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META-ANALYSIS

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

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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 transpirations 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; Haggar 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; Rakocevic 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.

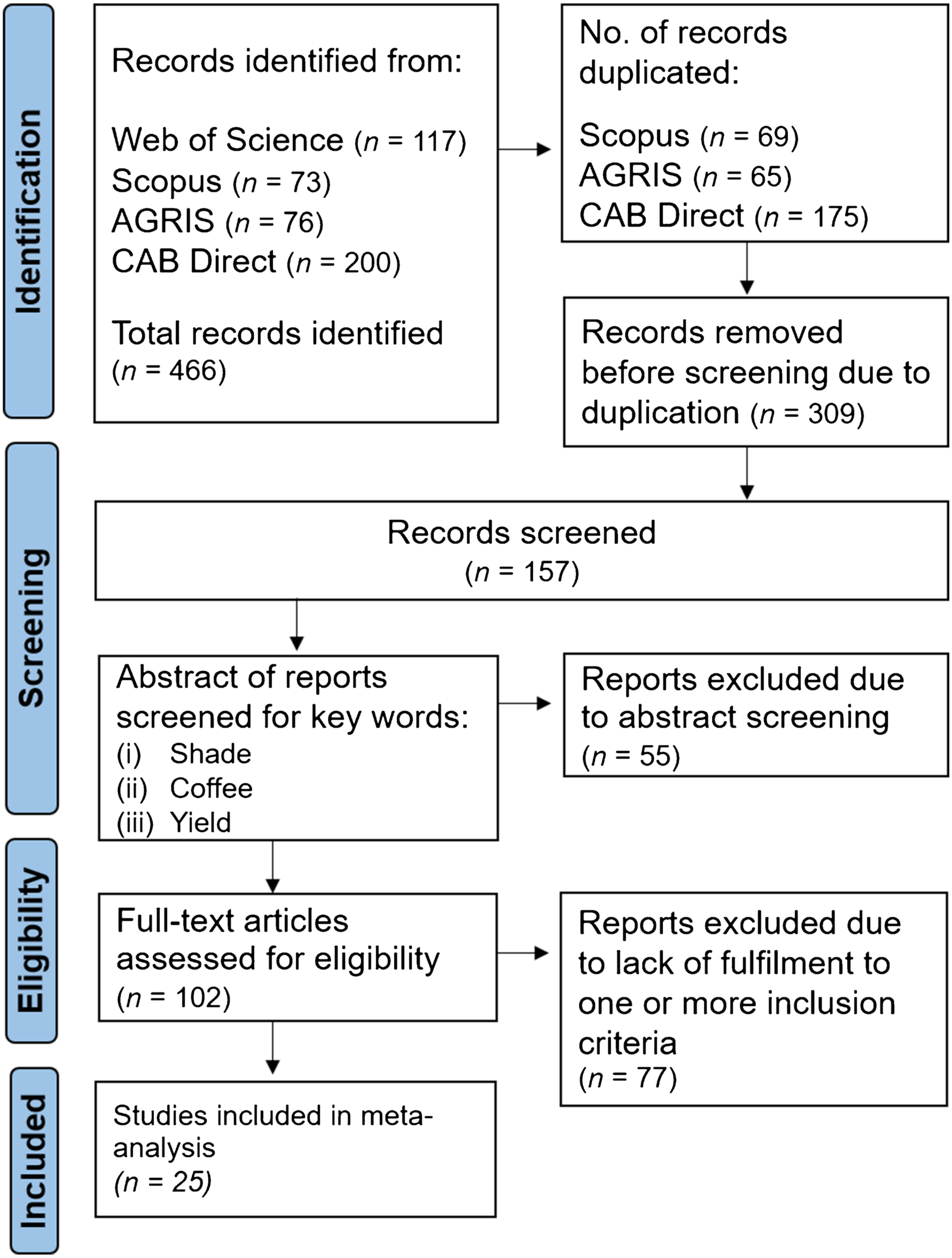


Fig. 2 PRISMA diagram of coffee yield data retrieval process for meta-analysis.

