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The impact of climate change and variability on coffee production: a systematic review

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Abstract
Coffee is one of the most important globally traded commodities and substantially contributes to the livelihoods of millions of smallholders worldwide. As a climate-sensitive perennial crop, coffee is likely to be highly susceptible to changes in climate. Using a systematic approach, we explore evidence from the published academic literature of the influence of climate change and variability, specifically drought, on coffee production. A number of mostly negative impacts were reported in the current literature, including declines in coffee yield, loss of coffee-optimal areas with significant impacts on major global coffee-producing countries and growth in the distribution of pest and disease that indirectly influence coffee cultivation. Current research also identified positive effects of climate change such as increases in coffee-producing niche, particularly in areas at higher altitudes; however, whether these gains might offset losses from other production areas requires further investigation. Other advantages include increases in pollination services and the beneficial effects of elevated carbon concentration, leading to potential yield improvements. Future priorities should focus on major coffee-growing regions projected to be adversely affected by climate change, with specific attention given to potential adaptation strategies tailored to particular farming conditions such as relocation of coffee plantations to more climatically suitable areas, irrigation and agroforestry. The majority of studies were based in the Americas and concentrated on Arabica coffee. A broader spread of research is therefore required, especially for the large growing regions in Asia and for Robusta coffee, to support sustainable production of the global coffee industry.

1 Introduction

The agricultural sector is expected to be substantially affected by climate change because of the sensitivity of crops to increasing temperature and water shortages (Mendelsohn 2008; Ramirez-Villegas and Challinor 2012). Apparent negative effects include declines in crop yield

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and quality and increases in pest and disease infestation, leading to reductions in crop production worldwide (IPCC 2014). These pose significant challenges to smallholder farmers, many of whom are dependent on rain-fed cultivation and have limited access to financial and technical support (Cohn et al. 2017; Holland et al. 2017) that could help them to respond to changing climatic conditions.

There has been a growing concern for coffee, a crop that is grown by over 25 million mostly smallholder farmers in more than 60 countries throughout the tropics (Jayakumar et al. 2017) and that is highly sensitive to local climate (DaMatta and Ramalho 2006). Coffee yield is strongly determined by climatic conditions, particularly during the vegetative and reproductive phases of the plant (Tavares et al. 2018). Increasing temperatures and precipitation shortages have negative impacts on flowering, fruiting and bean quality (Gay et al. 2006; Lin 2007). Furthermore, climate variables also control the incidence of serious pests and diseases such as coffee leaf rust and coffee berry borer which could reduce coffee yield and quality and increase production costs.

Coffee is the second-most globally traded commodity after oil (Davis et al. 2012) and contributes significantly to the socio-economic development of many tropical developing countries and the livelihoods of more than 120 million people worldwide (TCI 2016). Coffee production has doubled during the last 30 years, amounting to over 169 million bags in 2018 (ICO 2019b). The gross revenue of coffee production was estimated at US$11.6 billion per year during 2000–2012 while the total value of the entire coffee sector was more than US$173 billion in 2012 (ICO 2014). Brazil makes up about 36% of the world's production, followed by Vietnam (17%), Colombia (8%) and Indonesia (6%) (ICO 2019b). Apart from substantially contributing to agricultural GDP, coffee production provides millions of jobs and supports poverty alleviation (Chemura et al. 2016; Laderach et al. 2017). More than 70% of global coffee is cultivated by smallholder growers in Africa, Asia and the Americas with many of them relying on coffee as their major source of income (Fridell et al. 2008). In addition to social and economic benefits, coffee plantations, particularly shaded farms, also generate significant ecosystem services including biodiversity conservation (Jha et al. 2014), carbon sequestration (van Rikxoort et al. 2014) and soil protection (Meylan et al. 2017).

Globally, Arabica *(Coffea arabica)* and Robusta *(Coffea canephora)* coffees make up approximately 99% of global coffee production (Jayakumar et al. 2017). Arabica, which is often used in speciality coffees, grows best at 18–22 °C, while Robusta is of lower quality but hardier and productive at 22–28 °C (Magrach and Ghazoul 2015). Bean quality and yield of both species decline outside these optimum temperature ranges (Magrach and Ghazoul 2015), suggesting significant sensitivity to shifts in climatic conditions. Further, as coffee plantations have, on average, a 30-year lifespan and can remain productive for more than 50 years (Bunn et al. 2015b), they are likely to be subjected to the influence of climate change and variability. Smallholder coffee farmers might also be highly vulnerable to changes in climate as adaptation in perennial crops like coffee may take several or even many years to take effect (Laderach et al. 2017). From a socio-economic perspective, understanding the extent of climate-driven impacts on coffee production and the benefits of potential adaptation strategies will be of vital importance to maintaining and improving coffee productivity and profitability and sustaining the livelihoods of smallholder producers all over the world.

This review assesses current research on the impacts of climate change and variability, specifically drought, on coffee production. We systematically examined the literature to determine: (i) the geographic distribution of the research; (ii) the types and characteristics of the impacts investigated; (iii) the methods used to analyse the impacts; (iv) the adaptation measures involved; and (v) any potential research gaps. On this basis, we identify target areas for future research to better support sustainable and viable coffee production.

2 Methods

Using the methods outlined in Pickering and Byrne (2014), we conducted a systematic quantitative review of the academic literature on climate-driven impacts on coffee production. This is a robust systematic and reproducible approach used to comprehensively survey, select and categorise the literature on a particular research topic (Pickering et al. 2015).

Applying a set of key search terms, we surveyed the literature in three scholarly electronic databases (Scopus, Web of Science and Science Direct) in October–November 2018 to identify relevant papers. The string of key search words used were combinations of ‘coffee’ and ‘climate’, ‘climatic’, ‘ENSO’, ‘El Niño’, ‘La Niña’, ‘drought’, ‘impact’, ‘effect’, ‘yield’, ‘production’ and ‘productivity’. We searched within the abstract, title and keyword database categories of original research papers published in peer-reviewed English language academic journals. Publications such as review articles, book chapters, reports and conference proceedings were excluded. However, reference lists in review papers and in the original research articles were checked for additional academic papers missed in the initial search.

