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Berry shade tolerance for agrivoltaics systems: A meta-analysis

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ABSTRACT

Agrivoltaics, i.e. the placement of photovoltaic panels above crops, can contribute to more sustainable energy and food systems. However, the current large knowledge gap on crop yield response to shade is a limiting factor to agrivoltaics development. Berries have been identified as a shade benefitting crop group with a high potential for agrivoltaics, but little is known on their individual crop shade response. We examine the berry crop group more in detail through a meta-analysis of strawberry (*Fragaria ananassa*), blueberry (*Vaccinium sect. Cyanococcus*), blackberry (*Rubus subg. Rubus*), and black currant (*Ribes nigrum*), to distinguish between individual crops and assess their suitability for agrivoltaics systems. This study provides the first yield response curves of individual berry crops to increasing shade, also distinguishing between different radiation intensity environments. The response curves provide valuable information for the design of agrivoltaics systems and can help in selecting optimal crop and panel density combinations for different locations. We find that low levels of shade are relatively less detrimental to yield than high levels of shade, and that yield response differs significantly between crops and between low and high radiation intensity environments. We conclude that, although generally classified as shade-benefitting in previous literature, not all berries are equally suitable for the shaded conditions in agrivoltaics. Whereas blueberry yield at high radiation intensities can benefit from up to 50 % shade, other berry types are better classified as shade tolerant, enduring up to around 35 % shade without yield loss but declining afterwards.

1. Introduction

In recent years, agrivoltaics has come into the spotlight as a concept that could contribute to both the transition towards sustainable energy and to more climate resilient food systems (Al Mamun et al., 2022). It consists of placing solar panels above crops, such that both crop and energy production are combined on the same field. In agrivoltaics, the panels are placed at a lower density than in standard solar fields, so that radiation is shared between the panels and the crop below. This type of system can have a range of benefits. The combination of solar panels and crops can allow for a more efficient land use compared to separate systems, and keeps agricultural land in production (Dupraz et al., 2011). The panels can provide protection from climate extremes to the crop and improve water use efficiency due to lower evapotranspiration, making the cropping system more climate resilient (Gomez-Casanovas et al., 2023). The panels can also replace plastic covers currently used in some crops, leading to more durable growing systems and less plastic waste (Jung and Salmon, 2022). Finally, the panels can also benefit from the crop below, as crop evapotranspiration can cool the panels and allow a higher efficiency, especially in warm conditions (Barron-Gafford et al., 2019; Williams et al., 2023).

To design agrivoltaics systems with the benefits outlined above, combinations of crops and panel densities are needed which strike the right balance in sharing radiation between the crop and the panel. On one hand, panel density must be high enough so that electricity generation is still economically viable. On the other hand, it must be low enough that the crop can maintain its yield and cultivation practices are not hampered. A key aspect to identify these synergistic combinations is the response of different crops to shade, and the level of shade they can endure without yield loss. However, although differences in shade tolerance between plant species are generally recognized on a qualitative level (Gommers et al., 2013), there is still a large quantitative knowledge gap on crop shade response (Weselek et al., 2019). To our knowledge, quantitative overviews of individual crop response to different levels of shade are not available. This is further complicated by the possible interactions between crop shade response and environmental factors such as radiation intensity, temperature, and water availability, meaning that optimal crop and shade level combinations

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can differ per region.

With the currently available information, literature generally points towards berries as a high potential crop group for agrivoltaics systems (El Boujdaini et al., 2023; Widmer et al., 2024). In berry production systems, solar panels could be placed with little to no adaptation of cultivation practices, and the panels could replace hail nets and plastic covers (Trommsdorff et al., 2022). The origin of berries as forest undergrowth species also suggests a relatively high shade tolerance, making them overall suitable candidates for agrivoltaics. However, the quantitative effect of shade on yield of individual berry crops is still unclear. While the mini-review by Touil et al. (2021) identifies strawberry as a shade benefitting crop in terms of yield, the review by Obergfell (2012) concludes the opposite and classifies strawberry as a shade sensitive crop with detrimental effects on yield. In their meta-analysis, Laub et al. (2022) identify berries as a shade benefitting crop group, with positive yield effects at up to 60 % shade. Although this result suggests suitability of berries overall, the aggregation into groups masks differences in shade tolerance that exist between individual types.

In this study, we examine the berry crop group more in detail to distinguish between individual types and assess their suitability for agrivoltaics systems. The objective of this study is to determine the quantitative effect of increasing shade on yield across different berry types. We do this through a meta-analysis of published berry shade experiments. We describe our method in Section 2, present and discuss our results in Sections 3 and 4, and finally present our main conclusions in Section 5.

