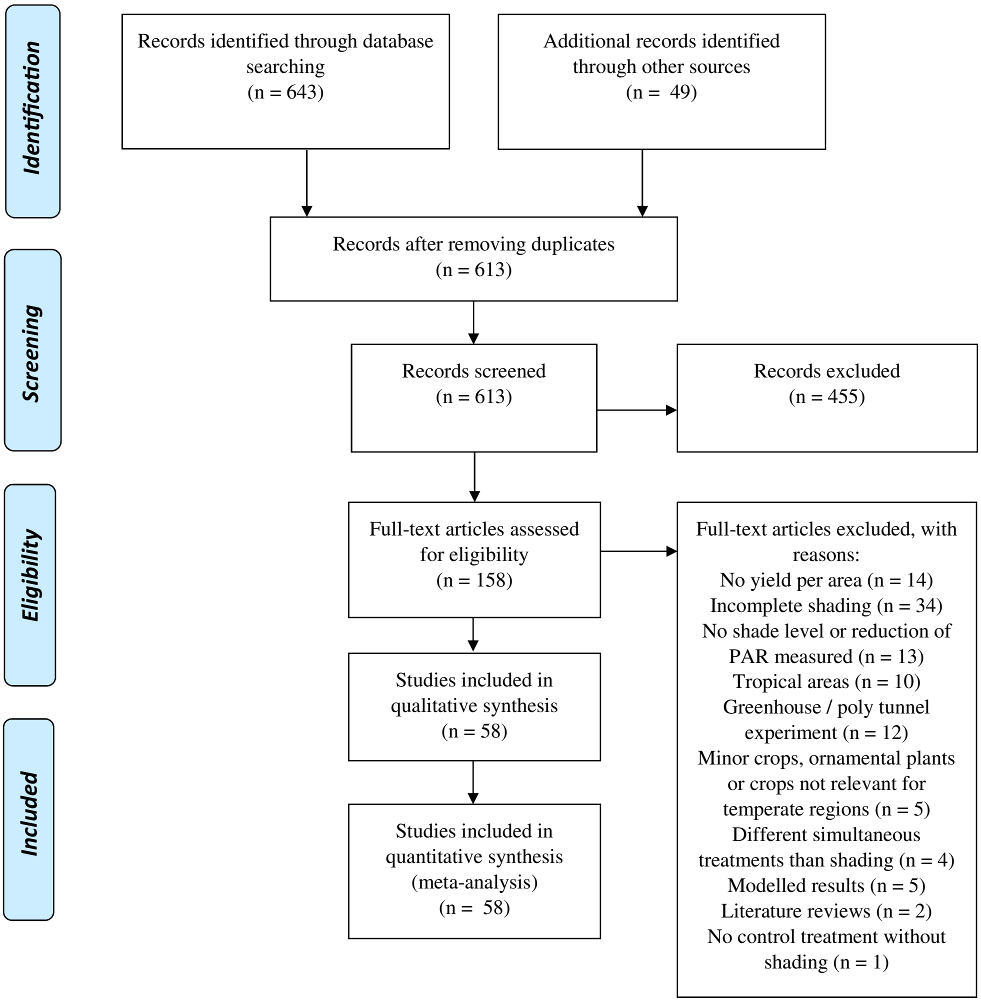

Fig. 2 Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) Flow Chart describing the steps conducted in the search and selection of publications within this meta-analysis. Further details about the final 58 studies are presented in Table S 1.

- 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 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 their own data.
- Experiments without an unshaded control treatment.

Data of eligible publications were systematized into a table, extracting all data available from either tables or figures. The data from figures were digitized using WebPlotDigitizer software version 4.4 (Rohatgi 2020). The yields were standardized to the variable "relative yield under shading," defining the unshaded control as 100% yield. The standardization was done because the focus of this study was the yield response to shading and this allowed for a common scale across included publications. This was assumed to be the best manner to manage 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, each year was included as an individual data points. Covariates of interest were crop type and the reduction in solar radiation or light intensity, which was expressed differently in the varying studies, e.g., reduction in 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, without always stating the baseline level of radiation, we chose to use the relative RSR compared to the control, as a standardized measure across the different studies. This RSR was either 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/). We used this global dataset because the absolute radiation was not measured in many of the studies. 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) vs. intercropping experiments (including agroforestry), were also included in the systematized table.