Climate change and variability and drought are also likely to influence the entire coffee supply chain including harvesting and processing activities; however, such impacts were not included in this review as our focus was on direct and indirect impacts of climate on coffee yield (i.e. tonnes of coffee harvested per hectare) and coffee production (i.e. tonnes of coffee harvested in an area of cultivation).

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram (Moher et al. 2009) to track the process of identifying and selecting relevant papers for this study (Fig. 1). Using the key search terms listed, we found 339 journal and review articles in the three above-mentioned databases plus an additional 28 articles from the citation lists of these, from which we excluded 171 duplicates and any review articles. We then excluded 162 articles that were neither relevant nor sufficiently focused on the impacts of climate change or variability or drought on coffee production. Finally, a total of 34 relevant peer-reviewed articles was selected to be fully examined in this study.

Data on each article were recorded in a customised database, including information on geographic distribution and spatial scale of studies and types of methods used to investigate the impacts. Characteristics, sources and outcomes of impacts and adaptation and management practices mentioned in the literature were also entered into the database to identify patterns and gaps and to inform future research recommendations.

3 Results and discussion

A total of 34 peer-reviewed research articles that specifically discussed the impacts of climate change or climate variability or drought, either directly or indirectly, on coffee production were fully examined. These papers were published in 17 different journals (Table S1 in the Electronic supplementary material), with the majority in the journals *Climatic Change* and

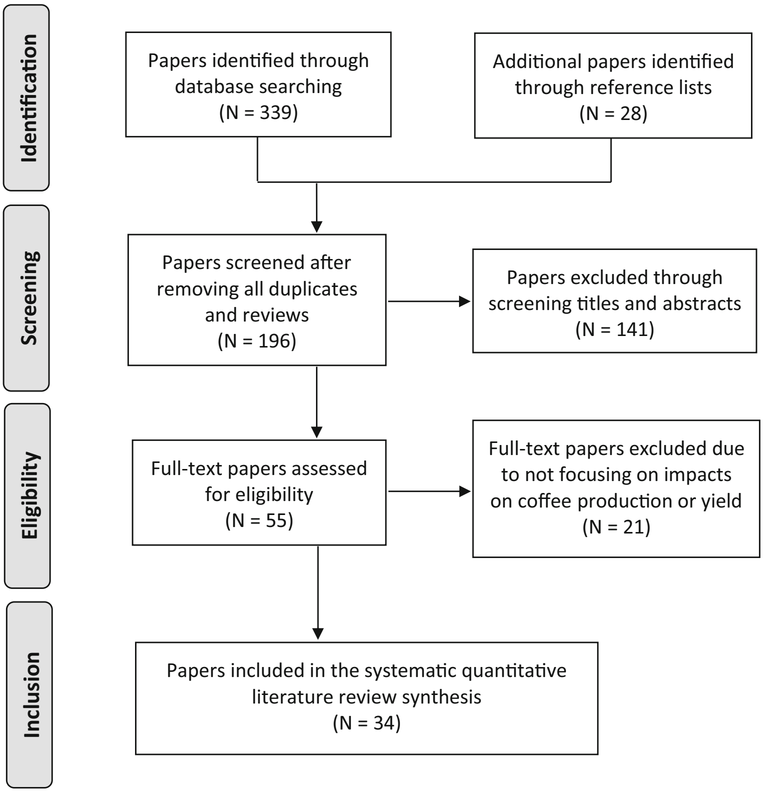

Fig. 1 Steps taken for the systematic quantitative literature review (adapted from Moher et al. 2009), *N*, number of original research papers

PLoS One (eight articles each). The journal *Regional Environmental Change* had three articles and the journal *Mitigation and Adaptation Strategies for Global Change* had two, while each of the remaining 13 journals had just one article.

Much of this research had been recently published (71% between 2014 and 2018), indicating an increasing interest in the potential impacts of climate variability and change on coffee production (Fig. S1 in the Electronic supplementary material).

Existing research mostly focused on Arabica (79%) with less consideration given to both coffee species, Arabica and Robusta (15%) (Table S1). No study solely concentrated on Robusta, despite this variety accounting for approximately 40% of global production (ICO 2019b). One explanation for this may be that many of the studies included in this review were conducted in the Americas where Arabica predominates. Another reason could be the greater heat tolerance of Robusta which might therefore be considered less vulnerable to rising temperatures than Arabica (Chengappa et al. 2017). However, Robusta may be susceptible to increasing intra-seasonal variability in temperatures (Bunn et al. 2015b), thus could still be negatively affected by changing climatic conditions. Given the decreasing bioclimatic suitability for Robusta production projected in some global studies, further research for this coffee species, particularly at finer spatial scales is necessary.

3.1 Geographic distribution of the research

Research in the papers included in this review was predominantly from the Americas (19 papers) with a majority of studies based in Central America (12 papers). Seven papers focused on coffee production in Africa and four in Asia (Fig. 2). Four papers reported on global studies covering all three of these continents (Table 1).

Most studies in the Americas were conducted in Brazil (six papers), followed by Mexico and Nicaragua (four papers each). The remaining research was limited to one or two papers per country in all three continents. The predominance of research in the Americas might reflect the fact that the world's top ten coffee-producing countries in this continent account for more than half of total global coffee production (Fig. 2). On the other hand, research from countries in Asia, where many of the other major coffee producers of the world are located, was relatively limited with only a small number of studies having been undertaken in large coffee-growing countries, including India and Indonesia. Interestingly, there were no papers targeted at regional, national or local levels for Vietnam, which is the world's second largest coffee-producing country with 17% of global coffee production (ICO 2019a). While Asia is expected to be negatively affected by climate change (Field et al. 2014), more research on climate-driven impacts on coffee is needed to support sustainable coffee development in regions with significant levels of production, particularly where communities are highly dependent on coffee cultivation.

Research into climate-driven impacts on coffee production has to date also been limited in scale (Table 1). Many of current studies primarily consider national (14 papers) and sub-national (11 papers) scales of production with less attention given to regional (or multinational) (four papers) or global scales (four papers). This is potentially because coffee data at large spatial scales are reportedly inadequate and uncertain (Eriyagama et al. 2014) while results of small-scale research are not easily extrapolated globally (Bunn et al. 2015a).

