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Athina Koutouleas, Thuan Sarzynski, Benoît Bertrand, Mélanie Bordeaux, Aske Skovmand Bosselmann, et al.. Shade effects on yield across different *Coffea arabica* cultivars - how much is too much? A meta-analysis. *Agronomy for Sustainable Development*, 2022, 42 (4), pp.55. 10.1007/s13593-022-00788-2 . hal-04132281

HAL Id: hal-04132281

<https://hal.science/hal-04132281>

Submitted on 19 Jun 2023

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Shade effects on yield across different *Coffea arabica* cultivars — how much is too much? A meta-analysis

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Accepted: 25 May 2022 / Published online: 16 June 2022
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Abstract

The coffee research community has maintained a long ongoing debate regarding the implications of shade trees in coffee production. Historically, there has been contrasting results and opinions on this matter, thus recommendations for the use of shade (namely in coffee agroforestry systems) are often deemed controversial, particularly due to potential yield declines and farmers' income. This study is one of the first demonstrating how several *Coffea arabica* cultivars respond differently to shade with respect to yield. By standardising more than 200 coffee yield data from various in-field trials, we assembled the so-called “Ristretto” data pool, a one of a kind, open-source dataset, consolidating decades of coffee yield data under shaded systems. With this standardised dataset, our meta-analysis demonstrated significant genotypic heterogeneity in response to shade, showing neutral, inverted U-shaped and decreasing trends between yield and shade cover amongst 18 different cultivars. These findings encourage the examination of *C. arabica* at the cultivar level when assessing suitability for agroforestry systems. Comparison of productivity is also encouraged across a range of low to moderate shade levels (10–40%), in order to help elucidate potential unknown optimal shade levels for coffee production.

Keywords Coffee · Agroforestry systems · Climate change · Crop management · Light intensity · Meta-analysis · Yield

Abbreviations

AFS Agroforestry systems
FS Full-sun
GxE Gene-environment interaction
cv. Cultivar

1 Introduction

Coffea arabica L. is an allotetraploid species derived from spontaneous hybridization between *Coffea canephora* Pierre ex A. Froehner, and *Coffea eugenioides* S. Moore (Lashermes

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et al., 1999). It is indigenous to the understory montane rain forests of southwestern Ethiopia and South Sudan, representing its primary centres of diversity (Sylvain, 1955; Friis, 2015). Yemen is the accepted secondary dispersal centre of *C. arabica* (Fernie et al., 1968; Montagnon et al., 2021). In the areas of origin, coffee grows wild under the canopy of tall trees. However, reports on early cultivation suggest that sun-exposed fields with terracing dominated agricultural practices in Yemen (Friis, 2015).

A large genetic diversity analysis of the coffee genome (Scalabrin et al., 2020) has revealed that the majority of coffee grown around the world still very much resemble the original cultivars found in East Africa and the Arabian Peninsula. Many cultivars have been characterised with very low nucleic polymorphism (Scalabrin et al., 2020); thus, a bottleneck in genetic diversity exists in many of the commercial Arabica cultivars. Despite this, coffee is known to have a high degree of phenotypic plasticity to environmental variations (Kufa & Burkhardt, 2011a, b; Tounekti et al., 2018; DaMatta et al., 2019), although cultivar performances can vary greatly depending on the given cultivation site (Matos et al., 2009). Moreover, current coffee breeding programs utilising wild and cultivated crosses are, in some cases, demonstrating hybrid superiority (colloquially described as “hybrid vigour” and also referred to as “heterosis”) in new Arabica cultivars when evaluated across different environments (Bertrand et al., 2019, 2021; Georget et al., 2019; Marie et al., 2020; Pappo et al., 2021).

C. arabica can be cultivated under a number of light management systems (Fig. 1). Intensive production usually involves full-sun (FS) systems, while fast-growing shade species such as banana (*Musa* spp.) are often used to establish new coffee agroforestry systems (AFS). The inclusion of hardwood shade tree species is also found in mature coffee AFS (Fig. 1). For many smallholder coffee farmers, AFS offer benefits that go beyond direct impact on coffee production (Beer et al., 1997; Vaast et al., 2005; Méndez et al., 2010; Jezeer et al., 2019). For instance, AFS have shown to buffer climatic fluctuations, enhance ecosystem services, and provide alternate income sources (by use of shade tree products) for coffee farmers (Vaast et al., 2005; Camargo, 2010; Dubberstein et al., 2018; Duangsodsri et al., 2019; de Sousa et al., 2019; Gerlicz et al., 2019; as reviewed in Koutouleas et al., 2022a). Additionally, coffee AFS often offer lower management costs per hectare compared to FS systems, with lower inputs in the forms of labour and/or expensive agrochemicals (Jezeer et al., 2017). However, in some cases, coffee pest and disease pressures under AFS may be higher compared to FS systems. This is due to the modified microclimate (e.g., higher relative humidity) under the shade canopy, which may favour specific disease cycle or development stages of the pathogen or pest (Righi et al., 2013). This is especially the case for foliage diseases (i.e., coffee leaf rust, coffee berry disease, and American leaf spot) (as reviewed by Koutouleas

et al., 2022b). Thus, coffee AFS may sometimes be coupled with higher on-farm usage of inputs such as fungicides.