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

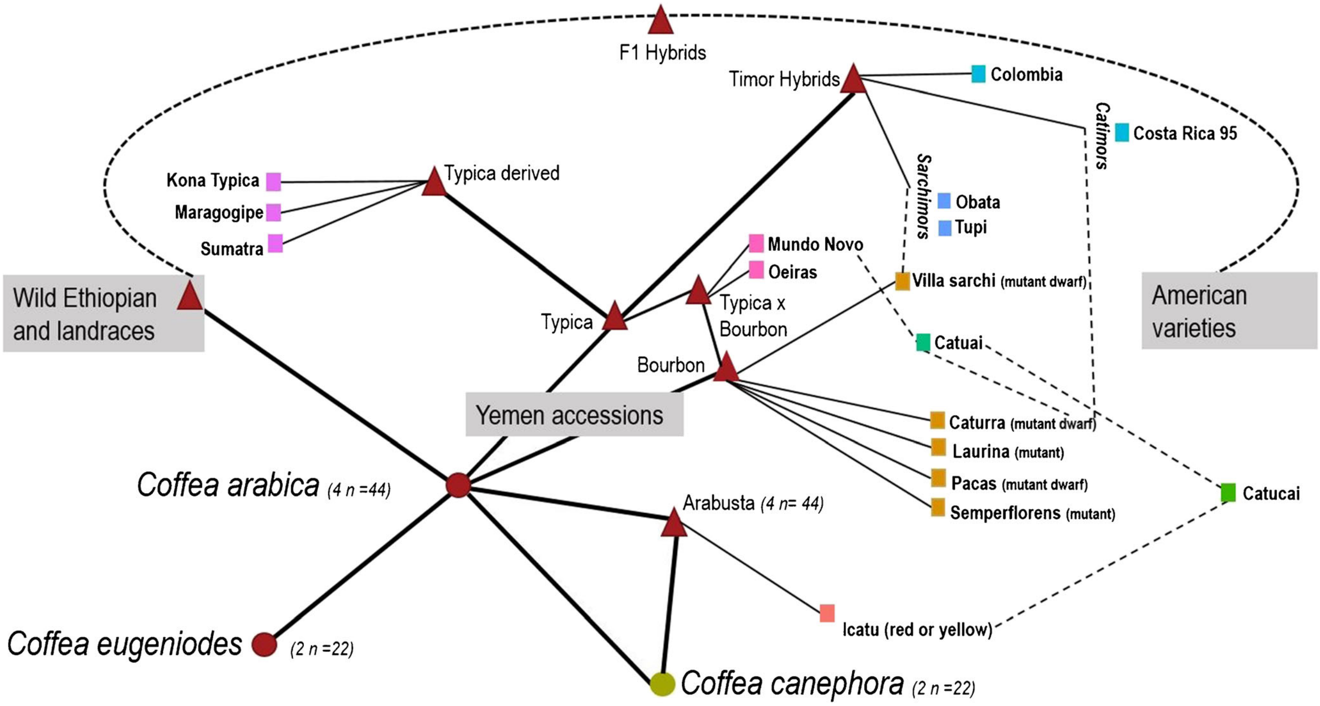


Fig. 3 Phylogenetic tree of genetic diversity and origin of common coffee cultivars examined in the meta-analysis. The cultivars (squares) present in this meta-analysis are shown with respect to their original genetic families (triangles) and species (circles). The bold lines show connections between 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; Haggar 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 percentage^2)" and "cultivar: (shade trees per hectare^2)" 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: '***'$\leq$ 0.001. '**'$\leq$ 0.01. '*'$\leq$ 0.05.

	Sum of squares	Mean of squares	No. degrees of freedom	Denominator degrees of freedom	*F* value	*p* Value for *F* 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; Haggar 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