2.2 Data analysis

The 58 studies provided data on the effects of shade on the yield of 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, C_3 cereals, maize, tubers/root crops, grain legumes, as well as forages (including grasses, forage legumes and multispecies forage stands). The table containing the complete dataset of the analysis can be found in the Zenodo 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 within a meta-analysis may improve model performance in some cases, but the choice of data used has the strongest impact. Using all suitable observations without weighting, was thus considered superior to including only half the dataset and conducting a 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 their interactions with crop types. To test the hypothesis stating that the yield response curve would be different between different absolute levels of radiation, we tested for a significant interaction of RSR and its quadratic term with absolute radiation of each location, as well as for a three-way interaction of RSR with absolute radiation and crop type. Interactions of the quadratic term 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 at a time starting with the least significant term. Individual independent variables were only removed 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. These were 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. 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. Note, that a random intercept was intentionally not allowed to assure that all the random regressions were 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. Furthermore, 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 (see also 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).

3 Results

3.1 Different crop types show different reactions to shading

Despite showing a high scatter within the raw data, the loss of crop yield at higher levels of RSR is evident for all crop types (Figure 3). However, the shape of the curves is profoundly different. The analysis of variance (Table 1) shows that despite the log transformation of the response variable, the quadratic term of RSR is a significant predictor ($p \leq 0.005$) when considering yield reduction for all crop types, suggesting strongly non-linear response curves. However, there are highly significant differences ($p \leq 0.001$) between the crop types in the yields response to increasing levels of shading,

Table 1 Analysis of variance of fixed effects of the mixed linear model, applied within this study (Type III). Displayed here are the initial full model and the final reduced model after removing the insignificant interactions. Three way interactions with RSR^2 were not tested, as the models including them would not converge.

Model	Fixed effect	Num DF	Den DF	F-value	*p*-value
Initial full model	RSR	1	33	0.08	0.7858
	RSR^2	1	5.263	0.41	0.5504
	RSR x crop type	7	31.34	2.06	0.0788
	RSR x experiment type	1	9.501	0.14	0.7172
	RSR x climatic zone	1	2.941	8.10	0.0669
	RSR x colored nets	2	51.23	2.32	0.1088
	RSR x shade type	3	13.99	1.11	0.3785
	RSR x annual radiation	1	35.53	0.25	0.6185
	RSR x annual radiation x crop type	8	26.81	1.03	0.4392
	RSR^2 x crop type	7	20.37	1.11	0.3932
	RSR^2 x experiment type	1	3.44	0.23	0.6592
	RSR^2 x climatic zone	1	1.173	4.31	0.2557
	RSR^2 x colored nets	2	49.26	1.60	0.2115
	RSR^2 x shade type	3	6.161	0.41	0.7493
	RSR^2 x annual radiation	1	4.19	0.87	0.4004
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

RSR(^{2})= reduction in solar radiation (squared); Num/Den DF = numerator/ denominator degrees of freedom

corroborating the assumption that a varying behavior of different crop types to RSR exists. In contrast, there is no evidence of a significant difference in the response of yield to RSR between intercropping and shading-only experiments. Further, no significant differences were found whether cloths, PV panels or nets were used for shading. Additionally, the