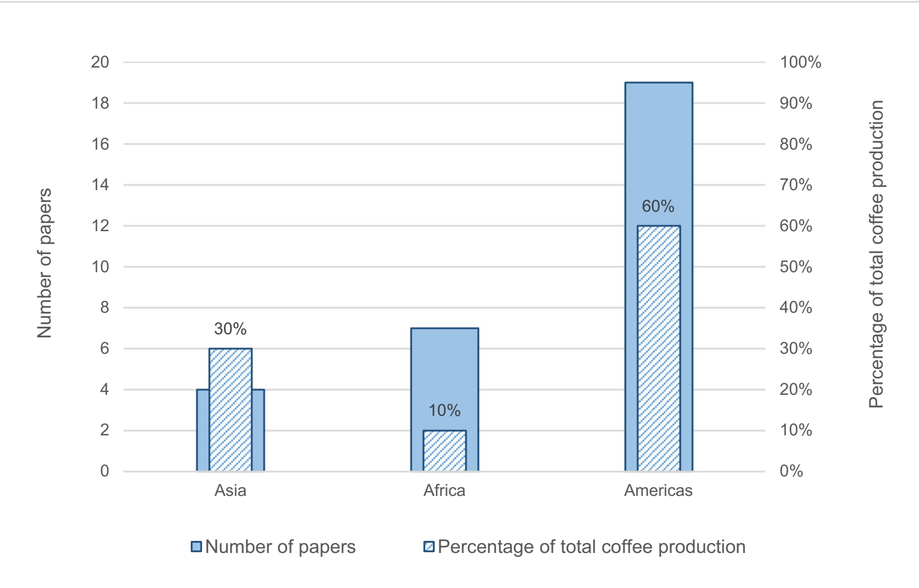

Fig. 2 Number of papers by continent reviewed and continental percentage of total global coffee production (ICO 2019b)

Table 1 List of reviewed original research papers on climate-driven impacts on coffee production published to November 2018

Reference	Location	Spatial scale	Source of impact	Method	Type and overall result of impact						
					P	S	Q	PE	DI	PS	Main finding
Global											
Bunn et al. (2015a)	Global	G	CC	Modelling (random forest)		±					An overall global loss of suitable areas for coffee by 2050s
Bunn et al. (2015b)	Global	G	CC	Modelling (support vector machines, random forest, MaxEnt)		±					A global loss of 50% of suitable areas by 2050
Magrach and Ghazoul (2015)	Global	G	CC	Modelling (MaxEnt)		±		–			A drop of 56% of current suitable areas for Arabica and 55% for Robusta by 2050. Future suitable areas for Robusta could be double. Distribution of coffee berry borer would increase
Ovalle-Rivera et al. (2015)	Global	G	CC	Modelling (MaxEnt)		±					An average loss of 19% of global suitable areas by 2050
The Americas											
Imbach et al. (2017)	Latin America	R	CC	Modelling (MaxEnt)		±				±	A loss of 73–88% of suitable areas by 2050. A drop of 8–18% in bee richness in future suitable areas, but pollination services are expected to continue
Baca et al. (2014)	Mesoamerica (Mexico, Nicaragua, Guatemala and El Salvador)	R	CC	Modelling (MaxEnt)		–					Reductions of at least 40% of suitable areas in 28% of total areas; 20–40% in 34% of areas and under 20% in 36% of areas by 2050
Harvey et al. (2018)	Central America (Costa Rica, Honduras and Guatemala)	R	CC	Interview	–			–	–		Negative impacts on yield and increases in pest and disease outbreak
Avelino et al. (2015)	Central America and Colombia	R & N	CV	Document analysis	–				–		A decline of 31% in production for 2008–2011 compared with 2007 in Colombia; 16% for 2012–2013 compared with 2011–2012 in Central America
Bastianin et al. (2018)	Colombia	N	CV	Modelling (econometric model)	±						Coffee production gains benefits from El Niño but loses from La Niña
Bacon et al. (2017)	Nicaragua	N	D & CV	Surveys, interviews, focus groups and modelling (statistical analysis)	–				–		Harvest losses of 60–72% from 2011–2012 to 2013–2014
Laderach et al.	Nicaragua	N	CC	Modelling (MaxEnt and CaNaSTA)		±	±				

Table 1 (continued)

Reference	Location	Spatial scale	Source of impact	Method	Type and overall result of impact						
					P	S	Q	PE	DI	PS	Main finding
(2017)											A loss of 10–25% of currently suitable areas by 2050. A decline in suitability to produce good quality coffee beans. Suitability will move to higher elevations
Fain et al. (2018)	Puerto Rico	N	CC	Weighted overlay analysis in GIS		–					A loss of 60–84% of highly suitable municipalities by 2070
Alves et al. (2011)	Brazil	N	CC	Modelling (non-linear regression)					–		A shift toward the south in areas favourable for coffee rust
Ghini et al. (2011)	Brazil	N	CC	GIS spatial analysis					–		A decrease in the incubation period and thus more severe epidemics
Ghini et al. (2008)	Brazil	N	CC	GIS spatial analysis				–			An increase in pest infestation and number of generations
Verhage et al. (2017)	Brazil	N	CC	Modelling (Arabica coffee yield model)	±						Yield will reduce by 7.5% in 2040–2070 but can increase 0.8% due to CFE
Junior et al. (2006)	Brazil	SN	CC	Modelling (agricultural zoning)		–					A reduction of 41 and 70% of suitable areas if temperature increases by 1 and 3 °C, respectively
Tavares et al. (2018)	Brazil	SN	CC	Modelling (agroclimatic zoning)	–	–					Losses of 36–64% of current suitable areas and 25% of Arabica yield by 2100
Estrada et al. (2012)	Mexico	SN	CC	Modelling (econometric model)	–						Costs of climate change for coffee production are estimated to be 3 to 14 times (273–1273 million dollars) the current value of coffee
Gay et al. (2006)	Mexico	SN	CC	Modelling (econometric model)	–						A drop of 19–34% in production by 2020
Schroth et al. (2009)	Mexico	SN	CC	Modelling (MaxEnt)		–					A strong decline of 98% of currently highly suitable areas by 2050s
Rahn et al. (2014)	Nicaragua	SN	CC	Modelling (MaxEnt)	–	–					A decrease of climatic suitability for coffee cultivation
Guido et al. (2018)	Jamaica	SN	D	Interview and focus group	–						Lower quality and quantity of coffee, leading to lower production
Asia											
Ranjitkar et al. (2016)	Nepal	N	CC	Modelling (an ensemble of 19 SDM algorithms)		–					A drop of 72.6 ± 4.4% of current suitable areas by 2050. Only 11.9 ± 2.3% of new areas become suitable for coffee