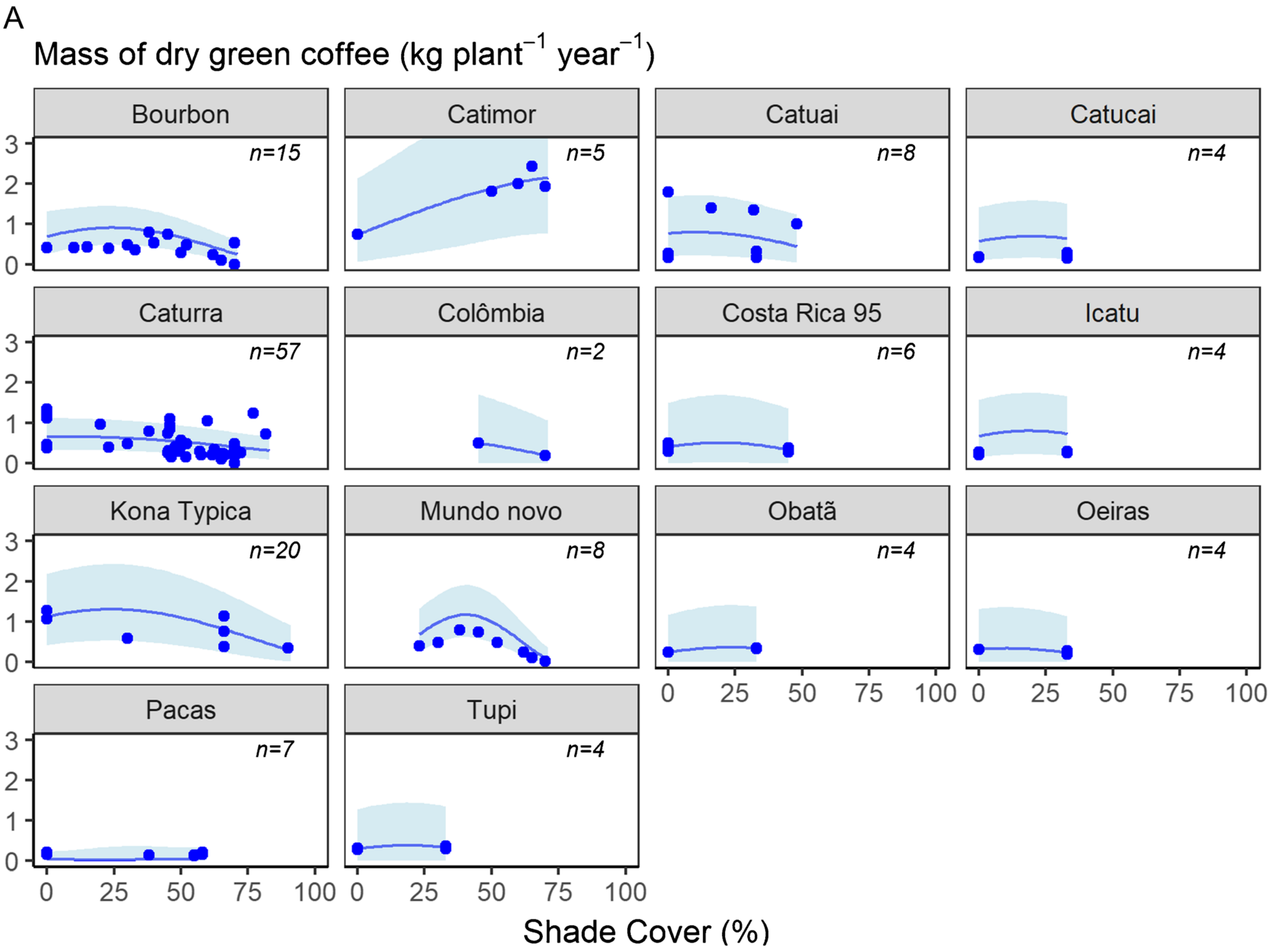


Fig. 4 Meta-analysis of average coffee yields with **a** shade expressed as a percentage of irradiance reduction compared to full sun (0% of shade cover) for each cultivar, and **b** shade expressed as the number of shade trees per hectare to FS for each cultivar. Lines are shown for the cultivars fitted 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, Icatú, 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 Icatú. In contrast, Kona Typica showed decreasing yields at all shade levels (Fig. 4A). The cultivars Bourbon and Mundo Novo (Typica × 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

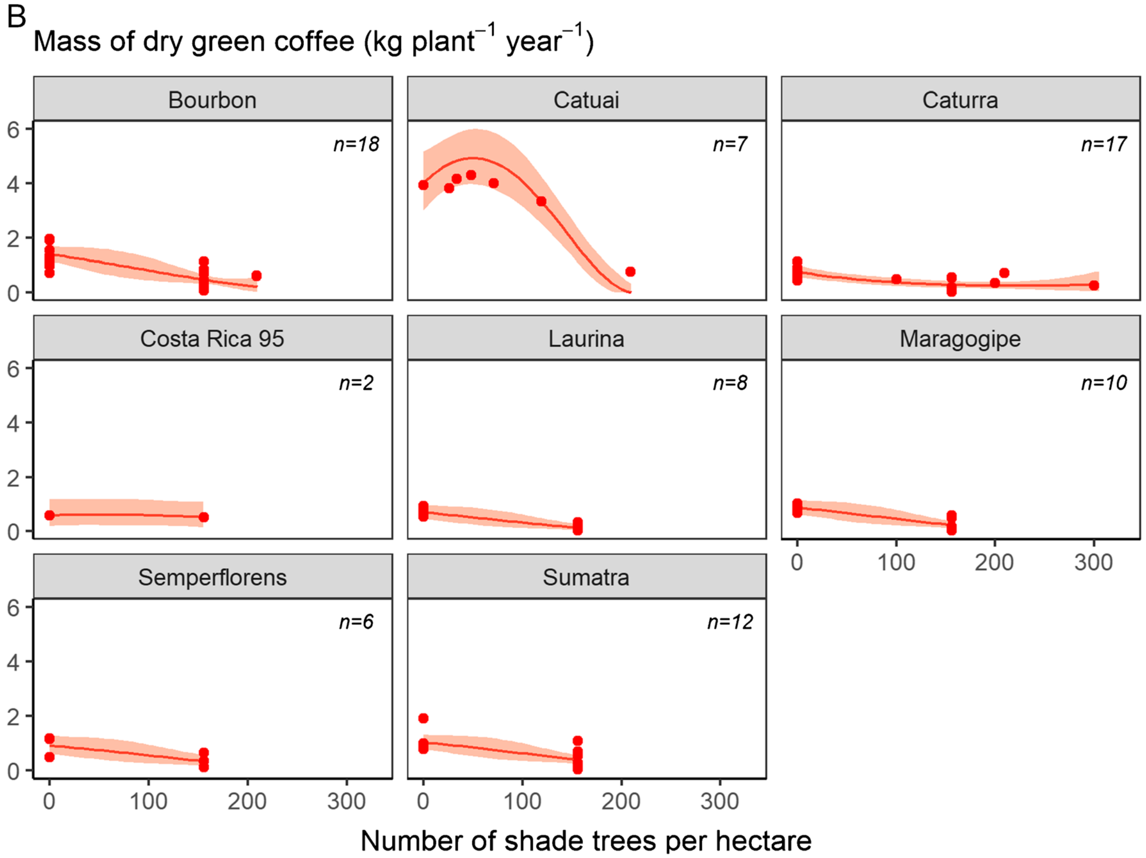


Fig. 4 (continued)