Natural shaded coffee systems (such as AFS) have been reported to reduce air temperature fluctuations, lower irradiance incidence, and increase air relative humidity near the coffee plants, whilst decreasing wind and frost damages (Staver et al., 2001; Vaast et al., 2005; DaMatta & Ramalho, 2006; Morais et al., 2006; van Kanten & Vaast, 2006; Oliosi et al., 2016; Coltri et al., 2019; Sarmiento-Soler et al., 2019; Rigal et al., 2020). Therefore, AFS can be a beneficial approach for coffee farmers using rain-fed systems in regions prone to environmental stresses, such as drought, high irradiation and supra-optimal temperatures. However, these benefits are conditional to the optimal selection of shade tree species, exhibiting low transpiration rates and complimentary root systems, thus minimising competition for in-field water and nutrient resources (Schaller et al., 2003; van Kanten & Vaast, 2006). Other ecosystem services include positive effects on soil fertility, total organic matter, recycling of nutrients, decreased soil evaporation, reduced erosion, and higher overall carbon sequestration (Rigal et al., 2020; Villarreyna et al., 2020). Moreover, the environment within and surrounding coffee AFS tends to possess an enhanced biological richness in terms of tree species, epiphytes, mammals, birds, reptiles, amphibians, and arthropods (Perfecto et al., 1996, 2005; Moguel & Toledo, 1999). This increased biodiversity can in turn benefit coffee production, for example, by lowering dominance of pests through both direct and indirect interactions (Kellermann et al., 2008; Perfecto et al., 2014) and improving fruit set through increased presence of pollinators (Moreaux et al., 2022). Despite these positive aspects, the recommendation of AFS in coffee production is still of controversial nature due to a large body of data showing significant single-year yield reductions under shaded coffee environments compared to FS (Clemens & Zablah, 1993; Beer et al., 1997; Carelli et al., 2001; DaMatta, 2004; Campanha et al., 2004; Haggard et al., 2011). Furthermore, recent studies have demonstrated that self-shading under highly dense planting management can also negatively impact coffee yield (Cheng et al., 2020; Rakocovic et al., 2021). Coffee yield differences between FS and AFS can be skewed by the strong biannual variation and overbearing branch die-back reported predominantly under FS systems (Vaast et al., 2005). In this context, cumulative coffee yield over a 5- or 6-year period may in fact be similar across the two production systems. Yet, few studies to date have closely examined the effect of different shade levels on coffee yield in a single trial over multiple production years.

An inverted U-shaped (“parabolic”) nature of shade and coffee yields has been uncovered (Baggio et al. 1997; Soto-Pinto et al. 2000), suggesting the existence of a potential optimal shade range at which yields are improved compared to FS production. Contrastingly, others have found a general negative relationship between high-shade environments and



Fig. 1 *C. arabica* cultivation approaches. Top row: full sun coffee cultivation (no shade trees grown directly over coffee plants) in São Paulo, Brazil (left); Finca Tolosa, Matagalpa, Nicaragua (centre); and Fazenda Santa Monica, Minas Gerais, Brazil (right). Middle row: newly established coffee agroforestry systems with *Macadamia* spp. and *Musa* spp. (Banana) in Son La province, Vietnam (left); *Musa* spp. (banana) in Armenia, Colombia (centre); and *Cedrela odorata* (Spanish cedar), Finca La Cumplida, Matagalpa, Nicaragua (right). Bottom row: mature coffee

agroforestry system with old hardwood species including *Swietenia macrophylla* (Honduran mahogany), *Juglans macrocarpa* (Walnut) and *Inga* spp. in Finca La Cumplida, Matagalpa, Nicaragua (left); *Samanea saman* (Acacia) and *Pentaclethra macroloba* (Pracaxi) in Cielo Ciudad Colon, Costa Rica (centre); and *Acrocarpus fraxinifolius* (Pink cedar) at the INIFAP station in Teocelo, Veracruz state, Mexico (right). Photos © B. Bertrand, M. Bordeaux, H. Etienne, J.C. Ramalho, and T. Sarzynski.

coffee yields (Clemens & Zablah, 1993; Campanha et al., 2004; DaMatta, 2004).

Comprehensive reviews have been conducted on the benefits and disadvantages of coffee production under shaded and unshaded conditions (Beer, 1987; DaMatta, 2004). These reviews highlighted the effects of climatic factors (i.e., radiant energy, temperature, wind, and relative humidity) and shade management on gas-exchange, carbohydrate allocation, and branch dieback, as well as desirable characteristics for perennial crop shade trees (in relation to competition for light, water and nutrients between coffee, and their intercropped shade trees). In addition to these works, other more recent reviews and modelling efforts have examined shade effects on coffee in the AFS context (Van Oijen et al., 2010a, b; Jha et al., 2014; Hirons et al., 2018; Rahn et al., 2018; Assefa & Gobena, 2020; Mussetta & Hurlbert, 2020; Piato et al., 2020). The most recent review by Piato et al. (2020) examined the effects of shade trees on *C. canephora* coffee growth, yield, and quality and was able to pinpoint specific clones showing an increased productivity (from 17 to 280%) under moderate shade levels in the range of 41–65%. However, no available literature review has examined the cultivar-specific response of *C. arabica* to shade in terms of yield. Evaluation of crop

performance at the cultivar level provides plant breeders with crucial guidance for planning of future breeding programs, especially when facing challenging cultivation environments. In this context, the main goal of this study is to explore the relationship between different shade levels and yield of coffee cultivars. To achieve this goal the “Ristretto” database was developed.

2 Methods

We used a systematic review accompanied by a meta-analysis to examine coffee yield data under shaded systems (Suppl. 1). Primary literature was gathered and selected by use of the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) (Moher et al., 2009) (Fig. 2 and Suppl. 1). To ease the systematic review process at the cultivar level, a list of popular Arabica cultivar names and families was generated and used in the data search (Suppl. 2). An inclusion criterion (Suppl. 1) was used to determine which primary literature source could be used in the subsequent meta-analysis. All coffee yield data and experimental site information were collected and standardised in the “Ristretto” data pool (Suppl.