2. Method

In our meta-analysis, we first developed a search query, performed a systematic search to gather publications (Section 2.1), and selected the relevant publications based on our criteria (Section 2.2). Then we collected data from the selected publications (Section 2.3), and analyzed the collected data (Section 2.4).

2.1. Systematic search

We developed a search query to gather publications on the main commercial berry types: strawberry, blueberry, raspberry, blackberry, black currant, and red currant. The query was aimed at finding agronomic experiments of these berry types, implementing at least two light levels, and reporting on crop yield. The query therefore consisted of three term groups: berry names, synonyms for light and shade conditions, and synonyms for yield and crop productivity. The list of terms in each group was developed iteratively, checking the completeness of the query search results and adding terms if necessary. A fourth term was added to the query to exclude publications on coffee and grapes, also commonly referred to as berries. All terms in the query were included in English, Dutch, and Spanish, and for the crop names also in Latin. The final version of the search query was executed in CAB Abstracts and Web of Science on 21–02–2022, and resulted in 3677 publications after removal of duplicates.

2.2. Publication selection

We identified a set of criteria that publications must meet in order to be included in the meta-analysis. The criteria were determined such that the agronomic conditions of the collected data would be as close as possible to agrivoltaics systems' conditions, while at the same time allowing enough data for analysis. The following criteria were used:

- The publication reports on empirical yield results of an agricultural experiment of either strawberry (*Fragaria ananassa*), blueberry (*Vaccinium sect. Cyanococcus*), raspberry (*Rubus idaeus*), blackberry (*Rubus subg. Rubus*), black currant (*Ribes nigrum*), or red currant (*Ribes rubrum*).
- The experiment has at least two different radiation treatments, reported quantitatively either as measured radiation or as a radiation level relative to unshaded conditions.
- The radiation treatments are created by decreasing solar radiation, i.e. with shade. Treatments using artificial radiation were not included.
- The radiation treatments are created either with shade nets, natural foliage, or a vertical light gradient in a stair-like vertical growing system. Radiation treatments created with enclosed impermeable covers such as plastic tunnels or glass greenhouses were excluded due to the insulation offered by these materials. Publications were accepted with all radiation treatments in an open system, or with all radiation treatments within the same impermeably covered system (e.g. all in a greenhouse), but not if comparing radiation treatments of an open and an impermeably covered system.
- The radiation treatments encompass the whole solar radiation wavelength spectrum. Treatments influencing specific wavelengths such as ultra-violet, infrared, or specific colors were not included. Changes in the wavelength composition of the incident radiation can lead to changes in crop physiology (Orde et al., 2021), which would not be encountered in present agrivoltaics systems that are based on crystalline silicon modules (Trommsdorff et al., 2022). Treatments with shading nets were therefore only included if the nets were either black, grey, white, or green, which are the industry standard for shade netting and have a relatively low impact on spectral composition (Kittas et al., 2008; Kotilainen et al., 2018).
- The experiment takes place in the main production season for the studied berry at the experiment's location. If not specified in the publication, the main production season at the location was assumed to be the growing season as estimated by WeatherSpark (2023). Publications reporting only on off-season production or forcing of early production were not included.
- The temperature remains above 0 °C throughout the duration of the experiment. In experiments with frost occurrence, yield differences between shaded and unshaded treatments can largely be attributed to the frost protection offered by the shading net. While agrivoltaics can also offer frost protection, in this study we aim to understand the effect of shade, not of insulation, and therefore exclude studies with freezing temperatures to avoid confounding effects.
- For strawberry, the requirement was set that the different radiation levels must be applied throughout the whole production season. This requirement was set to resemble the placement of agrivoltaics, which are generally permanent structures and would cover the crop the whole production season. This requirement could not be set for blueberry, raspberry, blackberry, black currant, or red currant, as this would not have allowed enough data for analysis. It should be noted therefore that results on these berry types only provide information on the effect of partial shade during the production season, and should be interpreted with care.
- The publication must be either in English, Dutch, or Spanish.

Publications were accepted if they contained at least two treatments that met all the above requirements, including an unshaded control. The selection criteria resulted in 23 publications eligible for data extraction. As the search resulted in only a single publication on raspberry and none on red currant, these crops were not further analyzed. The final number of publications in the meta-analysis is therefore 22, as listed in Table 3 in the Results Section.