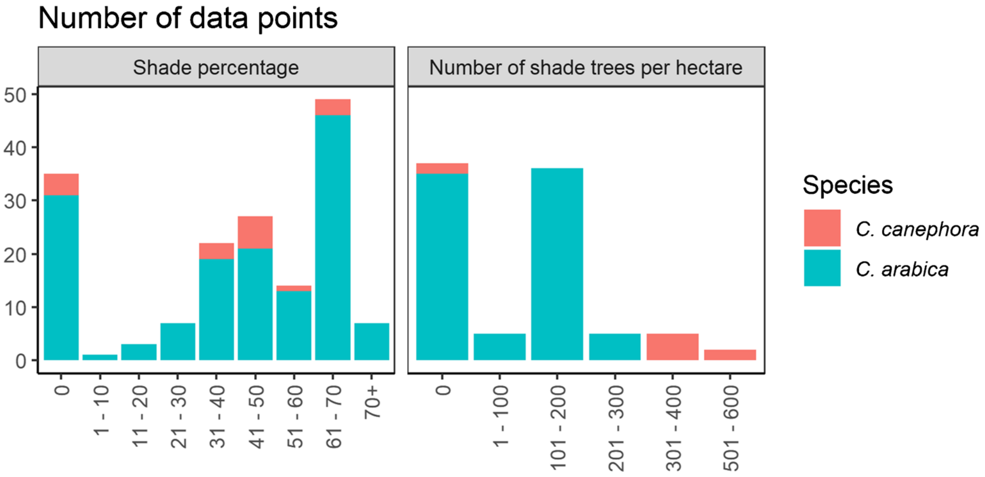
shade cover (approximately 10–40%) in many cases has little negative impact on yields, and in some cases, a beneficial effect can occur (as is the case for Arabica cultivars Bourbon and Mundo Novo). However, this finding requires further validation by assessing more cultivars within this shade range 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 shortwave 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 × 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.

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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.

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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.

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References

Araújo AV, Partelli FL, Oliosi G, Pezzopane JRM (2016) Microclimate, development and productivity of robusta coffee shaded by rubber trees and at full sun. Rev Ciênc Agron 47(4):700–709. https://doi.org/10.5935/1806-6690.2016008

Assefa A, Gobena A (2020) Review on effect of shade tree on microclimate, growth and physiology of *Coffee arabica*: In case of Ethiopia. Int J For Hortic 5(3):31–46. https://doi.org/10.20431/2454-9487.0503004

Baggio AJ, Caramori PH, Androcioli Filho A, Montoya L (1997) Productivity of southern Brazilian coffee plantations shaded by different stockings of *Grevillea robusta*. Agrofor Syst 37(2):111–120. https://doi.org/10.1023/a:1005814907546

Beer J (1987) Advantages, disadvantages and desirable characteristics of shade trees for coffee, cacao and tea. Agrofor Syst 5(1):3–13. https://doi.org/10.1007/bf00046410

Beer J, Muschler R, Kass D, Somarriba E (1997) Shade management in coffee and cacao plantations. Agrofor Syst 38(1-3):139–164. https://doi.org/10.1007/978-94-015-9008-2_6

Bertrand B, Breitler JC, Georget F, Penot E, Bordeaux M, Marraccini P, Léran S, Campa C, Bonato O, Villain L, Etienne H (2019) New varieties for innovative agroforestry coffee system. In: The agroecological transition of agricultural systems in the Global South. Quae Editor, Versailles, pp 161–176. https://doi.org/10.35690/978-2-7592-3057-0

Bertrand B, Hincapié AMV, Marie L, Breitler JC (2021) Breeding for the main agricultural farming of Arabica coffee. Front Sustain Food Syst 5:303. https://doi.org/10.3389/fsufs.2021.709901

Camargo MBPD (2010) The impact of climatic variability and climate change on Arabic coffee crop in Brazil. Bragantia 69(1):239–247. https://doi.org/10.1590/s0006-87052010000100030

Campanha MM, Santos RHS, De Freitas GB, Martinez HEP, Garcia SLR, Finger FL (2004) Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais, Brazil. Agrofor Syst 63(1):75–82. https://doi.org/10.1023/b:agfo.0000049435.22512.2d

Carelli MLC, Fahl JI, Alfonsi EL (2001) Efeitos de níveis de sombreamento no crescimento e produtividade do cafeeiro. Embrapa Café. Online document. http://www.sbicafe.ufv.br/handle/123456789/1228.Accessed 28 July 2020

Carvalho A, Krug CA, Mendes JET, Antunes Filho H, Junqueira AR, Aloisio Sobrinho J, Rocha TR, Moraes MV (1961) Melhoramento do Cafeeiro: XXI-Comportamento regional de variedades. Linhagens e progênies de café ao sol e à sombra. Bragantia 20:1045–1142. https://doi.org/10.1590/S0006-87051961000100046

Cheng B, Smyth HE, Furtado A, Henry RJ (2020) Slower development of lower canopy beans produces better coffee. J Exp Bot 71(14):4201–4214. https://doi.org/10.1093/jxb/eraa151

Clemens H, Zablah JS (1993) Tecnología y desarrollo del sector cafetalero en Nicaragua: Caracterización del manejo del cultivo del café en la IV Región. ciclo 1990/91. Online document. https://www.revistas.una.ac.cr/index.php/historia/article/view/3437. Accessed 4 Feb 2020

Coltri PP, Pinto HS, do Valle Gonçalves RR, Junior JZ, Dubreuil V (2019) Low levels of shade and climate change adaptation of Arabica coffee in south eastern Brazil. Heliyon 5(2):e01263. https://doi.org/10.1016/j.heliyon.2019.e01263

DaMatta FM (2004) Ecophysiological constraints on the production of shaded and unshaded coffee: a review. Field Crop Res 86(2-3):99–114. https://doi.org/10.1016/j.fcr.2003.09.001

DaMatta FM, Rahn E, Läderach P, Ghini R, Ramalho JC (2019) Why could the coffee crop endure climate change and global warming to a greater extent than previously estimated? Clim Chang 152(1):167–178. https://doi.org/10.1007/s10584-018-2346-4)

DaMatta FM, Ramalho JC (2006) Impacts of drought and temperature stress on coffee physiology and production: a review. Theor Exp Plant Physiol 18(1):55–81. https://doi.org/10.1590/s1677-04202006000100006

de Sousa K, van Zonneveld M, Holmgren M, Kindt R, Ordoñez JC (2019) The future of coffee and cocoa agroforestry in a warmer Mesoamerica. Sci Rep-UK 9(1):8828. https://doi.org/10.1038/s41598-019-45491-7

Duangsodsri T, Léran S, Villegas AM, Vestalys I, Artins A, Etienne H, Breitler JC, Villain L, Bertrand B, Campa C (2019) A global approach to decipher molecular basis of coffee tree adaptation to shade. In: 4th World Congress on Agroforestry. 20-22 May 2019.