Table 1 (continued)

Reference	Location	Spatial scale	Source of impact	Method	Type and overall result of impact						
					P	S	Q	PE	DI	PS	Main finding
Schroth et al. (2015)	Indonesia	N	CC	Modelling (MaxEnt)		±					An overall loss of 33% of suitable areas by 2050
Chengappa et al. (2017)	India	SN	CV	Interview	±						A decrease in Arabica yield and an increase in Robusta in the past 10 years
Jayakumar et al. (2017)	India	SN	CV	Modelling (statistical analysis)	±						A decline in production during 2001–2006 due to rising temperature. Arabica yield was adversely impacted during strong El Niño years
Africa											
Jaramillo et al. (2011)	East Africa	R	CC	Modelling (CLIMEX)				–			An increase in number of pest generations from 5 to 10/year
Kutywayo et al. (2013)	Zimbabwe	N	CC	Modelling (boosted regression trees and generalised linear models)				–			An increase in suitable areas for the pest by 16–62% by 2080
Chemura et al. (2016)	Zimbabwe	N	CC	MaxEnt		±					A loss of 8.3–13.8% of suitable areas by 2050
Moat et al. (2017)	Ethiopia	N	CC	Modelling (an ensemble of 6 SDM methods)		±					A decline of 39–59% of current suitable areas by 2100
Craparo et al. (2015)	Tanzania	N	CC	Modelling (statistical analysis)	–						A loss of 244 ± 41 kg/ha in yield by 2030 and 145 ± 41 kg/ha by 2060 without adaptation
Davis et al. (2012)	Ethiopia, Sudan and Kenya	SN	CC	Modelling (MaxEnt)		–					Reductions of 65–100% of suitable localities; 38–90% of suitable areas by 2080
Rahn et al. (2018)	Uganda and Tanzania	SN	CC	Modelling (process-based model)	±						A decline of 32% in yield at low altitude areas by a 2.5-degree temperature increase without carbon fertilisation effect (CFE) consideration. If with CFE, negative impacts can be offset by 13–21%

G, global; *R*, regional; *N*, national; *SN*, sub-national; *CC*, climate change; *CV*, climate variability; *D*, drought; *P*, production; *S*, suitability; *Q*, quality; *PE*, pest; *DI*, disease; *PS*, pollination services; '+' positive impact; '–' negative impact

3.2 Sources and types of impacts

In this assessment, sources of impacts were classified into three groups: climate change, climate variability and drought. Impacts were also categorised as direct (i.e. variations in yield or production or in bioclimatically suitable areas for coffee cultivation) and indirect (i.e. changes in coffee quality or in the distribution of pests or diseases or pollination services).

In total, 12 studies examined direct impacts of climate change or climate variability, while only two addressed direct impacts of drought on coffee yield or production. Seventeen studies analysed direct impacts of climate change on bioclimatic suitability for coffee cultivation, driving changes in optimal coffee-growing areas. The remaining studies reported indirect impacts of climate variability or climate change with ten studies on pest and disease distribution and one each on pollination activities and coffee quality (Table 1).

Much of the literature reviewed focused on the influence of climate change or climate variability, indicating increasing recognition of their potential impacts on coffee production. In contrast, the number of studies on drought impacts was small despite reports of severe droughts in some coffee-growing areas such as Central America (Baca et al. 2014; Guido et al. 2018). As drought is a major climatic constraint for coffee production (DaMatta and Ramalho 2006) and expected to increase in frequency and severity in many regions across the world under climate change (Field et al. 2014), more research specifically on its impacts and on adaptation solutions should be considered for drought-prone coffee cultivation areas. Further, current research is dominated by studies that project changes in the distribution of areas suitable for growing coffee, with less consideration given to analysis of direct effects on coffee yield, or indirect effects on pest and disease distribution as a result of changes in climate. As some of the major coffee pests and diseases will likely benefit from rising temperatures, more research on their responses to changing climatic conditions and on adaptation mechanisms to minimise exposure and vulnerability of the coffee crop to these risks is needed.

3.3 Methods used in the research

A variety of research methods has been used to investigate coffee's exposure to climate risks. Quantitative methods (29 papers) were predominant over qualitative methods (four papers), with only one study using mixed methods.

Qualitative approaches used interviews (four papers), focus groups (two papers), household surveys (one paper) and document analysis (one paper) to explore the influence of climate change or climate variability or drought either directly on coffee production or indirectly on pest and disease distribution. Further application of these methods in future research would benefit assessments on climate-driven impacts and adaptation of coffee production systems as they can provide context-specific information including the perceptions and experiences of local farmers and their responses to climate change.

Quantitative studies included a range of modelling approaches aimed at investigating the influence of climate variability and change in coffee production systems (Table 1). Many studies used machine-learning techniques (15 papers), particularly Maximum Entropy (MaxEnt; 13 papers), of which most focused on current and future climatic suitability for coffee cultivation.

MaxEnt is a popular method for determining the spatial distribution and the environmental niche of species (Elith et al. 2011; Merow et al. 2013). Its predominance is probably due to its ability to easily extrapolate (Fitzpatrick et al. 2013) and provide improved outputs with presence-only species data (Elith et al. 2011; Mateo et al. 2010) compared with other correlative ecological niche models. MaxEnt has been widely used to project species distribution ranges in ecology (Merow et al. 2013) and might be suitable for a climate-sensitive crop such as coffee, especially in the context of data limitations in many coffee cultivation areas, as noted above.