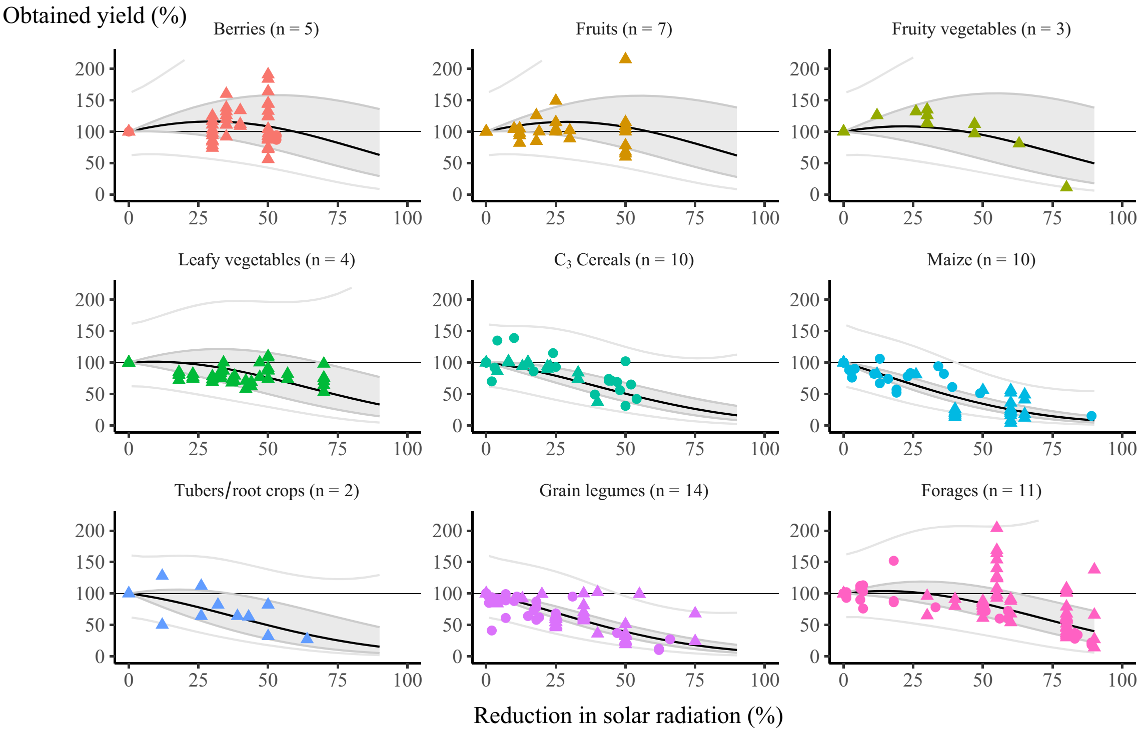

Fig. 3 Original data and derived crop type specific meta-regressions (black line) of obtained yield as function of reduction in solar radiation (RSR). The dark grey shaded band and light grey lines depict the 95% confidence intervals and prediction intervals, respectively. Triangles (Δ) represent data 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.

absolute level of radiation did not significantly affect the response curves.

The strong difference in the estimated susceptibility of the different crop types to shading is shown by the different shapes of the predicted response curves to RSR and in the difference in estimated means (Figure 4). For a more detailed analysis of where yield losses start, Fig. S 1 shows the estimated slope of the yield reductions for varying levels of RSR across the nine crop types. The meta-regressions suggest that berries, fruits and fruity vegetables may experience increases in harvestable yield until about 30, 25 and 20% RSR, respectively. To levels of at least 20% RSR, several other crop types show a yield decrease that is less than proportional to the RSR. Those are in order of increasing yield losses: forages, leafy vegetables and tubers/root crops. C_3 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 logarithmic transformation, uneven 95% confidence intervals (CI) around estimated means are predicted. Uncertainties in the predicted crop yields depend strongly on the number of available measurements. They are also influenced by how strong the response deviates from the general linear and the quadratic effect of RSR and by the range of RSR for which observations are available. Therefore, berries and fruits, which show mostly positive responses in the experiments and no data points at very high levels of shading, are subject to the highest level of uncertainty for yield prediction. Larger uncertainty than the rest of the crop types was also associated to tubers/root crops and fruity vegetables, which have few observations overall.

