ENVIRONMENTAL RESEARCH
LETTERS

LETTER • **OPEN ACCESS**

Climate risks to Brazilian coffee production

To cite this article: Ilyun Koh *et al* 2020 *Environ. Res. Lett.* **15** 104015

Environmental Research Letters

CrossMark

OPEN ACCESS

RECEIVED
30 December 2019

REVISED
24 June 2020

ACCEPTED FOR PUBLICATION
9 July 2020

PUBLISHED
21 September 2020

LETTER

Climate risks to Brazilian coffee production

Ilyun Koh[1], Rachael Garrett[1,2], Anthony Janetos[1,3] and Nathaniel D Mueller[4,5]

[1] Department of Earth and Environment, Boston University, Boston 02215, United States of America
[2] Environmental Policy Lab, Department of Humanities, Social and Political Science and Department of Environmental Systems Science, ETH Zurich, Sonneggstrasse 33, 8092 Zurich, Switzerland
[3] Pardee Center for the Study of the Longer Range Future, Boston University, Boston 02215, United States of America
[4] Department of Ecosystem Science and Sustainability, Colorado State University, Fort Collins 80523, United States of America
[5] Department of Soil and Crop Sciences, Colorado State University, Fort Collins 80526, United States of America

E-mail: rgarrett@ethz.ch

Keywords: climate change, agriculture, smallholder, vulnerability, Cerrado, Latin America, coffee

Supplementary material for this article is available online

Abstract

Brazil is the world's leading coffee exporter, contributing billions of dollars to the global food economy. Yet, a majority of Brazilian coffee farms are operated by 'smallholders', producers with relatively small properties and primarily reliant on family labor. While previous work indicates that climate change will decrease the area suitable for coffee production in Brazil, no study has assessed the impacts of climate change on coffee yields or the relative exposure and vulnerability of coffee producing regions to changes in climate hazards (climate-associated losses in yield). To address these knowledge gaps, we assess the sensitivity of coffee yields to temperature and precipitation variation from 1974 to 2017 to map coffee climate hazards. Next, we identify which coffee producing regions in Brazil have the highest exposure to climate hazards due to high dependence of coffee production as a proportion of agricultural area. Finally, we generate a Vulnerability Index to identify which regions are theoretically least able to adapt to climate hazards. Our study finds that since 1974, temperatures in Brazilian coffee growing municipalities have been increasing by ~0.25 °C per decade and annual precipitation has been decreasing during the blooming and ripening periods. This historical climate change has already resulted in reductions in coffee yield by more than 20% in the Southeast of Brazil. Minas Gerais, the largest coffee producing state in Brazil, has among the highest climate hazard and overall climate risk, exacerbated by ongoing coffee expansion. Additionally, many municipalities with the lowest adaptive capacity, including the country's mountainous regions, also have high climate exposure and hazards. Negative climate hazard and exposure impacts for coffee producing regions could be potentially offset by targeting climate adaptation support to these high-risk regions, including research, extension, and credit subsidies for improved coffee varieties, irrigation, and agroforestry and diversifying agricultural production.

1. Introduction

Coffee is highly valuable agricultural export for the global South and accounted for US$846 billion of global agricultural export value in 2017 (FAO 2018). Although it is produced in a small area globally (11 million hectares) (FAO 2013), coffee production contributes substantially to foreign exchange in producing countries (Akiyama 2001). In the last two decades, Arabica coffee farmers in Latin America have endured numerous threats to their livelihoods due to plummeting coffee prices, a shift in the power of the supply chain structure away from producers toward consumer-facing companies (i.e. roasters and retailers), and changing rural demographics (i.e. out-migration and an aging population (Bacon 2005)). Coffee farmers in many regions now face the risk of declining coffee yields and quality due to global changes in temperature and precipitation (Gay *et al* 2006, Schroth *et al* 2009, Zullo *et al* 2011). Given the already low profit margins (and low farm-gate prices) associated with coffee production (Bacon

2005), declines in coffee yields could make existing coffee producing regions both economically and biophysically unsuitable for production in the future (Zullo *et al* 2006, de Sousa *et al* 2019).

The most suitable growing regions for Arabica coffee are where the annual temperature average is between 18 °C and 22 °C (Camargo 1985b) and in mountain regions where the altitude is above 1000 or 1200 m (Schroth *et al* 2015). Both very high and very low temperatures can result in yield and quality losses (Zullo *et al* 2011c, Camargo 1985b). Climate change is expected to alter temperatures and precipitation, and increase extreme events in many coffee producing regions throughout the world (Läderach *et al* 2010, Ovalle-Rivera *et al* 2015). These impacts will undoubtedly compound the economic and demographic challenges currently faced by small-scale coffee farmers.