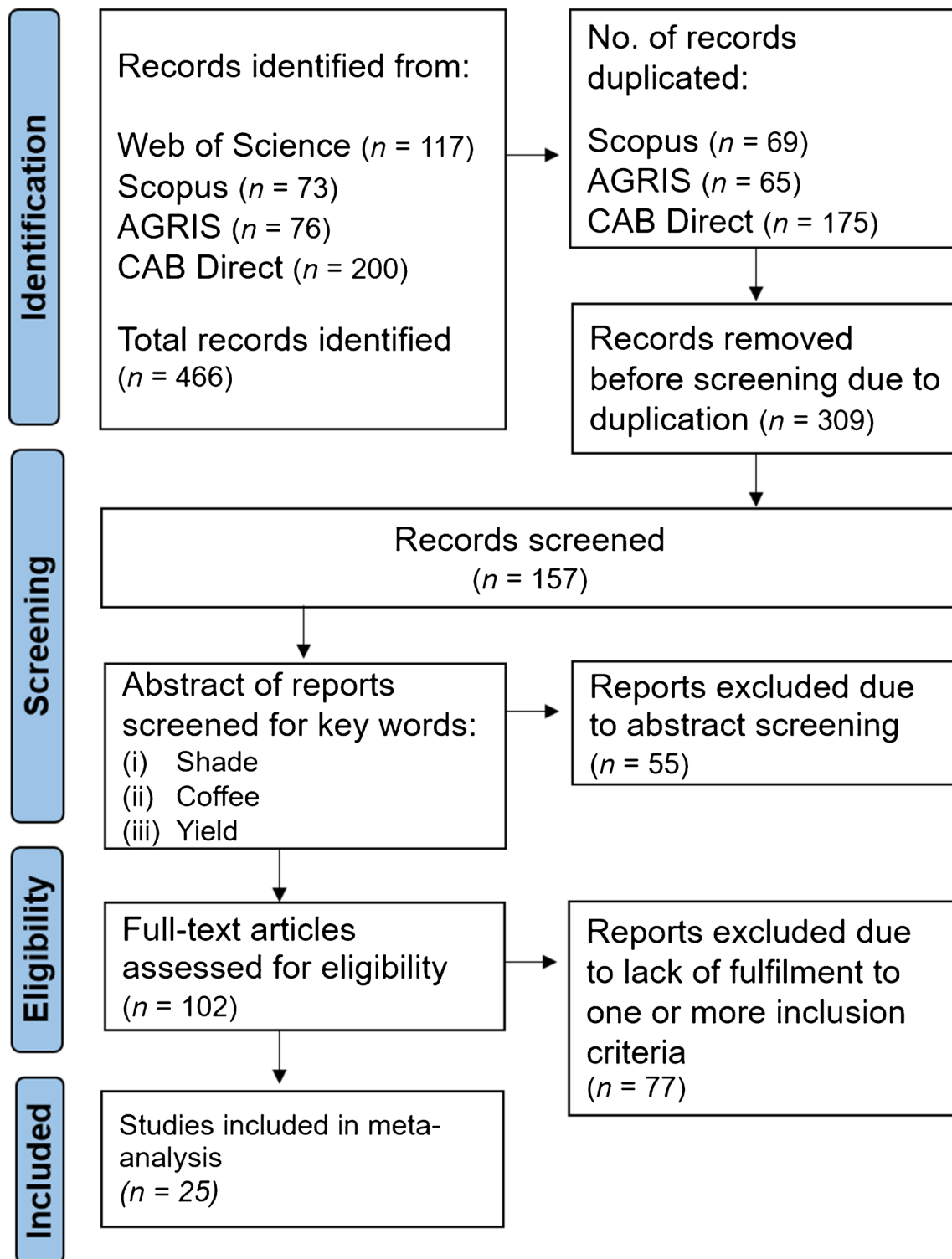


Fig. 2 PRISMA diagram of coffee yield data retrieval process for meta-analysis.

3). Shade cover was quantified as either a percentage of shading in the system, or as the number of shade trees per hectare. The meta-analysis was performed in order to test the hypothesis that different cultivars will exhibit different responses to shade in terms of coffee yield (Suppl. 1). For the meta-

analysis, we used a linear mixed effect model. Yield was the dependent variable (transformed by the square root), whilst altitude (m.a.s.l.) and annual average rainfall (mm) were co-variates. The interaction between the cultivar and the shade percentage and/or number of shade trees per hectare was