Dubberstein D, Rodrigues WP, Semedo JN, Rodrigues AP, Pais IP, Leitão AE, Partelli FL, Campostrini E, Reboredo F, Scotti-Campos P, Lidon FC, Ribeiro-Barros AI, DaMatta FM, Ramalho JC (2018) Mitigation of the negative impact of warming on the coffee crop – the role of increased air [CO_2] and management strategies. In: Climate Resilient Agriculture - Strategies and Perspectives. Intechopen LTD, UK. pp. 57-85. https://doi.org/10.5772/intechopen.72374

Estivariz Coca JJ (1997) Efecto de sombra sobre la floración y producción de *Coffea arabica* var caturra. despúes de una poda completa en Turrialba, Costa Rica. Shade effect on flowering and production of *Coffea arabica* var Caturra, after a complete pruning in Turrialba, Costa Rica. Dissertation, CATIE, Turrialba (Costa Rica).

Farfan F, Mestre MA (2004) Respuesta del café cultivado en un sistema agroforestal a la aplicación de fertilizantes. Cenicafé 52(2):161–174 https://biblioteca.cenicafe.org/handle/10778/168

Fernie LM, Greathead DJ, Meyer FG, Monaco LC, Narasimhaswamy RL (1968) FAO coffee mission to Ethiopia. Online document. FAO, Rome, Italy. pp.1964-1965. https://agris.fao.org/agris-search/search.do?recordID=XF2015002286. Accessed 7 Feb 2020

Friis I (2015) Coffee and qat on the Royal Danish expedition to Arabia–botanical, ethnobotanical and commercial observations made in Yemen 1762–1763. Arch Nat Hist 42(1):101–112. https://doi.org/10.3366/anh.2015.0283

Gale J (2004) Plants and altitude—revisited. Ann Bot 94(2):199. https://doi.org/10.1093/aob/mch143

Georget F, Marie L, Alpizar E, Courtel P, Bordeaux M, Hidalgo JM, Marraccini P, Breitler JC, Déchamp E, Poncon C, Etienne H, Bertrand B (2019) Starmaya: the first Arabica F1 coffee hybrid produced using genetic male sterility. Front Plant Sci 10:1344. https://doi.org/10.3389/fpls.2019.01344

Gerlicz A, Méndez VE, Conner D, Baker D, Christel D (2019) Use and perceptions of alternative economic activities among smallholder coffee farmers in Huehuetenango and El Quiché departments in Guatemala. Agroecol Sust Food 43(3):310–328. https://doi.org/10.1080/21683565.2018.1532480

Gobbi JA (2000) Is biodiversity-friendly coffee financially viable? An analysis of five different coffee production systems in western El Salvador. Ecol Econ 33(2):267–281. https://doi.org/10.1016/S0921-8009(99)00147-0

Haggar J, Barrios M, Bolaños M, Merlo M, Moraga P, Munguia R, Ponce A, Romero S, Soto G, Staver C, Virginio E d MF (2011) Coffee agroecosystem performance under full sun, shade, conventional and organic management regimes in Central America. Agrofor Syst 82(3):285–301. https://doi.org/10.1007/s10457-011-9392-5

Hernández Guerra OR (1995) Yield and financial analysis of an agroforestry system with coffee (*Coffea arabica* cv caturra) and poro (*Erythrina poeppigiana*) under different densities of laurel (*Cordia alliodora*). Dissertation, CATIE, Turrialba (Costa Rica).

Hirons M, Mehrabi Z, Gonfa T, Morel AC, Gole T, McDermott C, Boyd E, Robinson E, Sheleme D, Malhi Y, Mason J, Norris K (2018) Pursuing climate resilient coffee in Ethiopia – a critical review. Geoforum 91:108–116. https://doi.org/10.1016/j.geoforum.2018.02.032

Jaramillo-Botero C, Santos RHS, Martinez HEP, Cecon PR, Fardin MP (2010) Production and vegetative growth of coffee trees under fertilization and shade levels. Sci Agric 67(6):639–645. https://doi.org/10.1590/s0103-90162010000600004

Javier Lopez-Garcia F, Escamilla-Prado E, Zamarripa-Colmenero A, Guillermo Cruz-Castillo J (2016) Yield and quality of coffee cultivars (*Coffea arabica* L.) in Veracruz, Mexico. Rev Fitotec Mex 39(3):297–304. https://doi.org/10.35196/rfm.2016.3.297-304

Jezeer RE, Verweij PA, Santos MJ, Boot RG (2017) Shaded coffee and cocoa–double dividend for biodiversity and small-scale farmers. Ecol Econ 140:136–145. https://doi.org/10.1016/j.ecolecon.2017.04.019