Throughout the world, there is increasing evidence that coffee farmers are already suffering from the impacts of climate change (Baker and Haggar 2007, Haggar 2016). In their study of Mesoamerican coffee producing regions, Läderach and co-authors concluded that by 2050, changes in temperature and rainfall will decrease the area suitable for coffee production by at least 40% (Läderach *et al* 2010). In Brazil, the world's largest Arabica and Robusta coffee producing region, climate change is predicted to substantially reduce the amount of suitable area for production (Zullo *et al* 2006). In the Brazilian state of São Paulo, for example, the proportion of climatically low-risk areas for coffee production may decrease by ~20% by 2050 under a 1 °C increase in temperature relative to the current climate and as much as 75% under a 5.8 °C increase (Coltri *et al* 2012). A majority of the 308 000 coffee farms in the country are operated by 'family' (or smallholder) farmers,[6] who are potentially less capable of adapting to changes in temperatures and precipitation (IBGE 2017a). In the absence of adaptation, these shifts in climatic suitability are likely to substantially reduce coffee farmers' incomes and potentially force them to abandon production.

In this study, we assess the relative climate risk of coffee producing regions in Brazil through the concepts of hazard (potential harms to humans, infrastructure, and ecosystem services), exposure (the presence of humans, infrastructure, and ecosystem services in places that experience hazards), and vulnerability (the propensity of a system to be negatively affected by hazard) as defined by the IPCC (IPCC 2014). The intersection of climate hazards, exposure, and vulnerability influences the level of risk that a community faces. Where risk is high, it is very likely that losses in well-being will occur if steps are not taken to reduce risk, either by reducing exposure to the hazard or by increasing communities' ability to adapt to the changes induced by the hazard.

The impacts of climate hazard on crop yields, particularly annual crops, are becoming increasingly well understood (Knox *et al* 2012). Yet, the impacts of climate hazard on farmers' livelihoods are more difficult to assess due to a lack of longitudinal data about changes in rural livelihoods. Despite these data limitations, snapshots of the material measures of farmer livelihoods and broader socio-economic conditions do exist and can be used as a proxy to assess farmers' potential adaptive capacity in each region. Once potential adaptive capacity is assessed, it is possible to understand the degree to which high climate hazards and exposure are likely to overlap with high vulnerability. In regions where there is high overlap between hazards, exposure, and vulnerability, additional institutional support for climate adaptation will be most urgently needed.

To date, few studies have combined analysis of hazards, exposure, and risk at broad spatial scales. Nor have any studies in Brazil focused on identifying the relative vulnerability of different coffee communities and how it intersects with climate hazards and exposure. To contribute to this knowledge gap, our paper has two aims (i) *to assess spatial and temporal variations in climate hazards, exposure, and vulnerability* and (ii) *to identify which regions have the highest overall climate risk (overlap between high hazards, exposure, and vulnerability).*

To identify regions where coffee communities are most at risk to climate change, our methodological approach combines: (i) econometric modelling of the historical relationship between climate and coffee yield (*climate hazard*), (ii) mapping of coffee prevalence (*climate exposure*), and (iii) newly developed municipal-level estimates of relative *climate vulnerability*, based on underlying socio-economic characteristics. To draw inferences for the future, our analysis focuses on changes in the overlap of hazards, exposure, and vulnerability over time (2006 and 2017) and space (coffee producing municipalities in Brazil) using all available historical data.

2. Existing empirical work on climate risk

Many studies have analyzed climate hazards through the lens of potential impacts on crop yields. These studies draw on panel statistical models of historical weather data to explain the relationship between climate change and crop production at the global, national, and regional level, particularly for individual annual crops (Lobell and Field 2007, Schlenker and Roberts 2009, Schlenker and Lobell 2010, Butler

[6] The legal definition (Lei 11.326/2006) of an 'agricultor familiar' is an agricultural producer with a property that: (i) is less than four fiscal/tax modules in size, (ii) relies primarily on family labor, (iii) meets a certain minimum threshold of how much income they derive from their farm, and (iv) runs the farm with their family. The specific size of a fiscal module varies across municipalities and the threshold for income is defined by the executive branch (IBGE 2017a).

and Huybers 2015). To date, the focus of most climate and agriculture studies has been annual crops, such as maize, wheat, and rice, which are critical to global food security (Knox *et al* 2012). There are fewer studies of perennial species, which occupy less area globally, yet represent an integral component of many rural livelihoods (Samberg *et al* 2016, Hong *et al* 2020).