2.3. Data collection

From the 22 selected publications, we collected information that describes the experiment, together with quantitative data on yield and radiation (Table 1). Quantitative data were taken from the text, or extracted from figures using WebPlotDigitizer (Rohatgi, 2022). Each unique combination of publication, crop, variety, year, relative shade

Table 1
Variables collected across the selected publications for the meta-analysis on shade tolerance of different berry crops and their suitability for agrivoltaics systems.

Variable	Symbol	Unit	Definition
Crop	Crop	–	Berry type(s) tested in the experiment
Variety	–	–	Variety or varieties tested in the experiment
Year	–	–	Year(s) in which the experiment was executed
Other variable level	–	–	Level of other treatment in experiment (e.g. irrigation, fertilization, or temperature)
Relative shade rate	RSR	%	Average decrease in radiation relative to unshaded conditions, expressed as a percentage. If available, the RSR was determined from measured radiation data, otherwise the RSR stated by the authors was assumed.
Radiation intensity	RI	W/m^2	The hourly direct normal radiation intensity profile throughout the year was retrieved for each experiment's location from the Global Solar Atlas (ESMAP, 2019). The maximum value in the profile within the main growing season was used as a proxy indicator of the location's radiation intensity relative to the other studies in the meta-analysis. For experiments performed inside a plastic or glass system, we assumed a 90 % transmission of the cover material (Bartok, 2023; Farm Plastic Supply, 2023) and decreased the radiation intensity value by 10 %.
Radiation intensity level	RIlev	–	Classification of the location's radiation intensity into the discrete categories 'Low' and 'High' if the value was respectively below or above the midway value across all publications. Low = 264 to 571 W/m^2, High = 572 to 878 W/m^2
Shade type	ST	–	Shade type used in the experiment to create the radiation levels. This was categorized into 'Shade nets', 'Foliage' (e.g. intercropping and agroforestry), or 'Stair-like vertical growing systems'.
Absolute yield	–	g/plant	Harvested fresh yield of the crop in each treatment.
Relative yield	RY	%	Harvested fresh yield relative to the corresponding unshaded (control) object, expressed as a percentage. If not reported, this value was calculated using the absolute yield data.

rate (RSR), and level of other experimental variable was considered an individual data point (observation). Each observation had a corresponding relative yield (RY), radiation intensity level (RIlev), and shade type (ST).

2.4. Data analysis

2.4.1. General approach

The collected observations were analyzed following broadly the same approach as outlined by Laub et al. (2022). We fit a mixed effect model to account for the random differences between the publications. The response variable of the model was the relative yield, and we used a backwards elimination process to determine the significant fixed effects (i.e. explanatory variables).

2.4.2. Mixed effects model

The initial maximal model included the following fixed effects (FE):

FE1: The relative shade rate and its quadratic term, to determine whether low levels of shade are relatively less detrimental to yield than high levels of shade.

FE2: The interaction between the relative shade rate and the crop type, as well as its quadratic term, to determine whether different crops respond differently to shade

FE3: The interaction between the relative shade rate and the radiation intensity level, as well as the three way interaction with crop type. This term was included to determine whether yield loss as a result of shade is less pronounced in high radiation intensity environments.

FE4: The interaction between the relative shade rate and the shade type used in the experiment, to account for any confounding effects this might cause.

The model has a fixed intercept of 100, as we assume a relative yield of 100 % at unshaded conditions (RSR of 0 %). We included in the model a random effect of the linear term of shading rate where the levels of the random effects were the individual publications (n = 21). We did not include a random effect on the quadratic term of the relative shade rate as this prevented the model to be fitted in the cases where few observations per publication were present. As the model's intercept was fixed (RSR 0 %, RY 100 %), no random intercept was added and control observations were removed to avoid artificially inflating the number of observations. The number of observations for each crop is reported in Table 2. Like Laub et al. (2022), we did not include the uncertainty in the estimates for each point as is normal practice in meta-analyses because it was not possible to retrieve the uncertainty for many of the records.

2.4.3. Transformation

The response variable and the fixed intercept (100 % RY, 0 % RSR) were transformed using the square root function to improve homogeneity of variance of residuals. This transformation was selected after visual inspection of the q-q plots of standardized residuals fitted on the maximal model after no transformation (i.e. identity transformation), log transformation, and root-square transformation (Figure S1 in the Supplementary Information). Estimates were back-transformed using the power of two.