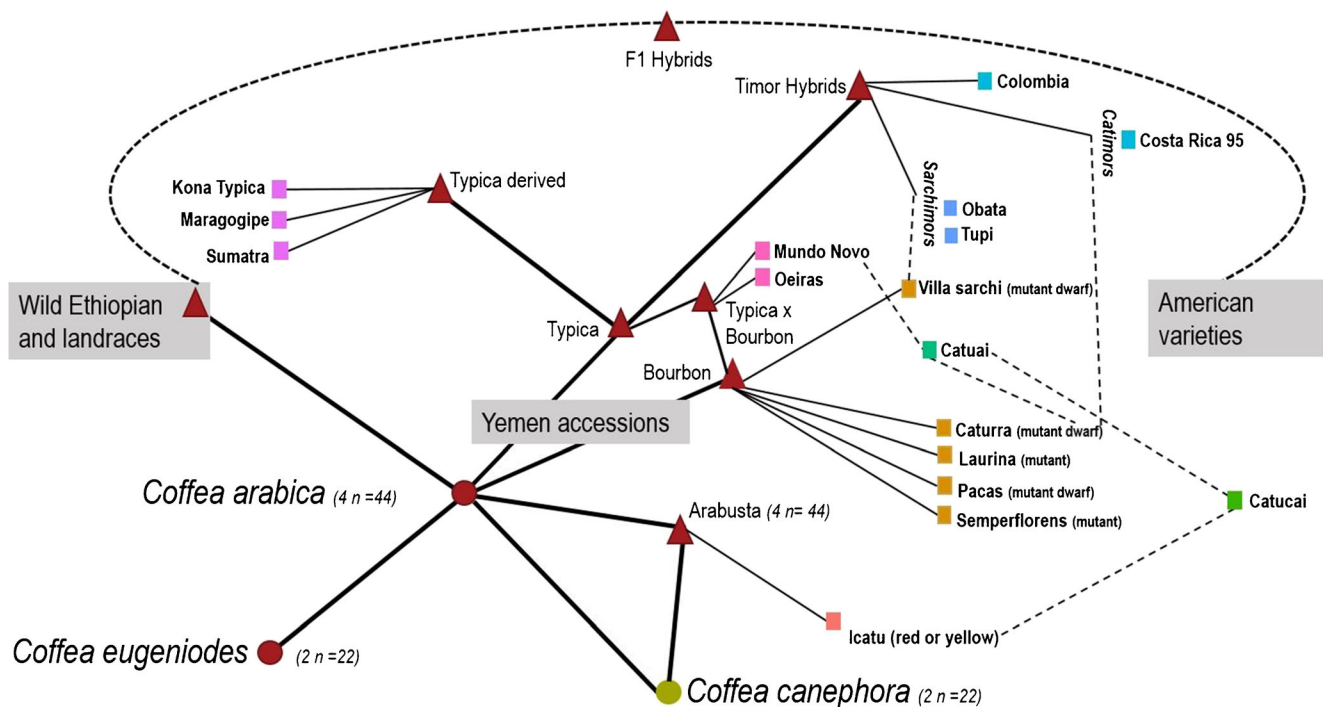


Fig. 3 Phylogenetic tree of genetic diversity and origin of common coffee cultivars examined in the meta-analysis. The cultivars (squares) present in this meta-analysis are shown with respect to their original genetic families (triangles) and species (circles). The bold lines show connections between

species and/or families within the *Coffea* genus. The dashed lines show genetic crosses between cultivars. The colours represent the cultivar families or hybrid-crosses.

investigated via a quadratic equation (Suppl. 1). This was based on the assumption that the possible shade optimum could be captured by an inverted U-shape relation. The random effects inherent to each independent primary dataset were represented by the site variable of each study. The estimated marginal means (Lenth, 2020) from the selected models were used with the main model to make predictions of coffee yield within the data range.

3 Results and discussion

3.1 Standardised data pool — “Ristretto”

Our final database search (conducted on 13 January 2021) gave rise to 117 records found by Web of Science (WoS), 73 records found by Scopus (of which only four were unique compared to the WoS results), 76 records from AGRIS (11 were unique compared to the other search engines) and 200 from CAB Direct (25 were unique compared to the other searches) (Fig. 2). Altogether, 157 publications were considered relevant to our data pool and meta-analysis based on the screening of the title, selecting 102 articles based on abstract content. Only 25 of these primary literature sources (Carvalho et al. 1961; Hernández Guerra, 1995; Baggio et al. 1997; Estivariz Coca, 1997; Gobbi, 2000; Soto-Pinto et al. 2000; Schaller et al. 2003; Farfan & Mestre, 2004; Pilati, 2005;

Ricci et al. 2006, 2011; Vaast et al. 2006; Merlo Caballero, 2007; Lin, 2009; Jaramillo-Botero et al. 2010; Siles et al. 2010; Haggard et al. 2011; Steiman et al. 2011; Somporn et al. 2012; Partelli et al. 2014; Virginio Filho et al. 2015; Araújo et al. 2016; Javier Lopez-Garcia et al. 2016; Oliosi et al. 2016; Venancio et al. 2019) met the criteria for inclusion into the data pool (Suppl. 1). Coffee yield, environmental and shade data from these literature sources, was then collated and standardised in our data pool and subsequently used in the meta-analysis (Suppl. 3). We called our data pool “Ristretto” (repository of in-field shade data to re-analyse trends and tendencies in coffee yield output), likening it to the “short shot” of espresso due to the condensed nature of the data relating to coffee under shaded systems. The “Ristretto” consists of 255 collated data relating to coffee yield under different levels of shade from 25 primary literature sources including 19 different coffee cultivars (Fig. 3, Suppl. 3). Seventeen different variables were standardised and collated in the “Ristretto”, allowing data from all 25 trials to be analysed as a single dataset (a full explanation of variables is provided in the guide of Suppl. 3). Our data pool included unique descriptions about the type of shade used in each trial (e.g., artificial shade nets, polyculture, agroforestry, or the specific shade tree species present). The Yemen accessions of Arabica were largely represented in “Ristretto” (229 data points), with the majority of cultivars derived from either Typica, Bourbon, or varieties introgressed from Timor hybrids (Fig. 3). Unfortunately, no

Table 1 Results of analysis of variance of yield as influenced by the shade percentage and/or number of shade trees per hectare, cultivar type, and covariates. Tests were conducted as type III tests with Kenward–Roger’s method for calculations of degrees of freedom. Note: “Site” refers to the study location and represents inherent random effects

associated with the different study methods and management inputs. *“(Cultivar: (shade percentage²))” and “cultivar: (shade trees per hectare²)” refer to the quadratic effect of the shade (either percentage or number of shade trees) together with an interaction of the cultivar type. Significance codes: “***” ≤ 0.001 . “**” ≤ 0.01 . “*” ≤ 0.05 .