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 as supplementary material (Table S 2). For maize, 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%). Additionally, grain legumes also show disproportionately large losses of grain 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%, respectively). Forages are also estimated to have little susceptibility 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 allows for identification of crops that are tolerant to—or can benefit from—low levels of shade

The results of this meta-analysis show a fact that may be exploited in optimizing AV systems: independent of the crop type, the relationship between RSR and crop yield is not simply proportional. Hence, a simple classification such as shade

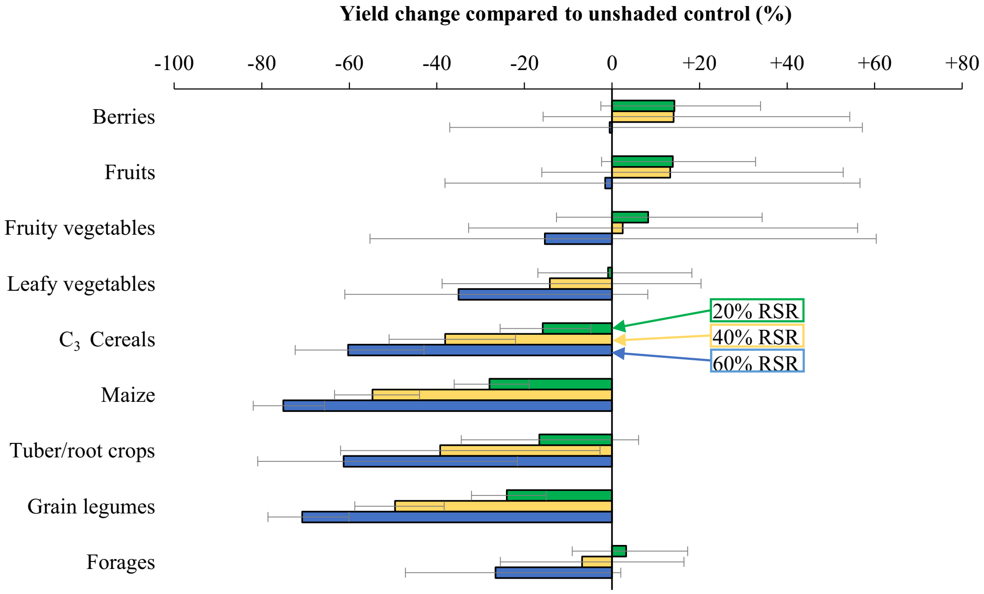

Fig. 4 Yield responses of different crop types to varying levels of reduction in solar radiation (RSR). Displayed are the least square means. Error bars delimit the 95% confidence intervals of the true mean. Within the same level of RSR, crop types with non-overlapping confidence intervals are significantly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

benefiting or susceptibility (e.g., Beck et al. 2012) is less meaningful than a detailed analysis of yield response curves, which helps to optimize the level of shade in AV systems. For example, while maize and grain legumes react most strongly to RSR, all other crop types tolerate low levels of shading. This is shown by the initial short range of less than proportional yield reduction in response to RSR. However, losses can become disproportionately large starting at 10% RSR for C_3 cereals, and shortly thereafter for tubers/root crops. At around 50% of shading, all crops show susceptibility. We classified areas of shade responses into phases of shade benefit, tolerance and susceptibility. The area of "shade benefit" shows situations in which yields of a crop type increase due to shading compared to the unshaded control. Shade tolerance is the area of less than proportional yield losses and 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 curve passes (Figure 5), helps to identify optimal shade levels for each crop type. For crop types whose curve passes through the "shade benefit" area, the yield may be maximized using the regression, by aiming for the RSR with the highest relative crop yield. For example, while berries at 40% RSR may still benefit from shade compared to no shading, their highest yield is expected at around 30% RSR. Analogously, the optimal level of shading for dual land-use systems may correspond to a RSR level that allows for less than proportional yield losses. According to this classification, forages are shade benefiting until 25% RSR, and shade tolerant at higher RSR, while C_3 cereals are not shade benefiting, but shade tolerant until 50% RSR and shade susceptible with a RSR of > 50% (Table S 2).