2.4.4. Backwards selection

To reach our final minimally adequate model we used a backward stepwise simplification approach where we started from an initial more complex model and reached a simpler model by sequentially removing less influential terms using the following algorithm:

1. Remove the highest order non-significant ($p < 0.05$) interaction term.
2. Test that the removal of the factor resulted in a significantly lower likelihood.
3. Repeat these steps until all terms remaining are significant.

Analyses were completed in the R statistical environment (version 4.04) using the lme4 and lmerTest packages for mixed models and calculation of degrees of freedom for the denominator, respectively (Bates et al., 2015; Kuznetsova et al., 2017) . The significance of each term was calculated using Fisher's F-test. Due to the use of a mixed model, the degrees of freedom were calculated using the Satterthwaite's method for approximating degrees (Giesbrecht and Burns, 1985; Kuznetsova et al., 2017). The terms included in the initial model and the terms retained in the final simplified model are listed in Table 4.

Table 2
Number of observations at low and high radiation intensity levels (RIlev) for each crop after removal of control values in the meta-analysis of berry crop tolerance to shade. Low = 264 to 571 W/m^2, High = 572 to 878 W/m^2.

Berry Type	RI Lev		Total
	Low	High	
Black currant	33	0	33
Blackberry	4	4	8
Blueberry	15	13	28
Strawberry	8	27	35
Total	60	44	104

Table 3
Publications and their experimental characteristics included in the meta-analysis on shade tolerance of different berry crops and their suitability for agrivoltaics systems. NA = Not available.

Publication	Country	Varieties	Years	Other variable	Growing system	Shade type
Strawberry						
Awang and Atherton (1995)	UK	Rapella	1992	Electrical conductivity	Glass greenhouse	Shade net
Chagas et al. (2018)	Brazil	Oso Grande	2016	Fertilization	Open field	Shade net
Demirsoy et al. (2007)	Turkey	Sweet Charlie	2002	None	Open field	Shade net
Rana and Sharma (2002)	India	Chandler, Ofra, Oso Grande	1988	None	Open field	Shade net
Sharma et al. (2006)	India	Chandler, Douglas, Etna, Fern, Sweet Charlie	2001	None	Open field	Foliage
Singh et al. (2012)	India	Ofra	2007	None	Open field	Shade net
Swapnil et al. (2015)	India	Winter Dawn	2013	None	Open field	Shade net
Tabatabaei et al. (2008)	Iran	Camarosa	*NA*	NO_3:NH_4 ratio	Glass greenhouse	Shade net
Velasco-López et al. (2020)	Mexico	Camino Real	2016	None	Plastic greenhouse	Stair-like vertical growing system
Wagstaffe and Battey (2004)	UK	Everest	2001	Temperature	Glass greenhouse	Shade net
Blueberry						
Hicklenton et al. (2004)	Canada	Bluegold, Brigitta	2000,2001	None	Open field	Shade net
Kim et al. (2011)	Korea	Bluecrop	*NA*	None	Plastic greenhouse	Shade net
Lobos et al. (2013)	USA	Elliot	2006	None	Open field	Shade net
Milivojević et al. (2016)	Serbia	Duke	2013,2014	None	Open field	Shade net
Retamales et al. (2008)	Chile	Berkeley	2003,2004	None	Open field	Shade net
Smith and Malladi (2017)	USA	Star	2016	None	Open field	Shade net
Black currant						
Djordjevic et al. (2015)	Serbia	Ben Lomond, Ben Nevis, Ben Sarek, Cacanska Crna, Ometa	2010, 2011	None	Open field	Shade net
Toldam-Andersen and Hansen (1993)	Denmark	Tenah	1992	None	Open field	Shade net
Wolske et al. (2021)	USA	Consort	2016,2017,2018	None	Open field	Shade net
Blackberry						
Ciobotari et al. (2013)	Romania	Lochness, Thornfree	2012	Irrigation	Open field	Shade net
Makus (2010)	USA	Kiowa	2008	Weed control	Open field	Shade net
Rotundo et al. (1998)	Italy	Black Satin, Smoothstem	1996	None	Open field	Shade net
Raspberry						
Warmund et al. (1995)	USA	Allen	1990	None	Open field	Shade net

Table 4
Analysis of variance table of initial (maximal) model and final model after backwards selection of fixed effects in the meta-analysis of berry shade tolerance. SumSq = sum of squares, MeanSq = mean square, NumDF = numerator degrees of freedom, DenDF = denominator degrees of freedom, *F* = *F*-value, *P* = *P*-value, RSR = relative shade rate, Crop = berry crop type, RIlev = radiation intensity level, ST = shade type. See Table 1 for explanation of the variables.