The existing literature on coffee-related climate change impacts and risks focuses heavily on ecological niche modelling, often coupled with machine learning techniques, to identify transitions in the suitability of regions for coffee production (Davis *et al* 2012, Ovalle-Rivera *et al* 2015, Schroth *et al* 2015, Bunn *et al* 2015, Pham *et al* 2019). Relatedly, several studies determine changes in climate risk by assessing to what degree future climate projections fall out of the optimal temperature or water deficit range, and exceed the frost probability threshold (Zullo *et al* 2006, 2011c, da Silva Tavares *et al* 2018). Statistical assessments of the impacts of historical changing temperatures and precipitation on coffee yields are limited and thus far constrained to India, Mexico, and Tanzania (Gay *et al* 2006, Craparo *et al* 2015, Jayakumar *et al* 2016). These studies in India, Mexico, and Tanzania all found significant negative yield impacts from increasing temperatures and decreasing rainfall (Gay *et al* 2006, Craparo *et al* 2015, Jayakumar *et al* 2016). To date no paper (to the best of our knowledge) has empirically examined the relationship between historical changes in coffee yield and historical climate change in Brazil. Instead, existing research on the impacts of climate change on coffee production in Brazil has focused on simulating potential changes in yields (Verhage *et al* 2017) and climate zoning (Zullo *et al* 2006, 2011, da Silva Tavares *et al* 2018).

The concepts of vulnerability and risk encompass a wide variety of potential components, many of which are difficult to measure, and few of which have been analyzed for causal impacts. Given these challenges, one leading empirical approach to both vulnerability and risk research has been to develop quantitative indices that vary over space and time (Cutter *et al* 2003, Cutter and Finch 2008, Hahn *et al* 2009, Cutter *et al* 2010, Gbetibouo *et al* 2010, Pandey and Jha 2012, Shah *et al* 2013, Ahsan and Warner 2014). These indices are based on existing theory and available data and provide estimates based on a range of variables that are theoretically likely to influence societies' ability to prepare for or adjust and respond to stress and mediate risk. By quantifying the conditions and assessing the variations in a single metric, indices are particularly useful for comparing the relative levels of social vulnerability over time and space (rather than absolute vulnerability). For work that spans larger geographical areas, rather than individual communities, vulnerability and risk research has highlighted the importance of the attributes of place, and thus many indices focus on the aggregate social aspects of a geographical location (Cutter 1996, Cutter *et al* 2003).

Given that overall risk encompasses both physical stress and human's capability to adapt, vulnerability indices tend to include both physical or socioeconomic data (Harlan *et al* 2006, Johnson and Wilson 2009). Whereas specifically 'social' vulnerability indices (e.g. Cutter *et al* 2003, Cutter and Finch 2008) encompass only socioeconomic and geographical characteristics. Since climate hazard and exposure are measured seperately, our vulnerability index focuses on the socio-economic dimensions of vulnerability. The interplay of climate hazard, exposure, and vulnerability then determine overall climate risk—the likelihood that climate hazards will negatively impact human well-being.

3. Methods

3.1. Study region

Our analysis centers on the South, Southeastern, and Center-west coffee producing states of Brazil (Goiás, Mato Grosso do Sul, Paraná, Minas Gerais, São Paulo, Rio de Janeiro, Bahia, and Distrito Federal), which produce approximately 90% of the country's Arabica coffee (IBGE 2017b) (figure 1). This region is expected to encounter substantial changes in climate; mean annual temperature is expected to increase by 4 °C in the summer and 2 °C to 5 °C in the winter by 2100 in the RCP 8.5 emissions scenario (Pachauri *et al* 2014). Higher temperatures are expected to reduce coffee bean quality and generate more favorable conditions for pests and diseases. Under all scenarios, the ideal climatic conditions for coffee production are expected to shift to the south of Brazil (Zullo *et al* 2011). Our unit of analysis is all of the municipalities in this region that produce coffee and have data for all variables of interest ($n = 935$). This is the smallest spatial scale at which socioeconomic data are available across the study region.