	Sum of squares	Mean of squares	No. degrees of freedom	Denominator degrees of freedom	<i>F</i> value	<i>p</i> Value for <i>F</i> statistic
Fixed effects						
Data relating to shade expressed as a percentage:						
Altitude	0.0054	0.0054	1	9.06	0.46	0.5127
Rainfall	0.0025	0.0025	1	19.85	0.21	0.6498
Cultivar: shade percentage	0.2092	0.0349	6	104.73	3.00	0.0095 ***
Cultivar: (shade percentage ²)*	0.2620	0.0437	6	104.06	3.76	0.0019 ***
Data relating to shade expressed as number of trees per hectare:						
Altitude	0.4268	0.4268	1	18.37	18.46	0.0004 ***
Rainfall	0.0008	0.0008	1	15.00	0.03	0.8573
Cultivar: shade trees per hectare	0.2611	0.1305	2	56.67	5.64	0.0058 **
Cultivar: (shade trees per hectare ²)*	0.6203	0.3101	2	53.08	13.40	<0.0001 ***
Groups		Variance	Standard deviation	Proportion of variation due to site effects		
Random effects						
Data relating to shade expressed as a percentage:						
Site		0.0618	0.2486	84%		
Residual		0.0116	0.1077	16%		
Data relating to shade expressed as number of trees per hectare:						
Site		0.0030	0.0550	12%		
Residual		0.0231	0.1520	88%		

wild Ethiopian or landrace cultivars were found via our data retrieval and are thus absent from the data pool. The “Ristretto” also contains 26 yield data points relating to *C. canephora* cultivars, which were omitted from the meta-analysis but remain in the database for future works. The single data point relating to the *C. arabica* cv. Catimor (in the “number of shade trees per hectare” data subset) was also omitted from the meta-analysis, as it did not contribute to the investigation of shade effects. “Ristretto” is a one of a kind open-source tool, which is available to download from the ERDA repository (<https://erda.ku.dk/archives/f2f20f87a73abaeb7dbb31bd78086c58/published-archive.html>) including instructions for additional data consolidation to aid future analyses of coffee yield data under shaded systems (Suppl. 3).

3.2 Shade effects on coffee yield

The controversy that surrounds the use of AFS for coffee production hangs largely on a considerable number of reports of single-year yield reductions under shaded coffee systems (Clemens & Zablah, 1993; Beer et al., 1997; Carelli et al.,

2001; DaMatta, 2004; Campanha et al., 2004; Hagggar et al., 2011). However, one of the major limitations of these studies is that often only a limited shade range was being used to compare shaded coffee yields to FS conditions, making it difficult to detect the differences across different shade levels from one study alone. Here, we performed a step-forward by assembling data points from a large number of shaded coffee studies over several years and across different sites into the “Ristretto” data pool (Suppl. 3). Through such approach, we can begin to evaluate whether there is a difference between shade levels, as compared to FS. Additionally, by exploiting these historical data, we were able to test whether responses to shade can be cultivar-specific and/or dependent on other environmental factors. Yield data from studies using shade percentage ($n=148$) to express the shade level vs. number of shade trees per hectare ($n=80$) were separated and individually analysed with the main model. The meta-analysis was conducted in this manner since, to the best of the authors’ knowledge, there was no previous reports regarding best practice of standardisation for such data sets (relating to shade levels).

Surprisingly only a small number of studies found in our systematic literature search clearly stated the name of the