Model term	SumSq	MeanSq	NumDF	DenDF	F	P
Initial model						
RSR	0	0	1	9.1	0.4	0.565
RSR^2	0	0	1	56.8	0.3	0.611
RSR x Crop	9	3	3	18.5	3.1	0.053
RSR x RIlev	0	0	1	10.9	0.3	0.597
RSR^2 x RIlev	0	0	1	9.5	0.5	0.510
RSR^2 x Crop	16	5	3	21.7	5.6	0.005
RSR x ST	1	0	2	10.7	0.3	0.744
RSR x Crop x RIlev	0	0	2	19.0	0.0	0.979
RSR^2 x Crop x RIlev	0	0	1	9.5	0.0	0.861
Final model						
RSR	9	9	1	92.8	9.0	0.003
RSR^2	18	18	1	22.8	18.4	0.000
RSR x RIlev	21	7	3	39.9	7.3	0.001
RSR x Crop	6	6	1	92.4	6.2	0.014
RSR^2 x RIlev	5	5	1	88.5	4.7	0.032
RSR^2 x Crop	22	7	3	43.6	7.5	0.000

2.4.5. Final model

Because the number of observations differed by crop and radiation level (see Table 2) we used type III ANOVA table from the package lmerTest, as this is best suited for unbalanced designs. The ANOVA was used to ensure that the terms removed did not have a significant effect on the variance of residuals. The predictions from the final model are shown in Fig. 1, with 95 % confidence ranges estimated using bootstrapping procedure (500 simulations).

3. Results

FE1: The analysis of variance of the final model shows that the quadratic term of relative shade rate is a significant predictor ($p \leq 0.001$) for yield response to shade (Table 4). The shape of the curves is generally concave (Fig. 1), indicating that low levels of shade are relatively less detrimental, or even beneficial, to yield than high levels of shade. An exception to this is the response of strawberry (Fig. 1D), which has a convex shape and therefore suggests increasing yields at high shade rates. Physiologically, this response is highly improbable and can likely be attributed to the limited number of data points at low shade rates.

FE2: Results indicate a significant difference between crops in their yield response to increasing shade ($p \leq 0.05$). This is reflected in the different response curve shapes of the crops, with different inflection points and relative shade rates they can endure without yield loss (Fig. 1). This result corroborates the importance of understanding individual crop yield response curves as opposed to crop groups, as the aggregation can mask differences between crops.

FE3: There is also a significant difference in crop yield response between environments with a high and low radiation intensity ($p \leq 0.005$). This indicates that yield loss as a result of shade is stronger in low radiation intensity environments. Shade at low radiation intensities generally results in reduced yields across all crops (Fig. 1), whereas at high radiation intensities a moderate shade may give an increased yield. This result underlines the importance of taking into account radiation intensity when interpreting crop shade response, and suggests that successes of one region will not necessarily hold somewhere else. A region's latitude and cloudiness determine its radiation intensity and consequently influence its suitability for agrivoltaics.

FE4: Shade type was not retained as a predictor in our final model, either because its role is marginal and/or that our dataset was not sufficiently large to estimate reliably its effect on yield.

4. Discussion

4.1. Berry crops for agrivoltaics

The generated yield response curves (Fig. 1) give a first insight on the suitability of specific berry crops for agrivoltaics systems at different radiation intensities and shade levels. The curves are limited by data availability, with some of the curves estimated based on only a few data points, or on data from a single study. We further expound on these limitations in Section 4.3. However, despite these drawbacks, the curves still give a broad insight on the differences in shade response that can be expected between berry crops. This information is valuable for the design of agrivoltaics systems, as it can help to select an adequate crop and panel density combination for an intended location. The curves can also serve as input for agrivoltaics modelling and estimating a system's viability in terms of crop production and economic feasibility.

Although berries have been classified as shade benefitting crops by Laub et al. (2022), these results indicate that there is likely more nuance to it. Conceptually, shade benefit is considered as an increase in yield compared to the unshaded condition (RY > 100 %), shade tolerance as a relative yield decrease above the direct proportional loss curve (at X% RSR, RY has decreased less than X%), and shade susceptibility as a relative yield decrease below the direct proportional loss curve (at X% RSR, RY has decreased more than X%). For a graphical representation of these definitions, see Laub et al. (2022). Of the four analyzed crops, only blueberry can be said to substantially benefit from low levels of shade, and only in high radiation intensity environments. Under these conditions, blueberry benefits optimally from around 25 % shade, and can endure up to almost 50 % shade without yield loss. This also applies for blackberry, but this crop's response curves have a very wide confidence interval based on a limited number of data points and should be interpreted with care.