Jezeer RE, Verweij PA, Boot RG, Junginger M, Santos MJ (2019) Influence of livelihood assets, experienced shocks and perceived risks on smallholder coffee farming practices in Peru. J Environ Manage 242:496–5

Jha S, Bacon CM, Philpott SM, Ernesto Méndez V, Läderach P, Rice RA (2014) Shade coffee: update on a disappearing refuge for biodiversity. Bioscience 64(5):416–428. https://doi.org/10.1093/biosci/biu038

Kellermann JL, Johnson MD, Stercho AM, Hackett SC (2008) Ecological and economic services provided by birds on Jamaican Blue Mountain coffee farms. Conserv Biol 22(5):1177–1185. https://doi.org/10.1111/j.1523-1739.2008.00968.x

Koutouleas A, Collinge DB, Ræbild A (2022b) Alternative plant protection strategies for coffee of tomorrow. A review. Plant Pathol (Submitted)

Koutouleas A, Sarzynski T, Bordeaux M, Bosselmann AS, Campa C, Etienne H, Turreira-García N, Rigal C, Vaast P, Ramalho JC, Marraccini P, Ræbild A (2022a) Shaded-coffee: a nature-based strategy for coffee production under climate change? A review. Front Sustain Food Syst 6:877476. https://doi.org/10.3389/fsufs.2022.877476

Kufa T, Burkhardt J (2011a) Spatial variability in water relations of wild *Coffea arabica* populations in the montane rainforests of Ethiopia. Ecologia 1(1):31–43. https://doi.org/10.3923/ecologia.2011.31.43

Kufa T, Burkhardt J (2011b) Variations in leaf water potential in the wild Ethiopian *Coffea arabica* accessions under contrasting nursery environments. J Agron 10(1):1–11. https://doi.org/10.3923/ja.2011.1.11

Lashermes P, Combes MC, Robert J, Trouslot P, D'Hont A, Anthony F, Charrier A (1999) Molecular characterisation and origin of the *Coffea arabica* L. genome. Mol Gen Genet 261(2):259–266. https://doi.org/10.1007/s004380050965

Lenth RV (2020) emmeans: estimated marginal means, aka least-squares mean. R package version 1.5.2-1. Online document. https://CRAN.R-project.org/package=emmeans. Accessed 8 Jan 2021

Lin BB (2009) Coffee (*Café arabica* var. Bourbon) fruit growth and development under varying shade levels in the Soconusco region of Chiapas, Mexico. J Sustain Agric 33(1):51–65. https://doi.org/10.1080/10440040802395007

Marie L, Abdallah C, Campa C, Courtel P, Bordeaux M, Navarini L, Lonzarich V, Bosselmann AS, Turreira-Garcia N, Alpizar E, Georget F, Breitler JC, Etienne H, Bertrand B (2020) G×E interactions on yield and quality in *Coffea arabica*: new F1 hybrids outperform American cultivars. Euphytica 216:78. https://doi.org/10.1007/s10681-020-02608-8

Matos FS, Wolfgramm R, Gonçalves FV, Cavatte PC, Ventrella MC, DaMatta FM (2009) Phenotypic plasticity in response to light in the coffee tree. Environ Exp Bot 67(2):421–427. https://doi.org/10.1016/j.envexpbot.2009.06.018

Méndez VE, Bacon CM, Olson M, Morris KS, Shattuck A (2010) Agrobiodiversity and shade coffee smallholder livelihoods: a review and synthesis of ten years of research in Central America. Prof Geogr 62(3):357–376. https://doi.org/10.1080/00330124.2010.483638

Merlo Caballero ME (2007) Productive behavior of the coffee (*Coffea arabica* var. Caturra), the poro (*Erythrina poeppigiana*), the amarillon (*Terminalia amazonia*), the casha (*Chloroleucon eurycyclum*) in agroforestry systeMON under managements conventionals and organics in Turrialba, Costa Rica. Master Thesis, CATIE, Costa Rica. http://orton.catie.ac.cr/repdoc/A1306e/A1306e.pdf. Accessed 19 Nov 2020

Moguel P, Toledo VM (1999) Biodiversity conservation in traditional coffee systems of Mexico. Conserv Biol 13(1):11–21. https://doi.org/10.1046/j.1523-1739.1999.97153.x

Moher D, Liberati A, Tetzlaff J, Altman DG (2009) Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med 6(7):e1000097. https://doi.org/10.1371/journal.pmed.1000097

Montagnon C, Mahyoub A, Solano W, Sheibani F (2021) Unveiling a unique genetic diversity of cultivated *Coffea arabica* L. in its main domestication center: Yemen. Genet Resour Crop Evol 68(6):2411–2422. https://doi.org/10.1007/s10722-021-01139-y

Morais H, Caramori PH, Ribeiro AMDA, Gomes JC, Koguishi MS (2006) Microclimatic characterization and productivity of coffee plants grown under shade of pigeon pea in Southern Brazil. Pesqui Agropecu Bras 41(5):763–770. https://doi.org/10.1590/s0100-204x2006000500007

Moreaux C, Meireles DAL, Sonne J, Badano EI, Classen A, González-Chavez A, Hipólito J, Klein A-M, Maruyama PK, Metzger JP, Philpott SM, Rahbek C, Saturni FT, Sritongchuay T, Tscharntke T, Uno S, Vergara CH, Viana BF, Strange N, Dalsgaard B (2022) The value of biotic pollination and dense forest for fruit set of Arabica coffee: a global assessment. Agric Ecosyst Environ 323:107680. https://doi.org/10.1016/j.agee.2021.107680