Other types of ecological niche modelling employed, included machine-learning techniques such as random forest (four papers), boosted regression trees (three papers) and support vector machines (two papers) and regression-based methods such as generalised linear model (three papers), generalised additive model (two papers) and multivariate adaptive regression splines (two papers).

Fewer studies applied statistical analysis (four papers) and econometric models (three papers) to analyse direct impacts of climate change or climate variability on coffee production, or on changes in pest and disease distribution. Several studies used other modelling methods such as agricultural zoning (two papers) and other types of species distribution modelling (two papers).

While studies using MaxEnt or other bioclimatic modelling approaches have estimated the potential distribution in areas of suitability for coffee production under current and future climates, they have yet to include phenotypic plasticity (Nicotra et al. 2010) or mechanistic processes to predict the responses (Rahn et al. 2018) of the coffee plant to changes in climate or the effect of adaptation measures. For example, the potential influence of carbon fertilisation on coffee physiology as a result of rising carbon dioxide in the atmosphere could, if considered, provide somewhat different results. Elevated carbon concentration might enhance the photosynthetic process and increase yield (Ghini et al. 2015; Rodrigues et al. 2016), potentially mitigating, at least partially, the harmful impacts of warming climatic conditions on coffee yield (Verhage et al. 2017). Thus, projections that failed to take this into account might have over-estimated yield impacts (Rahn et al. 2018). However, Moat et al. (2017) argued that increasing drought stress, together with the potential effects of deforestation on local climate, could outweigh this beneficial influence in the long run. These interactions depend on particular contexts and therefore require further investigation.

The use of mechanistic or process-based models to analyse potential climate-driven impacts on coffee production in current research was limited, being represented by one study (Rahn et al. 2018) which explored responses of the coffee plant to interactions between atmospheric carbon dioxide enhancement, increased temperature and water scarcity and the efficacy of shade management. Mechanistic modelling has been widely applied in agricultural research into the impacts of climate change on the performance of crops such as wheat, maize and rice (Kang et al. 2009; White et al. 2011). Such models could be a valuable approach to better understanding climate change impacts, including the effect of modified microclimate under management practices on coffee production systems, allowing analysis of interactions between climate, soil and coffee plant parameters (Rahn et al. 2018). However, uncertainties may arise where there are insufficient data on coffee performance and ecological conditions for model calibration (Luedeling et al. 2014), which might be the case for many coffee-producing regions.

Correlative species distribution models have been broadly applied to predict potential shifts in the distribution of species under scenarios of future climate (Franklin 2010; Kearney et al. 2010). These methods exclusively focus on geographic distribution and generally involve only location data and corresponding environmental conditions of existing areas (Luedeling et al.

2014; Machovina and Feeley 2013). Future species distribution is projected solely based on the relationship between current distribution assuming to remain constant and climate (Dormann 2007; Thuiller et al. 2005) without taking account of the species' genetic structure and the influence of limiting factors, biotic interactions and other disturbances and processes that may be affected by changing climatic conditions (Evans et al. 2016; Fitzpatrick and Hargrove 2009). Process-based models, on the other hand, are able to capture the dynamics underpinning species distributions across spatial and temporal scales—including physiology, biotic interactions and other factors—under environmental change, and hence can provide more credible projections than species distribution modelling (Evans et al. 2016). Nevertheless, these models generally require many parameters for estimations, thus involve large data requirements which often cannot be met due to limitations at high resolutions (Dormann et al. 2012). Application of process-based models, particularly for planning adaptation of coffee production systems to climate change deserves additional examination.

Current studies on climate change impacts on the suitability of coffee-growing areas use a range of climate models with diverse levels of spatial resolution, ranging from 30 arc-seconds (1 km^2) to 30 arc-minutes (50 km^2), which may explain the wide range of reported estimates. Coarse spatial resolutions may fail to capture local characteristics such as the heterogeneous topography of coffee-growing areas. Uncertainties and errors may increase due to the process of downscaling and interpolating climate projection data (Fain et al. 2018) where agricultural landscapes exhibit topographic heterogeneity (Daly et al. 2003). Low temporal and spatial resolution of climate models also pose challenges in linking climate scenarios to biological responses, including pest or disease development, which entail daily or even hourly data (Ghini et al. 2008, 2011). The use of models with high spatial and temporal resolution would benefit climate impact simulations, facilitating the capture of non-homogenous topographies and thus better representing microclimatic characteristics (Tavares et al. 2018) and reducing uncertainties through the use of more refined climate data (Ghini et al. 2011).

Assessment of uncertainties related to climate variables and scenarios, interpolation processes used for climate projection data, model parameters, socio-economic factors and interactions between the coffee plant and the environment is still limited in current research. Only a few studies (Estrada et al. 2012; Rahn et al. 2018; Verhage et al. 2017) partly or explicitly analysed uncertainty. One suggested solution for minimising uncertainties due to biased representation of suitable climate is to incorporate outputs from a multimodel ensemble to provide improved predictions (Bunn et al. 2015b; Ranjitkar et al. 2016). It should be noted that ensemble modelling, however, might produce incorrect outcomes resulting from errors and biases in the individual species distribution models (Beaumont et al. 2016).

3.4 Impacts of climate variability and change on coffee production

Of all studies investigating the impacts of climate variability and change or drought on coffee production examined in this review, 20 indicated negative impacts and 14 reported mixed results (Table 1). Four papers using qualitative approaches described observed negative consequences on coffee production and on the distribution of pests and diseases, and only one paper presented mixed effects, with perceived declines in Arabica but increases in Robusta yield in India (Chengappa et al. 2017). Quantitative studies, on the other hand, demonstrated more varied results, specifically in projected outcomes under climate change scenarios. However, none of the current studies reviewed suggested wholly positive outcomes.

Of studies on the direct impacts on coffee yield or production, nine papers indicated negative outcomes and five revealed both positive and negative results. Harvest losses due to drought and climate variability were reported mostly in the Americas and could be as much as 70% (Bacon et al. 2017). Fewer studies analysed reductions in coffee production as a result of climate change; such impacts were identified in Tanzania (Craparo et al. 2015), Mexico (Estrada et al. 2012; Gay et al. 2006) and Brazil (Verhage et al. 2017). Studies showing mixed results included positive outcomes of El Niño intra-decadal climate phases on coffee production and exports in Colombia (Bastianin et al. 2018), increases in Robusta yield in India due to climate variability (Jayakumar et al. 2017) and in Arabica yield in Brazil and Nicaragua owing to carbon fertilisation effect (Rahn et al. 2018; Verhage et al. 2017).