As the large prediction intervals suggest, absolute yields will be site dependent and influenced by factors such as soil fertility and water availability. Notwithstanding, our results allow to assess the relative shade tolerance of different cop types compared to one another and hence to assess their suitability for AV systems. For example, at a typical shade level of 20 to 40%, berries, fruits and fruity vegetables are likely subject to much lower yield reductions than maize or grain legumes. Yet, reductions in yield may not be the only concern in AV systems, as the revenue obtained by the second land use activity can in many cases be of higher economic importance than the yield reduction (Kay et al. 2019). Hence, there may be a trade-off between optimizing crop yields through modifying shade levels and optimizing the total economic performance of a system. For the case of AV, it is the relative price level of agricultural and energy outputs that determine to what degree crop yields and electricity output are optimized (Feuerbacher et al. 2021).

4.2 What enables the shade tolerance of some crop types?

Our meta-analysis showed that berries, fruits and fruit vegetables may benefit up to 40% RSR. Additionally, C_3 cereals, leafy vegetables, forages, and tubers/root crops experience less than proportional losses. Both results are in alignment with the meta-analysis of Slattery et al. (2013), who suggest that shading increases plant energy conversion efficiency for many crops, which counteracts yield depressions. For yield increases, however, indirect benefits of shading, such as higher water use efficiency and/or lower transpiration, are needed. Indeed, many mechanisms that cause tolerance or

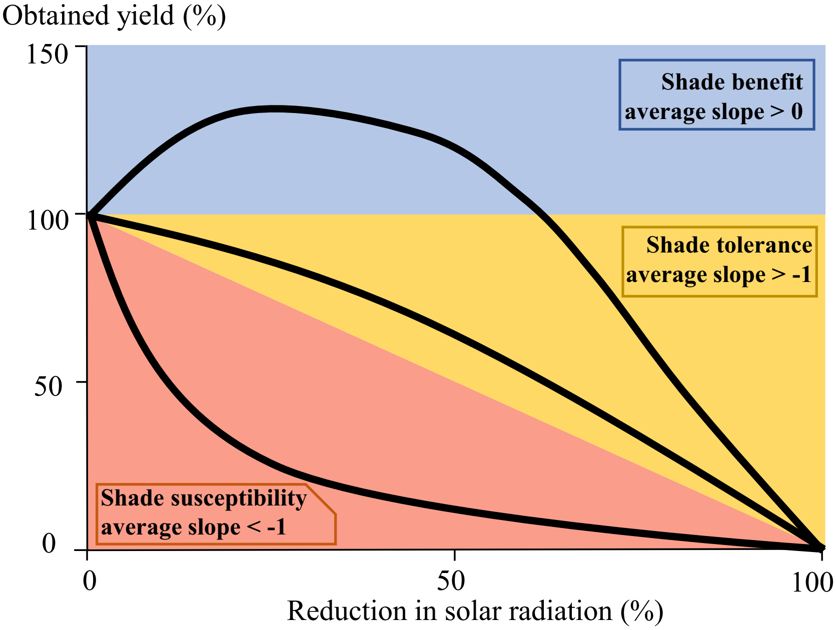

Fig. 5 A conceptual model showing three phases of shade sensitivity: shade benefit, tolerance and susceptibility. Some crops are initially classified as shade benefit (blue area) and most are at least shortly in the area of shade tolerance (yellow area), where their obtained yield is less than proportional to light reduction.