Mussetta P, Hurlbert M (2020) Vulnerability studies in the Americas: extreme weather and climate change. Cambridge Scholars Publishing, New York

Oliosi G, Giles JAD, Rodrigues WP, Ramalho JC, Partelli FL (2016) Microclimate and development of *Coffea canephora* cv. Conilon under different shading levels promoted by Australian cedar (*Toona ciliata* M. Roem. var. Australis). Aust J Crop Sci 10(4):528–538. https://doi.org/10.21475/ajcs.2016.10.04.p7295x

Pappo E, Wilson C, Flory SL (2021) Hybrid coffee cultivars may enhance agroecosystem resilience to climate change. Aob Plants 13(2):plab010. https://doi.org/10.1093/aobpla/plab010

Partelli FL, Araújo AV, Vieira HD, Dias JRM, de Menezes LFT, Ramalho JC (2014) Microclimate and development of 'Conilon' coffee intercropped with rubber trees. Pesq Agropec Bras 49(11):872–881. https://doi.org/10.1590/s0100-204x2014001100006

Perfecto I, Rice RA, Greenberg R, Van der Voort ME (1996) Shade coffee: a disappearing refuge for biodiversity: shade coffee plantations can contain as much biodiversity as forest habitats. Bioscience 46(8):598–608. https://doi.org/10.2307/1312989

Perfecto I, Vandermeer J, Mas A, Pinto LS (2005) Biodiversity, yield, and shade coffee certification. Ecol Econ 54(4):435–446. https://doi.org/10.1016/j.ecolecon.2004.10.009

Perfecto I, Vandermeer J, Philpott SM (2014) Complex ecological interactions in the coffee agroecosystem. Annu Rev Ecol Evol Syst 45:137–158. https://doi.org/10.1146/annurev-ecolsys-120213-091923

Piato K, Lefort F, Subía C, Caicedo C, Calderón D, Pico J, Norgrove L (2020) Effects of shade trees on robusta coffee growth, yield and quality. A meta-analysis. Agron Sustain Dev 40:38. https://doi.org/10.1007/s13593-020-00642-3

Pilati A (2005) Evaluación de tres diferentes tipologías de manejo agronómico, sobre la estructura de crecimiento, de productividad y calidad del café (*Coffea arabica* L.), en la zona del Pacífico Sur de Nicaragua. Dissertation, Universidad Nacional Agraria, Nicaragua. http://repositorio.una.edu.ni/id/eprint/1983. Accessed 19 Nov 2020

Rahn E, Vaast P, Läderach P, van Asten P, Jassogne L, Ghazoul J (2018) Exploring adaptation strategies of coffee production to climate change using a process-based model. Ecol Model 371:76–89. https://doi.org/10.1016/j.ecolmodel.2018.01.009

Rakocevic M, Matsunaga FT, Baroni DF, Campostrini E, Costes E (2021) Multiscale analyses of growth and berry distributions along four branching orders and vertical profile of *Coffea arabica* L. cultivated under high-density planting systems. Sci Hortic-Amsterdam 281:109934. https://doi.org/10.1016/j.scienta.2021.109934

Ricci MDSF, Costa JR, Pinto AN, Santos VLDS (2006) Organic cultivation of coffee cultivars grown under full sun and under shading. Pesqui Agropecu Bras 41(4):569–575. https://doi.org/10.1590/s0100-204x2006000400004

Ricci MDSF, Rouws JRC, Oliveira NGD, Rodrigues MB (2011) Vegetative and productive aspects of organically grown coffee cultivars under shaded and unshaded systems. Sci Agric 68(4):424–430. https://doi.org/10.1590/s0103-90162011000400006

Rigal C, Xu J, Vaast P (2020) Young shade trees improve soil quality in intensively managed coffee systems recently converted to agroforestry in Yunnan Province, China. Plant Soil 453:119–137. https://doi.org/10.1007/s11104-019-04004-1

Righi CA, Campoe OC, Bernardes MS, Lunz AMP, Piedade SMS, Pereira CR (2013) Influence of rubber trees on leaf-miner damage to coffee plants in an agroforestry system. Agrofor Syst 87(6):1351–1362. https://doi.org/10.1007/s10457-013-9642-9

Schaller M, Schroth G, Beer J, Jiménez F (2003) Species and site characteristics that permit the association of fast-growing trees with crops: the case of *Eucalyptus deglupta* as coffee shade in Costa

Rica. Forest Ecol Manag 175(1-3):205–215. https://doi.org/10.1016/s0378-1127(02)00079-8

Siles P, Harmand JM, Vaast P (2010) Effects of *Inga densiflora* on the microclimate of coffee (*Coffea arabica* L.) and overall biomass under optimal growing conditions in Costa Rica. Agrofor Syst 78(3):269–286. https://doi.org/10.1007/s10457-009-9241-y

Somporn C, Kamtuo A, Theerakulpisut P, Siriamornpun S (2012) Effect of shading on yield, sugar content, phenolic acids and antioxidant property of coffee beans (*Coffea arabica* L. cv. Catimor) harvested from north-eastern Thailand. J Sci Food Agric 92(9):1956–1963. https://doi.org/10.1002/jsfa.5568