In terms of suitability for growing coffee, all relevant studies revealed decreases or losses in areas suitable for coffee. Bunn et al. (2015b) indicated an overall global loss of up to 50% of optimal areas for both types of coffee by 2050, which is in line with other global studies (Bunn et al. 2015a; Ovalle-Rivera et al. 2015) with large parts of major coffee producers such as Brazil, Vietnam, Honduras and India becoming unsuitable. In studies at regional and national levels, the greatest reductions in suitability were projected for Ethiopia, Sudan and Kenya (up to 90% by 2080; Davis et al. 2012), Puerto Rico (84% by 2070; Fain et al. 2018), Mexico (98% by the 2050s; Schroth et al. 2009); and Latin America (88% by 2050; Imbach et al. 2017).

Key drivers of projected shifts in bioclimatic suitability for coffee cultivation are temperature and precipation variables. Global studies indicated that precipitation factors such as annual and seasonal precipitation were of less importance compared with temperatures in determining suitability (Bunn et al. 2015b; Ovalle-Rivera et al. 2015). In contrast, national (Chemura et al. 2016) and sub-national (Rahn et al. 2014) studies revealed that the amount and distribution of precipitation significantly influence coffee suitability. Despite recent improvements in the simulation of changes in precipation patterns, there is currently greater confidence in the ability of climate models to predict surface temperature changes (IPCC 2014). Increasing certainty in predicting future precipitation patterns at all scales will likely improve projections on coffee-favourable areas.

While a majority of existing literature specified substantial reductions in the suitability of coffee-growing areas globally, regionally and nationally, a few papers indicated that, under a changing climate, areas which are currently less optimal for coffee cultivation may become more productive. For example, several studies projected increases in coffee-suitable areas in South America, East and Central Africa and Asia (Bunn et al. 2015b; Magrach and Ghazoul 2015; Ovalle-Rivera et al. 2015; Schroth et al. 2015). Generally, suitability is predicted to shift to higher altitudes by many studies. Globally, Bunn et al. (2015b) indicated that areas at higher latitudes may be less affected while Ovalle-Rivera et al. (2015) suggested that they might decline in suitability, particularly in South America. Some regions projected to be favourable for coffee cultivation are open land such as those in East Africa (Bunn et al. 2015b; Ovalle-Rivera et al. 2015) but others, particularly in the Amazon basin, Asia and Central Africa, are currently under forest cover (Bunn et al. 2015b), protected areas (Schroth et al. 2015) or other agricultural land uses (Magrach and Ghazoul 2015). The continued expansion of coffee production to meet growing global demand (ICO 2019a) might generate economic opportunities in some regions but induce adverse socio-economic and environmental impacts associated with deforestation for coffee cultivation (Gaveau et al. 2009; Meyfroidt et al. 2013) elsewhere. Furthermore, open land at high elevations might be remote (Schroth et al. 2015) or too steep for growing coffee (Bunn et al. 2015a) and operating farming machinery (Tavares et al. 2018) or have soil that is too shallow (Bunn et al. 2015a; Chemura et al. 2016) or poor (Schroth et al. 2015). Shifting coffee-growing areas upslope might also incur conflicts with protected areas with significant ecosystem service values or other land uses with crops in higher demand than coffee (Magrach and Ghazoul 2015). Therefore, the feasibility of offsetting losses from areas with declining suitability by expansion or shifts to 'new' coffee-optimal areas needs additional investigation. Explicit research on future distribution of climatically favourable regions for coffee production which identifies and assesses potential conflicts and trade-offs with existing land uses, particularly at local scales, is required.

Negative results of indirect climate-related impacts on coffee production were reported in all studies on pests and diseases (ten papers), pollination services (one paper) and coffee quality (one paper). These included expected increases in the distribution of pests such as the coffee berry borer (Magrach and Ghazoul 2015) and coffee white stem borer (Kutywayo et al. 2013) and in their reproductive rate (Jaramillo et al. 2011). Diseases such as coffee rust already damaged large parts of production areas in Colombia, Central America and Nicaragua (Avelino et al. 2015; Bacon et al. 2017). There were projected decreases in the incubation period of coffee rust which may result in more severe epidemics (Ghini et al. 2011) and in future pollinator richness in Latin America (Imbach et al. 2017) which may affect coffee production. One study, in Nicaragua, also suggested that the quality of coffee beans may be negatively impacted (Laderach et al. 2017).

In summary, most of the current literature indicates negative consequences of climate change and variability or drought on coffee production. However, positive impacts including increases in coffee yield or in suitability of coffee-cultivating areas, particularly at higher elevations, are also reported on all three coffee-producing continents. Climate change might also bring other advantages, such as growth in pollination activities owing to increasing bee richness (Imbach et al. 2017), resulting in positive effects on coffee yield (Roubik 2002). Some coffee cultivation areas may also benefit from elevated carbon concentration, which may enhance the photosynthetic rate (Trumble and Butler 2009) and heat tolerance of the plant, leading to crop growth and yield improvements (DaMatta et al. 2016; Rodrigues et al. 2016). Further work is needed to investigate the potential of pollination services and carbon fertilisation effect to counteract negative impacts of climate change on coffee production.

3.5 Adaptation measures

Adaptation and management practices were identified by more than 70% of total studies (25 papers), of which agroforestry, either through intercropping or shading, was most common (18 papers), followed by irrigation and efficient use and management of water (12 papers), development of new cultivars that are drought and heat-stress resistant and/or pest and disease tolerant (ten papers) and diversification of cropping patterns or livelihood activities (nine papers) (Fig. 3). Other measures included relocation of coffee plantations to more bioclimatically suitable areas (six papers), crop insurance (three papers), off-farm livelihoods (two papers),and shifts from Arabica to Robusta or cocoa (two papers).