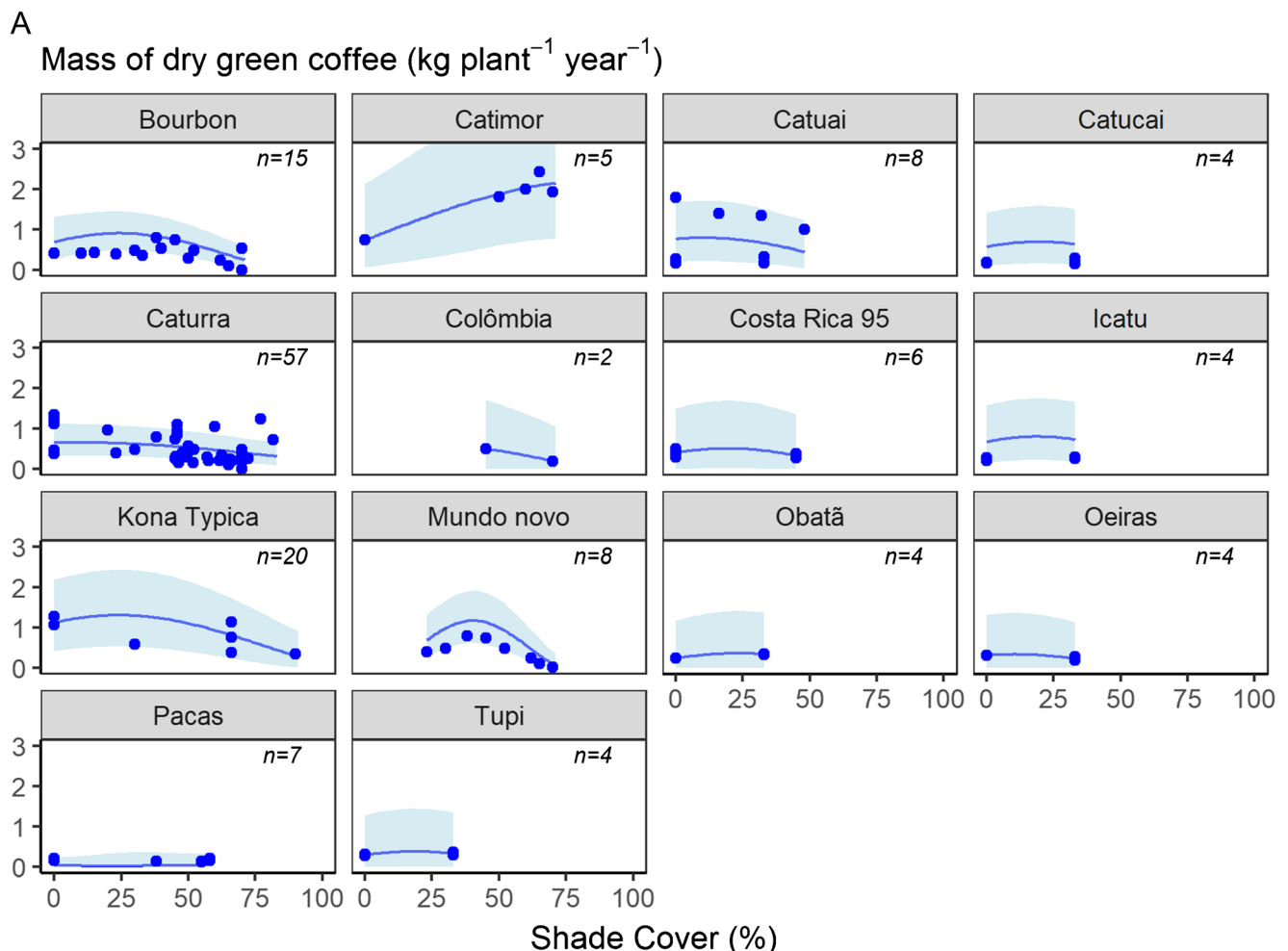


Fig. 4 Meta-analysis of average coffee yields with **a** shade expressed as a percentage of irradiance reduction compared to full sun (0% of shade cover) for each cultivar, and **b** shade expressed as the number of shade trees per hectare to FS for each cultivar. Lines are shown for the cultivars fitted with the model. The shaded areas represent the 95% confidence interval for the fitted model. Coffee yield predictions are based on the fixed effects in the model. Due to variations modelled by the random

effect of site, the predictions do not necessarily follow the observed values directly (as is the case for Catucaí, Icatu, and Mundo Novo). Note: data shown as Catimor are not specific to a commercial cultivar name (studied by Somporn et al., 2012). Therefore, these data were treated separately from other Catimors (i.e., Colombia and Costa Rica 95), n = number of yield data per cultivar.

coffee cultivar used. This led to a small dataset assembled for each individual coffee cultivar (as seen by the n values in Fig. 4 A and B). Despite this challenge, our linear mixed effects modelling showed a significant interaction between shade and cultivar type on coffee yield (Table 1). This interaction was highly significant in both the shade percentage dataset and the number of shade trees per hectare datasets (both cases with p value ≤ 0.001) (Table 1). These findings indicated that coffee cultivars display genotypic heterogeneity in their response to shade given that positive, neutral, and negative trends were found, thus confirmed our hypothesis (Suppl. 1). A number of Arabica cultivars responded either positively or neutrally to shaded environments (e.g., artificial, polyculture, or AFS) such as Catucaí, Catimors (including Costa Rica 95), Sarchimors (like Tupi and Obatã), Caturra, Oeiras, Pacas, and Icatu. In contrast, Kona Typica showed decreasing yields

at all shade levels (Fig. 4A). The cultivars Bourbon and Mundo Novo (Typica \times Bourbon) exhibited a tendency for an inverted U-shaped relationship between yield and shade (as a percentage), with a potential optimal range between 25 and 45% of shade cover (Fig. 4A).

Overall coffee yields tended to be highest in FS or in “low to moderate” shaded environments (approximately 10–39% of shade cover), while “high” (40–70%) and “very high” shade (greater than 70%) led to the lowest yields for most cultivars (Fig. 4A). These findings are supported by the previous work of Soto-Pinto et al. (2000), which demonstrated the same optimal shade cover between 23 and 38%, and that coffee yield could be maintained with a shade cover up to 48% declining after that (although these results are only valid for the specific site where the study carried out). A cautious conclusion of our meta-analysis results is that low to moderate