even positive yield responses of crops to shading can be related to morphological or physiological changes, also referred to as shade avoidance syndrome (Evans and Poorter 2001; Franklin 2008; Gratani 2014). Lettuce (*Lactuca sativa* spp.), for example, increases total and specific leaf area under shaded conditions, improving light interception while the total number of leaves per plant often decreases (Marrou et al. 2013b; Valle et al., 2017). These contrasting effects may explain the low yield losses of leafy vegetables under shading, that are predicted by our meta-regression. While stress may lead to an increase in vegetative biomass, the increase in blueberry (*Vaccinium corymbosum*) yield in subtropical Chile found by Retamales et al. (2008), was explained by the authors as a result from reduced stress improving the conditions for fruit set. Rotundo et al. (1998) reported that physiological adaptation mechanisms and a prolongation of the harvesting period increased the cumulative berry yield of shaded blackberries (*Rubus ulmifolius*) in Italy. However, deleterious effects of shading in perennial plants have been shown to accumulate over several years (Atlan et al. 2015). This study may underestimate such effects, since most studies only collected data from one or two years.

The low initial crop yield reduction of fruity vegetables due to RSR in our study may be due to a change in the different components making up the 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). Additionally, total leaf area of bell pepper increases with an increasing shade level (Rylski and Spigelman, 1986), and net photosynthesis is found to be highest (Kabir et al. 2020) or unaffected (Díaz-Pérez 2013) at 30% RSR. Forages also 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). Depending on the forage species, even a slight increase of dry matter yield at 45% RSR was reported (Pang et al., 2019). Varella et al. 2011) observed that alfalfa (*Medicago sativa*), a forage legume, can maintain an adequate photosynthetic activity even under dense shading conditions of 50% RSR and higher, suggesting that the light saturation point is reached, generally ranging between 25-60% of maximum sunlight for C_3 plants (Pang et al., 2019; Carrier et al., 2019).

Morpho-physiological changes due to RSR can also result in yield reductions. Maize (*Zea mays*) appears to be most susceptible to shading among all crop types studied as it is a C_4 plant. It can thus 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 a reduced seed yield and harvest index. Further, 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 internode length and stem elongation (Liu et al., 2017; Wu et al. 2017) resulting in plant lodging (Liu et al. 2015). Moreover, a reduced leaf area index was observed, which was shown to negatively affect soybean (*Glycine max*) yield (Su et al. 2014).

One potential confounder between crop types response to shading is that 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 provide biased results as 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 also due to changes in soil coverage (Marrou et al. 2013a). This condition can favor water flows into harvestable crop yield components and could therefore provide an explanation for differences in crop yield losses between crops whose yield is expressed as dry matter yield and those expressed as fresh biomass. For example, Artru et al. (2018) found that sugar beet (*Beta vulgaris*) under continuous shading in one experimental year, had significantly increased water content while root dry matter decreased at the same time, which led to reduced total sugar yield on a per area base.

4.3 Possible applications of shade response curves

With data ranging to at least 50% RSR, this meta-analysis includes a sufficient range to assess the suitability of crops in AV and other dual land-use systems, like agroforestry. AV systems in particular rarely exceed a RSR of 50%. In AV systems referred to as “half-density,” the RSR values of fixed solar panels typically range between 28% and 50% RSR (Dupraz et al. 2011; Elamri et al., 2018; Majumdar and Pasqualetti 2018; Marrou et al., 2013a; Valle et al., 2017) whereas in AV with solar tracking, they range between 15% to 36% RSR (Amaducci et al. 2018; Elamri et al., 2018; Valle et al., 2017). The level of RSR of AV systems depends inter alia on the density of PV panels (i.e., panel area per system area) and, in case of AV systems with solar tracking systems, whether the tracking algorithm aims to maximize solar power production, crop yields or a combination of both. In contrast, PV systems optimized for electricity production, which is often indicated as ‘full density’ in the literature, are assumed to reduce radiation by 50% and more (Dupraz et al. 2011). In agroforestry systems, the levels of shading are similar to typical AV systems (most agroforestry systems in this study ranged from 20 to 40%) but several studies reported levels above 80% RSR. Estimating the shade effect on crop yields for very high levels of RSR (>75%) is associated with high uncertainty as it would require extrapolations beyond the range of data available. However, very high levels of shade in agroforestry systems are usually only present when trees are not pruned and in systems where the component below the tree is of lesser importance.