The yields of black currant, blackberry, and blueberry under low radiation intensity conditions do not benefit from shade, but can sustain up to around 35 % shade without yield loss. Strawberry yields under high radiation intensity decline with increasing shade, but yield losses are less than proportional. These combinations of crop and radiation intensities would therefore broadly be classified as shade tolerant, rather than shade benefitting The strawberry yield response at low radiation intensities cannot be accurately classified due its physiologically unlikely shape and lack of data at low shade levels. However, given the steep yield reductions at the measured observations, it is likely the yield response is susceptible to shade or at best shade tolerant. Overall, the results confirm previous literature findings that berry crops are suitable candidates for agrivoltaics (Laub et al., 2022; Widmer et al., 2024), as their yield response to low levels of shade is either positive or tolerant. However, we find that not all berries are created equal, and propose that blueberry, blackberry, and black currant are more suitable than strawberry, and that shade benefits on yield should only be expected in regions with a high radiation intensity.

Compared to previous shade response reviews by Laub et al. (2022) and Touil et al. (2021), our results paint a less rosy picture of berry potential for agrivoltaics. This can be explained by methodological differences. Laub et al. (2022) report shade levels as stated by shade net manufacturers, as opposed to measured shade. These are not equal (Fig. S2 in Supplementary Information), and the large difference between these two shade levels in Retamales et al. (2008), which constitutes a substantial portion of the berry dataset in Laub et al. (2022), leads to an overestimation of the shade level that berries can tolerate. Additionally, four of the five berry studies in Laub et al. (2022) are classified in our study as having a high radiation intensity, skewing results towards a more positive shade response. Finally, the highest berry yield values in Laub et al. (2022) correspond to blueberry shading with red netting, which we have left out due to the effects on crop physiology that colored netting can have (Orde et al., 2021) and which would not be encountered in current agrivoltaics systems (Trommsdorff et al., 2022).