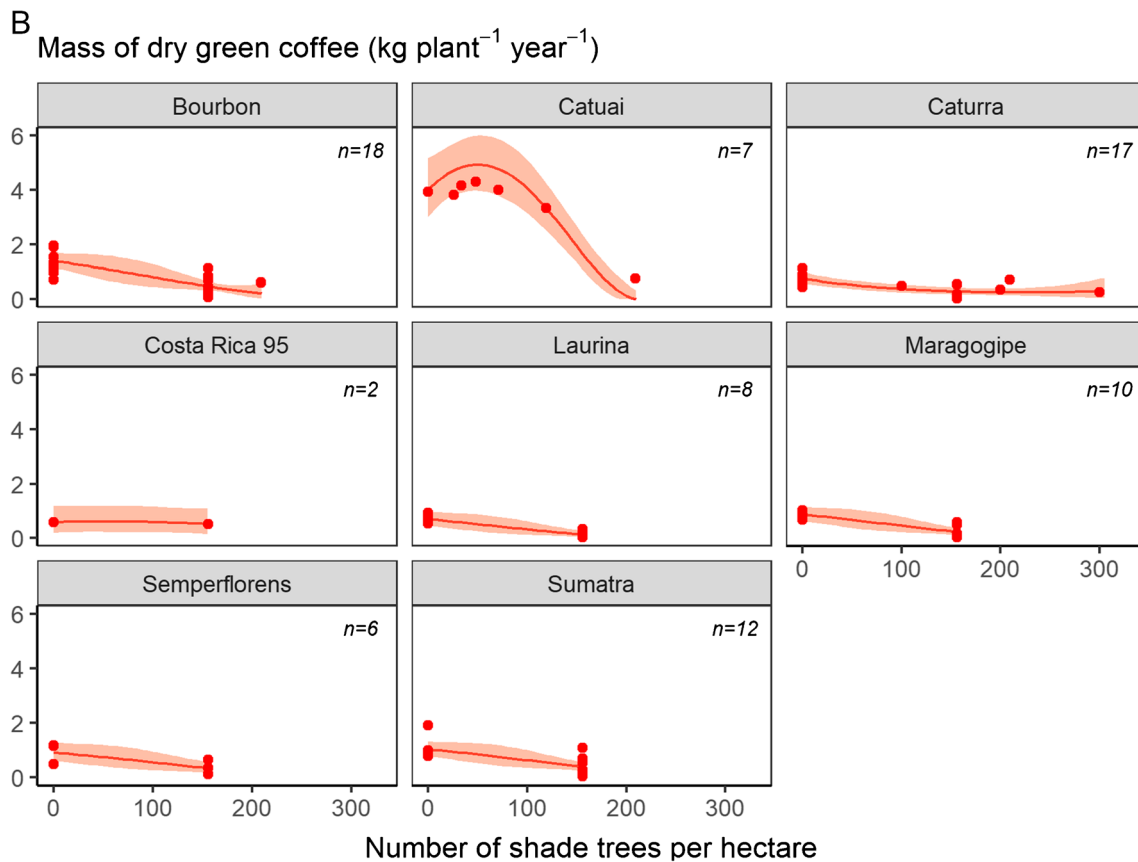


Fig. 4 (continued)

shade cover (approximately 10–40%) in many cases has little negative impact on yields, and in some cases, a beneficial effect can occur (as is the case for Arabica cultivars Bourbon and Mundo Novo). However, this finding requires further validation by assessing more cultivars within this shade range and taking into account specific interactions with other environmental variables in specific areas (i.e., cloud cover, maximal irradiance, accumulated hours of high irradiance) as well as the interactions between cultivars and popular shade trees species (due to the root traits and exudates).

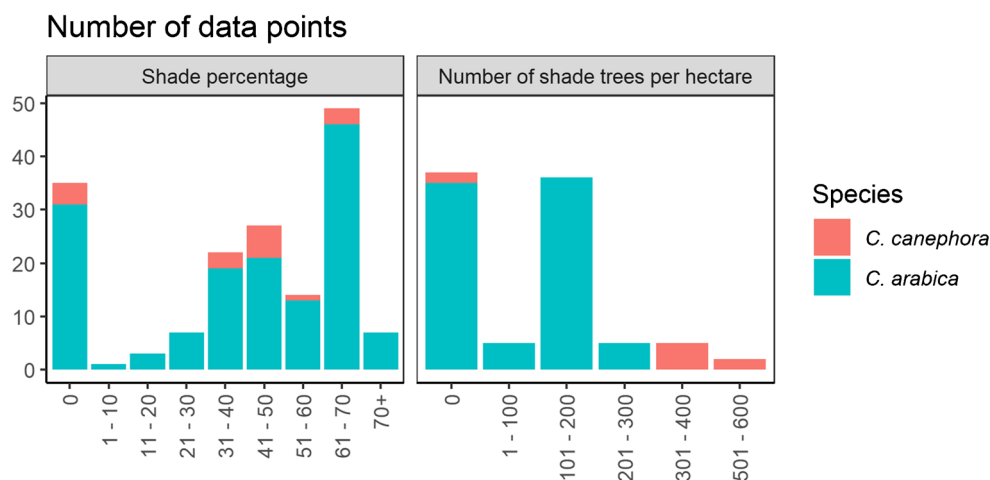
Analysis of coffee yield data relating to the number of shade trees per hectare showed an overall negative relationship between shade trees and yield, with exception of the cv. Catuaí, which showed an inverted U-shape trend (Fig. 4B). This trend may be an artefact of a relatively small dataset ($n=80$) or may pinpoint the relevance of other factors pertaining to the shade trees and management techniques which were not included into the model. These may include coffee planting densities (potential for self-shading), the type of shade tree species used and their canopy density, pruning frequency and timing and/or root architecture, among others. The on-farm shade dynamics that come with the use of natural shade trees have been examined by others in the context of coffee AFS (Beer, 1987; Beer et al., 1997; Wolf et al., 2017;

Rahn et al., 2018), however, pose a limitation in the context of this present meta-analysis.

Neither altitude nor average annual rainfall was found to have significant effects on coffee yield when shade was expressed as a shade percentage (Table 1). A possible explanation for this could be that the potential influence of these environmental factors on coffee yields have been mediated through the choice of cultivar. Yield data from studies expressing shade as number of trees per hectare did not show a significant effect of rainfall. However, altitude ($p = 0.0004$) had a direct effect on the yield, which could not be attributed to cultivar. The highest coffee yields in this data subset were observed at low altitudes (i.e., 250 m a.s.l.) (Suppl. 3). However, the altitude variable is closely linked to other factors relating to cloud dynamics such as air vapour pressure deficit; temperature decreases or inversions; and/or increases in short-wave solar radiation or reductions in the number of hours with high irradiance (Gale, 2004).

The inherent random effects across trials and years (represented by the site) were found to contribute 84% of the total variation in the shade percentage dataset and 12% in the number of trees per hectare dataset (Table 1). The model predictions (shown as lines in Fig. 4 A and B) represented the overall yield response to shade within cultivars, after corrections for

Fig. 5 Dispersion of yield data points relating to different levels of shade cover in the “Ristretto” data pool.



site differences (within the used dataset). The substantial variation between sites was visible for Catucaí and Icatú (Fig. 4A), as the model predictions were above the actual observations for these cultivars. This phenomenon was also visible for cv. Mundo Novo (Fig. 4A).

The type of shade used in the studies assembled in both the “Ristretto” and our meta-analysis could have also contributed to the random effects in our meta-analysis results. Shade covers varied on a spectrum from artificial shade nets, Kaolin foliar spray, and polyculture to mature AFS. The type of shade implemented may have influenced other above- and below ground dynamics (incl. light quantity and quality, humidity, and shelter effect), which may in turn have had an effect on the coffee yields obtained, thus poses as another limitation to our meta-analysis.