Due to the large range of RSR covered, the presented results could serve as an important data source 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). As the prediction intervals show, uncertainties due to random plot scale effects are large, while at country or continental scales the mean response to shading, represented by the confidence intervals, is the more valid estimator. The results may also contribute to standardization and policy forming processes, in which the eligibility for policy support of AV systems with different levels of shading has to be determined. 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% (MAFF, 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 better defining “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, where the electricity production is usually of highest economic value. Policies should assure that economic crop yields in AV systems stay high enough to avoid unintended side effects such as farmers abandoning the crop land below the AV system (Feuerbacher et al. 2021).

4.4 Limitations and recommendations for future studies

The normalization of data and the aggregation into crop types within this study comes with some limitations. The number of studies used for different crop types ranged between two and eleven, resulting in higher uncertainty for crop types with low availability of data points. While necessary due to a scarcity of studies on individual crops, the aggregation of crop types masks heterogeneities between different crops within a given crop type. It assumes significant differences in the response of one aggregated crop type compared to another, so if aggregated crop types are heterogeneous, this leads to a higher uncertainty for the predictions of that crop type. This was visible when comparing the relatively homogeneous C_3 crops and maize to forages and fruits, the latter comprising both temperate and subtropical fruit trees. Further, this meta-analysis cannot directly capture interactions of shading with other factors, such as water availability, where shading may reduce evapotranspiration and thus water stress. Dynamic crop growth models (e.g., Amaducci et al., 2018) may help to further optimize AV and agroforestry systems. However, further field experiments are needed especially for different AV designs (e.g., top-mounted AV panels with or without tracking or vertically mounted panels) to provide the input to calibrate these data hungry models. Thus far, there are few studies on crop growth beneath AV systems, and they are limited to top-mounted solar panels (n=4 in our meta-analysis). The type of shading (nets, cloths, PV modules or intercropping) was not a significant covariate in the final model. This supports the validity of our results, as the insignificant difference between cloths and intercropping should be higher than between cloths and AV. Yet, future studies are needed to examine if the lack of this difference is due to a lack of statistical power, since there were only two studies that tested different shade types at the same site. Also, despite the highly significant differences between the response of different crop types to RSR, our statistical model estimates the difference in the reaction to RSR between different crop types mostly based on independent experiments: few studies tested more than one crop type in the same location.

As a consequence of these identified shortcomings, we formulated recommendations to better understand the impact of soil type and climate and estimate better yield response curves to shading. Future studies should ideally 1) include various crop types at the same location, 2) focus on the crop types that were subject to the highest uncertainty (e.g., tubers/root crops and fruit vegetables were covered by few studies), 3) study different shade systems (e.g. intercropped systems, AV and shading nets) at the same locations, and 4) include different levels of shade at the same sites so that yield response curves can be created to optimize the level of shade. Finally, 5) different crop types need to be studied based on the same type of measurement. Dry matter-based yield should be preferred to assure that increased yields in fruits are not just the result of higher water contents.

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 of crops that 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 based on literature data. The results suggested that berries, fruits, and fruity vegetables may show initial benefits up to 40% shade. Forages, leafy vegetables and tubers/root crops start with a less than proportional 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 an increased level of shading. To optimize shade systems, e.g., for the design of AV systems, it is therefore 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 proportional. Estimating the response curves of crop yield to shading is therefore highly relevant. Results such as that of this study will be essential to better estimate the potential of AV systems in achieving a transition to renewable energies. It will additionally help to optimize agronomic output per unit of land in AV systems and thus allows us to design adequate policies supporting the adoption of these new technologies. 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.

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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.

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

Code availability

Not applicable

Declarations

Ethics approval Not applicable

Consent to participate Not applicable

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