Existing studies indicated that climate variability and change have directly or indirectly affected global coffee production to varying extents, with the majority of these indicating negative impacts. However, most did not quantitatively take account of the influence of adaptation measures which, if adopted, could potentially reduce these impacts. Quantitative analysis of adaptation was limited to just one study which demonstrated the beneficial effects of shade trees on coffee yield at lower elevations (Rahn et al. 2018).

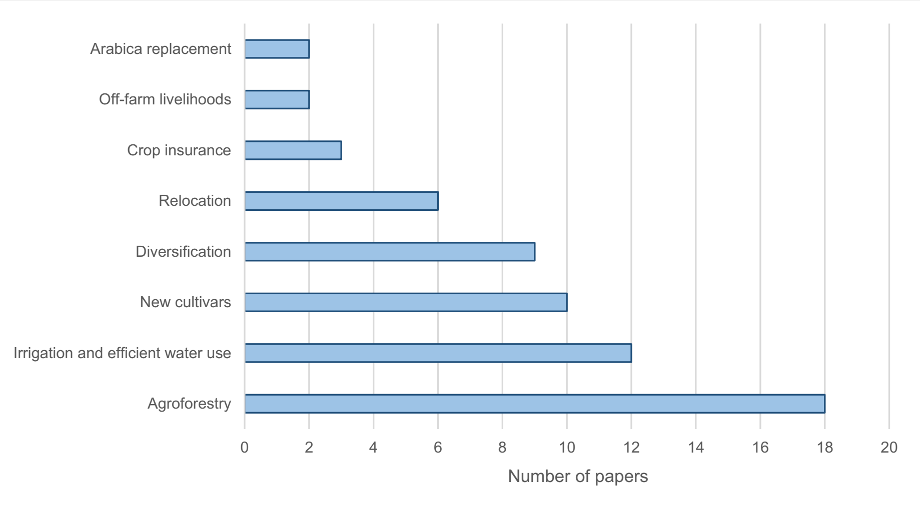

Fig. 3 Adaptation measures considered in the 34 reviewed studies

Relocation of coffee plantations to areas more climatically suitable for cultivation, particularly cool regions at higher altitudes (Laderach et al. 2017), was recommended in a number of studies examining coffee suitability. However, migration to higher elevations might lead to increased pressure on local ecosystems and might be challenged by topography and soil characteristics (Chemura et al. 2016), land tenure rights (Schroth et al. 2009), access to infrastructure (Moat et al. 2017) and ability and willingness of farming communities (Chemura et al. 2016; Magrach and Ghazoul 2015). While high elevations might be more climatically suitable for coffee, additional investigation is needed, with particular attention placed on potential opportunities and challenges, to ensure viable and sustainable coffee development in these areas.

Given the challenges associated with shifting coffee production to more climatically favourable areas, various in situ strategies should be further examined, including irrigation and shading existing coffee plantations to mitigate the adverse impacts of rising temperatures and drought stress and diversification to encourage alternative crops or income sources to assist coffee producers to cope with the impacts of declining coffee yields.

As a result of increasing temperatures and changes in precipitation, irrigation is considered one of the most important adaptive responses in many coffee-growing regions. Optimal use of water may include improved water storage and delivery (Baca et al. 2014; Chemura et al. 2016) through creating tanks and tube-wells and deepening existing bore-wells (Chengappa et al. 2017; Jayakumar et al. 2017) to enable irrigating coffee, particularly during droughts and dry periods. Surface water extraction from rivers and streams might be a cost-effective (Moat et al. 2017) temporary solution but is likely to be constrained during prolonged dry spells or droughts.

Drip, supplemental full or deficit irrigation has been demonstrated to improve coffee quality in Ethiopia (Tesfaye et al. 2013) and productivity in Brazil (Fernandes et al. 2016), especially in periods of water scarcity. However, investment in irrigation infrastructure including storage and transportation systems or in technologies like drip irrigation or water harvesting (Baca et al. 2014; Chengappa et al. 2017) is likely to be resource and labour intensive and costly and thus will be disadvantageous for small growers with limited capital and access to finance (Bryan et al. 2013). Such technological adaptation measures will likely require substantial government or industry support.

Agroforestry systems were mentioned as a potential adaptation strategy for coffee production systems which may benefit from shading or inter-cropping with other crops. Inter-cropping coffee with banana and *macauba*, for example, has proven more profitable than mono-cropping in Africa and South America; such systems reportedly reduce air temperatures and photosynthetic active radiation and increase coffee yield and productivity (Moreira et al. 2018; van Asten et al. 2011).

Shade trees may create a microclimate that provides various socio-economic and ecological benefits, including improved coffee quality (Nesper et al. 2017; Vaast et al. 2006), increased diversity of income sources (Chengappa et al. 2017; Jezeer et al. 2018) and provision of ecosystem services (Cerda et al. 2017; Meylan et al. 2017). Specifically, shading could reduce the mean and maximum air temperatures experienced by the coffee plants compared with full-sun coffee systems (Ehrenbergerová et al. 2017; Moreira et al. 2018), lower wind speeds (Pezzopane et al. 2011) and the risk of landslides (Philpott et al. 2008), enhance pest suppression (Jaramillo et al. 2013) and pollination activities (Jha et al. 2014) and improve soil conservation and water quality (Meylan et al. 2017).

Coffee grown under shade cover, however, might be less productive due to competition with shade trees for water (Ehrenbergerová et al. 2017; Rahn et al. 2018), light (Charbonnier et al. 2013) and nutrients (van Oijen et al. 2010). Additional research into the microclimate dynamics of shade systems, the selection of appropriate tree species, densities and technologies and the interactions between coffee physiology and shade trees under various climatic conditions will be necessary. Shade systems may also vary in their effects (positive or negative) on pests and diseases subject to specific environmental conditions (Jonsson et al. 2015; Liebig et al. 2016). Greater insight into potential synergies and trade-offs in shaded coffee plantations is needed to ensure appropriate responses to climate change in coffee production systems.