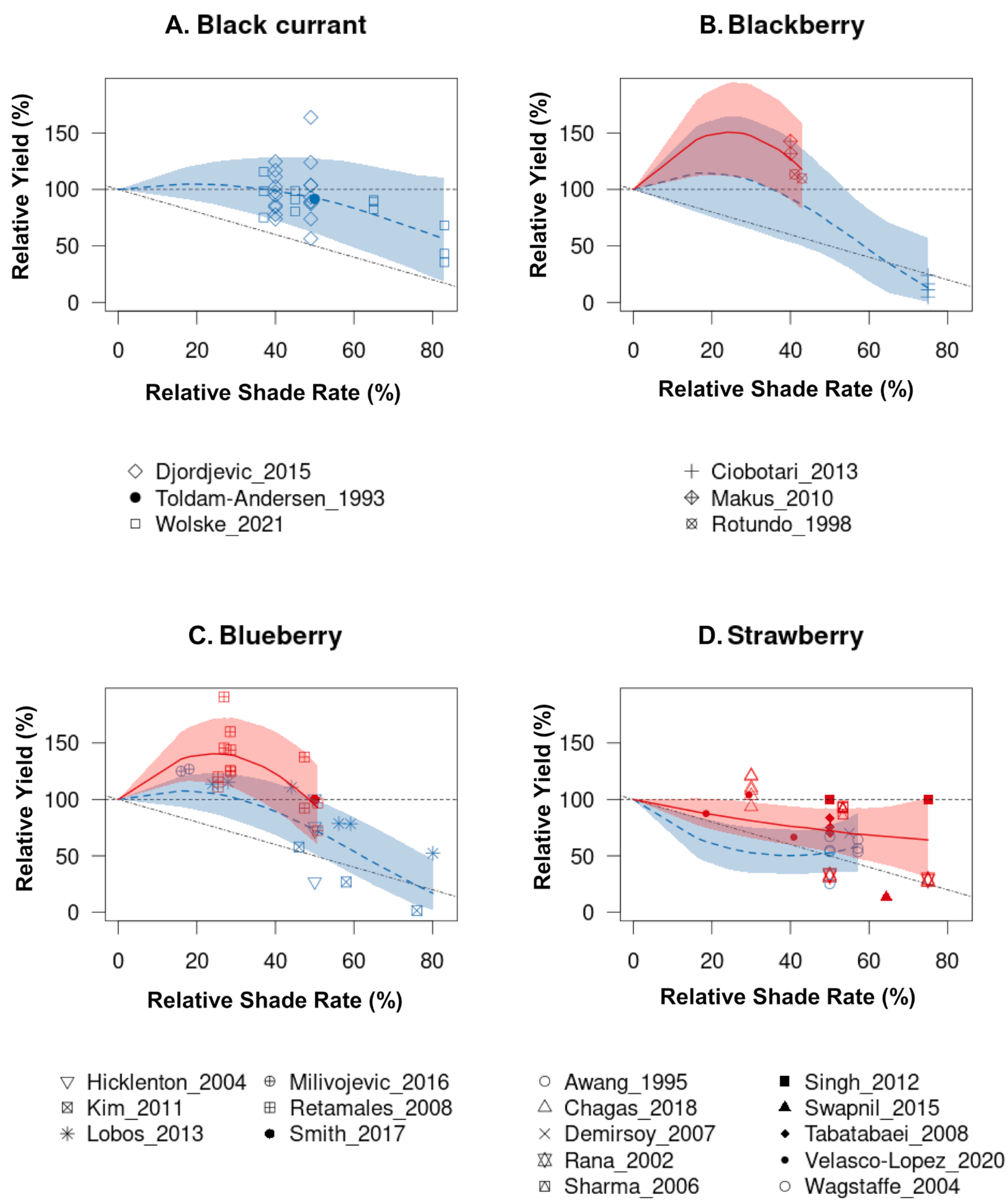

Fig. 1. Response curves of relative yield (RY) to relative shade rate (RSR) for (A) black currant, (B) blackberry, (C) blueberry, and (D) strawberry at the low (blue, dashed line) and high (red, solid line) radiation intensity levels predicted by the mixed effects model in the meta-analysis of berry shade tolerance. The 95 % confidence interval represents the confidence based only on fixed effects. The dotted lines indicate the direct proportional loss curve (diagonal, e.g. 10 % increase of relative shade rate results in 10 % yield decrease) and the 100 % relative yield (horizontal) as references.

The review by Touil et al. (2021) covers only strawberry from the berry crop group, and estimates a positive yield response to shade based on Cossu et al. (2020) and Tang et al. (2020). In our study, we have not included Cossu et al. (2020) as it is a modelling study without yield measurements, and we have also excluded Tang et al. (2020) as the experiment takes place outside the main growing season and the shade treatments are not clearly defined.

4.2. Physiological pathways

4.2.1. Differences between crops

Crop shade response is a complex subject on which much is still unknown (Valladares and Niinemets, 2008), and the differences in shade tolerance between berry types can involve many physiological pathways. The ability of black currant, blackberry, and blueberry to maintain or increase their yields at low shade levels could be explained by a greater ability of the shaded plants to intercept radiation (Tateno and Taneda, 2007). By increasing their surface area and chlorophyll content, leaves of shade tolerant species can adapt to shade by intercepting more of the incoming radiation. Although shaded leaves generally have lower photosynthetic rates per unit area than sun leaves (Atwell, 1999), Tateno and Taneda (2007) concluded that, when expressed on a per weight basis, the shaded leaves' photosynthetic rates can equal or surpass that of sun leaves for shade tolerant species. This suggests that the greater light intercepting ability of larger and thinner leaves can compensate for the lower incident radiation and for the lower photosynthetic rate per unit area. Black currant and blueberry were found to have a higher specific leaf area and total leaf area when shaded, supporting the possibility of increasing the fraction of radiation intercepted (Toldam-Andersen and Hansen, 1993; Retamales et al., 2008; Kim et al., 2011; Wolske et al., 2021). In contrast, strawberry increases its specific leaf area when shaded (Wagstaffe and Battey, 2004), but does not increase its total leaf area (Awang and Atherton, 1995; Wagstaffe and Battey, 2004; Tabatabaei et al., 2008). This suggests that the crop's leaves only get thinner, but not larger, and it therefore has a limited ability to increase its radiation interception under shade.

Differences in radiation interception could also be caused by the response in stem length. Black currant, blackberry, and blueberry exhibited stem elongation when shaded (Toldam-Andersen and Hansen, 1993; Rotundo et al., 1998; Retamales et al., 2008; Kim et al., 2011; Djordjevic et al., 2015; Smith and Malladi, 2017), whereas strawberry petiole length and plant spread decreased under shade (Swapnil et al., 2015). Although elongation is generally regarded as a shade avoidance response (Martinez-Garcia and Rodriguez-Concepcion, 2023), it can be advantageous to light interception (Valladares and Niinemets, 2008) and could therefore also play a part in the tolerance to moderate shade.