Of the studies expressing shade as a percentage, a large proportion of data points related to very high levels of shade cover, i.e., 61–70% ($n=49$) (Fig. 5). An explanation for this is that researchers hoped to mimic a mature AFS environment, which usually implies denser shade cover. However, these studies using high shade levels (as an experimental treatment) may have greatly contributed for the general negative view of shade in relation to coffee yield. Consequently, the low to moderate range of shade (21–30% shade cover) was not as prominently represented in the literature and subsequently in low numbers in our data pool (Fig. 5). Similarly, a large number of coffee yield data came from trials using either 0 (FS) or 101–200 shade trees per hectare (Fig. 5). This attributes some limitation in our understanding of this shade level effects on coffee yield, thus highlighting the need for future studies conducted under moderate to low shade treatments.

4 Conclusions and perspectives

Here, we showcased more than 200 cultivar-specific, coffee yield data relating to 25 independent in-field trials assembled

and standardised in our “Ristretto” data pool (Suppl. 3). This novel, open data source (retrieved here: <https://erda.ku.dk/archives/f2f20f87a73abaeb7dbb31bd78086c58/published-archive.html>) offers potential for additional entry of data and the re-examination of coffee cultivar yield responses across a wide range of shade conditions. Our data pool included unique findings about the type of shade used in each study (e.g., artificial shade nets, polyculture, agroforestry, or a specific shade tree species), which can also help guide future study designs in this context. This is a one of a kind data source for coffee, but the underlying concept and methodology can also be applied to other agricultural crop research interested in how GxE or AFS interactions can impact yield.

Our meta-analysis with the “Ristretto” data pool confirmed that coffee reacts differently to shade at the cultivar level. A number of Arabica cultivars reacted neutrally up to a certain level of shade (Catucaí, CR95, Caturra, Obatã, Oeiras, Pacas, Icatú, and Tupi). Kona Typica showed decreasing yield at all shade levels, while cv. Catimor exhibited a general positive trend to increasing shade. Interestingly the cultivars Bourbon and Mundo Novo demonstrated an inverted U-shape relationship in terms of shade vs. yield with their optimal range being between 35 and 50% shade cover. Additional meta-analyses would be of benefit, including more data points and cultivars, in order to vigorously test our preliminary findings. However, our findings highlighted that choice of Arabica cultivar remains an important decision to make when considering AFS as a potential production system to mitigate negative climate changes.

So how much shade is too much for coffee production? Coffee yield tended to be highest in FS and/or under low to moderate shade environments (10–39% shade). An overall decrease in the standardised Arabica coffee yields was observed above 40% shade cover. We elucidate that the commonly held negative perception of shade on coffee yield may be due to the historical testing of coffee under dense shade conditions exceeding greater than 40%. However, shade cover

up to approximately 39% may have a neutral effect or positive impact on yield compared to FS coffee cultivation (depending on the cultivar of choice and other environmental factors associated with each specific site).

Despite the low genetic diversity amongst many of the Arabica cultivars, our meta-analysis results are among the first to highlight that shade effects are cultivar specific. Given this finding, it is of great interest to further study shade effects (including the choice of tree shade species) at the coffee cultivar \times environment level instead of diluting the effects at the species level. To further elucidate this phenomenon, future studies examining shade and coffee are urged to include details about the cultivar used and environmental factors, such as agricultural inputs (e.g., fertilisation regime), extent of self-shading (based on coffee planting density), pruning of shade trees, and canopy density, as well as a better environmental characterisation (e.g., temperature, irradiance, number of daytime hours). Likewise, a more descriptive measurement of the shade level is of paramount importance for future AFS coffee studies.

Lastly, in order to expand on the research questions pertaining to shade and coffee, we encourage researchers to make use of (and add to) the “Ristretto” standardised data pool via the active DOI link and instructions provided. We hope this will enable extensive analyses of future coffee yield data under shaded systems and help define shade ranges, which may optimise both yields and ecosystem benefits for coffee farmers and the local environment.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-022-00788-2>.

Authors' contributions Conceptualization was conducted by AK, AR, BB, and HE. Data curation was conducted by AK, MB, and TS. Formal analysis and methodology of the meta-analysis data was conducted by AK, AR, and BM. Writing (original draft preparation) was conducted by AK, ASB, CC, JCR, HE, NTG, PM, PV, SL, and TS. All authors contributed to the writing (review and editing) and approved the final version of the manuscript. We also acknowledge the detailed and constructive feedback of the anonymous peer reviewers, who help us shape this work into a more succinct piece than its original form.

Funding This work was funded by and carried out in the context of the European Union's Horizon 2020 (H2020) research and innovation program by the BREEDCAFS (Breeding Coffee for Agroforestry Systems, www.breedcafs.eu) project (2017–2021) under the grant agreement No. 727934. Portuguese national funding from the Fundação para a Ciência e a Tecnologia (FCT), through the research units UIDB/00239/2020 (CEF) and UIDP/04035/2020 (GeoBioTec) are also acknowledged. Thuan Sarzynski benefits from a thesis scholarship jointly financed by the CIRAD and ECOM trading.

Data availability The datasets generated and/or analysed during the current study will be made publicly available in the ERDA repository, upon acceptance for publication. <https://erda.ku.dk/archives/f2f20f87a73abaeb7dbb31bd78086c58/published-archive.html>

Code availability The code generated during the current study will be made publicly available in the ERDA repository upon acceptance for publication.

<https://erda.ku.dk/archives/f2f20f87a73abaeb7dbb31bd78086c58/published-archive.html>

Additional documents: meta-analysis code for R (.Rmd file), guide to meta-analysis code for R (.html file).

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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