Other adaptation measures mentioned in current research involve opportunities to diversify coffee farmers' sources of income—such as off-farm labour, alternative cropping systems including fruit tree production (Bacon et al. 2017) and multicrop cultivation including pepper on shade trees (Chengappa et al. 2017)—and introduction of coffee varieties with better tolerance to high temperatures and pest and disease pressures (Ovalle-Rivera et al. 2015; Schroth et al. 2009). While smallholder farmers, using existing resources, might have the capacity to develop shading systems in coffee plantations and produce a variety of other crops, technological solutions such as development of new cultivars will require significant government or industry investment of capital, labour and expertise. A shift from Arabica to Robusta is recommended for zones at low altitudes in Nicaragua where significant reductions in climatic suitability for Arabica is projected (Laderach et al. 2017) and has been implemented in India to confront coffee white stem borer caused by climate variability (Chengappa et al. 2017). Improved profitability of Robusta in comparison with Arabica owing to its lower cultivation costs and higher yield was reported by Indian producers (Chengappa et al. 2014). Nevertheless, Arabica is considered superior in beverage quality to Robusta and realises higher prices; thus, whether and where it can be replaced by the latter require further examination. Crop insurance against the increased risks of extreme events has been implemented to assist coffee producers in Mexico but with limited success due to inadequate government funding and coordination (Schroth et al. 2009).

In summary, a variety of adaptation measures to manage climate-driven impacts on coffee production are identified in the literature. However, several qualitative studies have indicated that, while most farmers were aware of the impacts of climate on their farming and livelihoods, they were not active in adopting these measures into their management practices (Chengappa et al. 2017; Harvey et al. 2018). Adaptation should be tailored to specific farming conditions and socio-economic contexts and consider the capacity of coffee farmers, who are mostly smallholders, to access finance, credit, resources and technologies. Temporal challenges required for some adaptation measures, such as replanting with new cultivars for heat-stress tolerance and agroforestry systems which might take several years or even decades to become effective (Eske and Leroy 2008; Laderach et al. 2017), should also be taken into account. Raising awareness, building capacity, enhancing knowledge and experience exchange and providing technical and financial support should be emphasised to facilitate adaptation implementation and strengthen farmer resilience to climate variability and change. An integrated approach that incorporates flexible strategies might be required to address interactions between agricultural and ecological aspects of change (Hannah et al. 2017). Finally, a combination of appropriate policy measures, technical solutions and research outcomes and recommendations is crucial to facilitate adaptation processes amongst coffee smallholders.

4 Key conclusions and knowledge gaps

This paper offers a systematic quantitative analysis of the academic literature on the impacts of climate change and variability and drought on coffee production. An array of mostly negative outcomes was found in current studies. These included declines in coffee yield and in areas of suitability for coffee cultivation and increases in the distribution of pests and diseases that indirectly influence coffee production. Globally, indications are that there will likely be a loss of coffee-optimal areas with considerable impacts in major coffee-growing countries such as Brazil and Vietnam. Suitability is generally projected to shift to higher altitudes. Some areas of lower suitability might become more productive in the future but many of them are currently under other crops or forest cover. Investigation is required to evaluate whether gains in coffee-growing niche in ‘new’ areas might compensate for losses with declining suitability in other areas, with particular attention given to trade-offs with existing land uses. Further research on future distribution of coffee-favourable space with consideration to potential ecological and socio-economic impacts and associated opportunities and challenges is necessary to better support sustainable coffee development.

Our selection criteria may have excluded relevant publications from other sources including peer-reviewed literature published in non-English language journals and ‘grey’ literature such as reports and conference proceedings. Despite this, the review reveals some significant knowledge gaps on the topic. These include the disproportionate concentration of current studies in the Americas with less attention given to Asia where a number of countries are amongst the world’s major coffee producers. The predominance of current research in the Americas has drawn more focus of the research on Arabica with limited consideration of Robusta, particularly at national and sub-national scales, and of the influence of climate change on coffee suitability rather than coffee yield or pest and disease distribution. As the risks of pest and disease outbreaks are likely to increase, there is a need for research on these pressures under changing climatic conditions. Further, little research has specifically analysed the impacts of drought on coffee production in contrast to the more extensive literature on the effects of climate variability and change. Apart from relocating coffee plantations to more favourable areas, potential in situ adaptation measures suggested in the literature included agroforestry, irrigation and water management, development of new varieties and diversification of alternative crops or livelihoods. However, quantitative analysis on the effects of adaptation in mitigating climate change impacts was notably absent due to limitations in the modelling approaches applied in the research.

A range of models was employed to investigate the influence of climate change with the majority focused on the distribution of bioclimatic suitability for coffee cultivation, using bioclimatic modelling approaches including machine-learning and regression-based techniques. Due to the limited ability of correlative species distribution models to incorporate underlying factors and dynamic processes and their interactions operating across spatial and biological scales, we suggest further exploration of process-based models for coffee production systems such as those developed and widely applied for wheat, rice and maize. This will generate improved analysis of climate-driven impacts and of the effects of adaptation and management strategies to support decision-making for sustainable coffee production.

Further, increased knowledge is required regarding positive influences on coffee production, including the potential of elevated carbon concentration to offset negative impacts of warmer conditions and of pollination activities.

Finally, there is a need for inclusion of socio-economic factors and detailed analysis of the rationale of suggested response measures along with their quantified benefits in adapting coffee to climate change. While the economic benefits of these measures under changing climatic conditions are uncertain, a thorough evaluation for specific farming contexts will likely be beneficial to coffee farmers. Given the long lifespan of coffee plantations, a focus of research on these issues could mitigate some of the long-term consequences of climate change on the coffee industry and on the livelihoods of many smallholder farmers throughout the tropics.

In total, 34 relevant peer-reviewed journal articles were found and analysed in this review, which is a relatively small number compared with studies on climate change impacts on other crops such as wheat, maize and rice (Challinor et al. 2014; Knox et al. 2016; White et al. 2011). Given the significant contribution of the coffee sector to global socio-economic development, particularly to the livelihoods of millions of smallholders, more research on the climate-driven impacts is required for coffee production systems. This should focus on the direct and indirect effects on yield, particularly in production areas across Asia, on Robusta coffee and on the efficacy of adaption in maintaining the sustainability and viability of the coffee industry.

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