4.2.2. General shade tolerance

The tolerant and benefitting yield responses to shade could also be caused by a range of other factors. The lower incident radiation under shaded conditions can reduce photodamage (Kim et al., 2011), allowing for a higher photosynthetic efficiency. The shading treatment can also scatter the incoming radiation (Abdel-Ghany and Al-Helal, 2010). Scattering increases the amount of diffuse light, which is more efficiently used by plants compared to direct light (Li et al., 2014). The shift from direct to diffuse light can also be beneficial to avoid damage to the berries from direct light (Djordjevic et al., 2015). Shade also reduces evaporation from soil and transpiration by plants (evapotranspiration) and this water saving may prevent drought stress, especially under dry conditions (Hassanpour Adeh et al., 2018; Barron-Gafford et al., 2019)

4.3. Study limitations

Although the yield response curves give some first insight into individual crop shade tolerance, there are a number of limitations to the study. The analysis was to a large extent limited by the scarcity of available data. This led to a physiologically improbable strawberry response curve, highly uncertain response curves for blackberry, and no response curve for black currant at high radiation intensities. The limited data also made it necessary to simplify the analysis, disregarding possibly confounding factors. For this reason, we use a discrete and arguably subjective classification for radiation intensity into two categories as opposed to a continuous scale. We also do not differentiate between data from open field and greenhouse experiments despite the possible confounding effects of temperature and water use efficiency (Wagstaffe and Battey, 2004), nor do we distinguish between varieties to account for a possible genotype effect (Atlan et al., 2015; Malaviya et al., 2020). For black currant, blackberry, and blueberry we included experiments shading only part of the year, whereas agrivoltaics systems would involve year round shading. Moreover, the included studies only measure yield for a few years, while the effect of shade on perennials can be cumulative over time (Atlan et al., 2015). Finally, there can also be a bias in the data, as it is possible that research on shade happens more in areas where shade is likely to be beneficial. Considering these points, we stress that the response curves are only indicative, and that more research is needed to further underpin these results. Nevertheless, despite the drawbacks of the study, we consider the crop response curves the best estimates available at this moment and to be valuable for current agrivoltaics design.

4.4. Further research

The differences in shade response between crops and at different radiation intensities underline the importance of studying shade response for individual crops, and to disentangle the effects of environmental factors. Further research is needed to better understand the complex interactions at play between absolute and relative radiation, temperature, water use, and crop physiology. This requires extensive measurements of crop yield and physiological responses to year-round shade in actual agrivoltaics setups, at different shade levels and under different environmental conditions. For perennials, it is also of importance to research the long term effect of shade after multiple years, to better understand its cumulative effect over time. The differences in shade susceptibility between varieties should also be studied, as this would allow optimal use of the possible benefits of shade. Finally, while this study has solely focused on yield, shade can also have an impact on berry quality (Awang and Atherton, 1995; Ciobotari et al., 2013; Djordjevic et al., 2015). To accurately evaluate berry crop suitability for agrivoltaics systems, further research is also needed on the impact of shade on berry quality parameters such as organoleptic properties, sugar and dry matter content, and content of secondary metabolites.

5. Conclusion

We provided for the first time yield response curves of four berry types to increasing shade based on currently available data in a meta-analysis. The response curves provide valuable information for the design of agrivoltaics systems and can help in selecting optimal crop and panel density combinations for different locations. We find that low levels of shade are relatively less detrimental to yield than high levels of shade, and that yield response differs significantly between crops and between low and high radiation intensity environments. We conclude that, although classified as shade-benefitting in previous literature, not all berries are equally tolerant to shade. Whereas blueberry yield at high radiation intensities can benefit from up to 50 % shade, other berry types are better classified as shade tolerant, enduring up to 35 % shade without yield loss but declining afterwards. The crop yield response curves give a first insight on the suitability of specific berry crops for agrivoltaics systems at different locations and shade levels; however, more data is needed on crop response to shade across environments to further underpin the results.

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CRediT authorship contribution statement

Marleen I. Hermelink: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bernardo Maestrini:** Writing – review & editing, Visualization, Software, Formal analysis, Conceptualization. **Frank J. de Ruijter:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data analyzed during the current study are publicly available in the original publications, and the compiled dataset is also available in the supplementary information of this study.

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Supplementary materials

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