Soto-Pinto L, Perfecto I, Castillo-Hernandez J, Caballero-Nieto J (2000) Shade effect on coffee production at the northern Tzeltal zone of the state of Chiapas, Mexico. Agric Ecosyst Environ 80(1-2):61–69. https://doi.org/10.1016/s0167-8809(00)00134-1

Steiman S, Idol T, Bittenbender HC, Gautz L (2011) Shade coffee in Hawaii–Exploring some aspects of quality, growth, yield, and nutrition. Sci Hortic-Amsterdam 128(2):152–158. https://doi.org/10.1016/j.scienta.2011.01.011

Sarmiento-Soler A, Vaast P, Hoffmann MP, Rötter RP, Jassogne L, Van Asten PJ, Graefe S (2019) Water use of *Coffea arabica* in open versus shaded systems under smallholder's farm conditions in Eastern Uganda. Agric For Meteorol 266:231–242. https://doi.org/10.1016/j.agrformet.2018.12.006

Scalabrin S, Toniutti L, Di Gaspero G, Scaglione D, Magris G, Vidotto M, Pinosio S, Cattonaro F, Magni F, Jurman I, Cerutti M, Suggi Liverani F, Navarini L, Del Terra L, Pellegrino G, Ruosi MR, Vitulo N, Valle G, Pallavicini A, Graziosi G, Klein PE, Bentley N, Murray S, Solano W, Al Hakimi A, Schilling T, Montagnon C, Morgante M, Bertrand (2020) A single polyploidization event at the origin of the tetraploid genome of *Coffea arabica* is responsible for the extremely low genetic variation in wild and cultivated germplasm. Sci Rep 10(1):4642. https://doi.org/10.1038/s41598-020-61216-7

Staver C, Guharay F, Monterroso D, Muschler RG (2001) Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agrofor Syst 53(2):151–170. https://doi.org/10.1023/a:1013372403359

Sylvain PG (1955) Some observations on *Coffea arabica* L. in Ethiopia. Turrialba 5(1-2):37–53

Tounekti T, Mahdhi M, Al-Turki T, Khemira H (2018) Water relations and photo-protection mechanisms during drought stress in four coffee (*Coffea arabica*) cultivars from southwestern Saudi Arabia. S Afr J Bot 117:17–25. https://doi.org/10.1016/j.sajb.2018.04.022

Vaast P, Van Kanten R, Siles P, Dzib B, Franck N, Harmand JM, Génard M (2005) Shade: a key factor for coffee sustainability and quality. In: Colloque Scientifique International Sur Le Café. Association for Science and Information on Coffee (ASIC) 1997. 887-896. Nairobi. Kenya. https://agritrop.cirad.fr/529372/

Vaast P, Bertrand B, Perriot JJ, Guyot B, Génard M (2006) Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. J Sci Food Agric 86(2):197–204. https://doi.org/10.1002/jsfa.2338. Accessed 28 May 2020

van Kanten R, Vaast P (2006) Transpiration of *arabica* coffee and associated shade tree species in sub-optimal, low-altitude conditions of Costa Rica. Agrofor Syst 67(2):187–202. https://doi.org/10.1007/s10457-005-3744-y

Van Oijen M, Dauzat J, Harmand JM, Lawson G, Vaast P (2010a) Coffee agroforestry systems in Central America: I. A review of quantitative information on physiological and ecological processes. Agrofor Syst 80(3):341–359. https://doi.org/10.1007/s10457-010-9294-y

Van Oijen M, Dauzat J, Harmand JM, Lawson G, Vaast P (2010b) Coffee agroforestry systems in Central America: II. Development of a simple process-based model and preliminary results. Agrofor Syst 80(3):361–378. https://doi.org/10.1007/s10457-010-9291-1

Venancio LP, do Amaral JFT, Cavatte PC, Vargas CT, dos Reis EF, Dias JR (2019) Vegetative growth and yield of robusta coffee genotypes cultivated under different shading levels. Biosci J 35(5):1490–1503. https://doi.org/10.14393/bj-v35n5a2019-45039

Villarreyna R, Avelino J, Cerda R (2020) Ecosystem-based adaptation: effect of shade trees on ecosystem services in coffee plantations. Agron Mesoam 31(2):499–516. https://doi.org/10.15517/am.v31i2.37591

Virginio Filho EDM, Casanoves F, Haggar J, Staver C, Soto G, Avelino J, Tapia A, Merlo M, Salgado J, Noponen M, Perdomo Y (2015) La productividad útil, la materia orgánica y el suelo en los primeros 10 años de edad en sistemas de producción de café a pleno sol y bajo varios tipos de sombra y niveles de insumos orgánicos y convencionales en Costa Rica. Sistemas Agroforestales Funciones Productivas, Socioeconómicas Y Ambientales. Serie técnica. Informe técnico 402. CATIE, Turrialba, Costa Rica. Editorial CIPAV, Cali, Colombia. pp 131-159. https://agris.fao.org/agris-search/search.do?recordID=FR2017102414. Accessed 30 Dec 2020

Wolf JV, Gram G, Bukomeko H, Mukasa D, Giller O, Kirabo E, Angebault C, Vaast P, Asare R, Jassogne LT (2017) The shade tree advice tool. CCAFS Info Note. Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). 2-3. https://hdl.handle.net/10568/80473. Accessed 20 Feb 2020