3.2. Assessing climate risk

Our methodological approach for determining overall risk follows the conceptual approach of the IPCC (IPCC 2014)—a score for overall risk defined as the sum of individual estimates of climate hazards, exposure, and vulnerability:

$$\text{Risk} = \text{Hazard} + \text{Exposure} + \text{Vulnerability}. \quad (1)$$

To generate this overall risk score, the estimates of hazard, exposure, and vulnerability, explained below, are converted into indices along a uniform scale (1–5) using Jenks natural breaks and then summed (resulting in a total value ranging from 0 to 15). We also present results using breaks defined by Equal Weights Intervals and Quantiles.

Figure 1. Study region—major coffee producing states of Brazil (Goiás, Mato Grosso do Sul, Paraná, Minas Gerais, São Paulo, Rio de Janeiro, Bahia, and Distrito Federal).

3.2.1. Climate hazard

To measure climate hazard, we examine how historical changes in precipitation and temperature have influenced coffee yields. We used global gridded (0.25 degree) monthly average air temperature and total precipitation data from 1974 to 2017 (the period for which we also have data on municipality-level coffee yields) by Willmott and Matsuura.[7] This dataset interpolates weather station data and is drawn from recent versions of the Global Historical Climatology Network (GHCN version 2) and the Global Surface Summary of Day archive. The version of the temperature and precipitation data are 1900–2017 Gridded Monthly Time Series V 5.01. From the dataset, the gridded data are averaged across each coffee growing municipality.

We average the gridded climate data at the municipality level for each coffee phenological season. Given the differential exposure of coffee to weather fluctuations across different phenological stages (Camargo 2010), we separate out the blooming (September to November), ripening (December to May) and harvesting periods (June to August) for coffee plants in the study region. The blooming period is the time where coffee flower bud blooms, initiated by the first rains after the dry season (Barros *et al* 1999). During the blooming period, high temperatures coupled with a lack of rainfall can impact coffee flower buds (Camargo 1985a). High temperatures (above 23 °C) are also thought to be detrimental during the ripening period (when the coffee beans develop and mature) and harvesting period, by influencing both yield and quality (Camargo 1985a). Finally, excess rain during the harvest period can inhibit optimal harvesting.

The historical relationship between coffee yield, temperature, and precipitation is examined using the following panel econometric model:

$$\begin{aligned} Log(Yield)_{it} = {} & Tmp\_blooming_{it} + Tmp\_ripening_{it} \\ & + Tmp\_harvesting_{it} \\ & + Tmp\_blooming^2_{it} \\ & + Tmp\_ripening^2_{it} \\ & + Tmp\_harvesting^2_{it} \\ & + Log(Pcp\_blooming)_{it} \\ & + Log(Pcp\_ripening)_{it} \\ & + Log(Pcp\_harvesting)_{it} \\ & + Log(Pcp\_blooming^2)_{it} \\ & + Log(Pcp\_ripening^2)_{it} \\ & + Log(Pcp\_harvesting^2)_{it} \\ & + municipality_i + year_t + state\_trend_j \end{aligned} \quad (2)$$

where *Log(Yield)* is the log of coffee yield (kg per hectare) in municipality i and year t, which spans from 1974 to 2017. *Tmp_* is the average monthly temperature and *Log(Pcp_)* is the log of the average monthly precipitation during a particular season. Both the yield and precipitation variables are highly non-normally distributed. This non-normal distribution leads to heteroscedasticity in the relationship between precipitation and yields. To avoid this problem, we log-transform both variables, including the squared precipitation terms. The temperature variables are normally distributed so they are not log-transformed. We included *municipality* and *year* fixed effects, as well as a state (j) time trend, to control for unobserved, non-climatic factors influencing yields.

Predicting yield on climate factors may be too complex to describe using only linear relationships (Watson 1963). Using the Ramsey RESET test, which tests whether the model is missing important nonlinearities, we confirmed that the results supported the use of quadratic terms for average temperature and precipitation to specify a quadratic functional form. In addition, a quadratic functional form generates optimum values by calculating the highest point in the curve and enables better modeling of crop yield responses to climate variables (Gay *et al* 2006).

We conducted a Hausman test to test whether fixed effects or random effects are more suitable for the panel data analysis. The p-value is significant at the 99.9% level, supporting the use of fixed effects. We include municipality fixed effects to account for unobservable spatial variation and time-invariant effects such as soil type and elevation (Welch *et al* 2010, Blanc and Schlenker 2017). This makes the model less prone to omitted variable bias because

[7]http://climate.geog.udel.edu/~climate/html_pages/download.html#ghcn_T_P_clim.

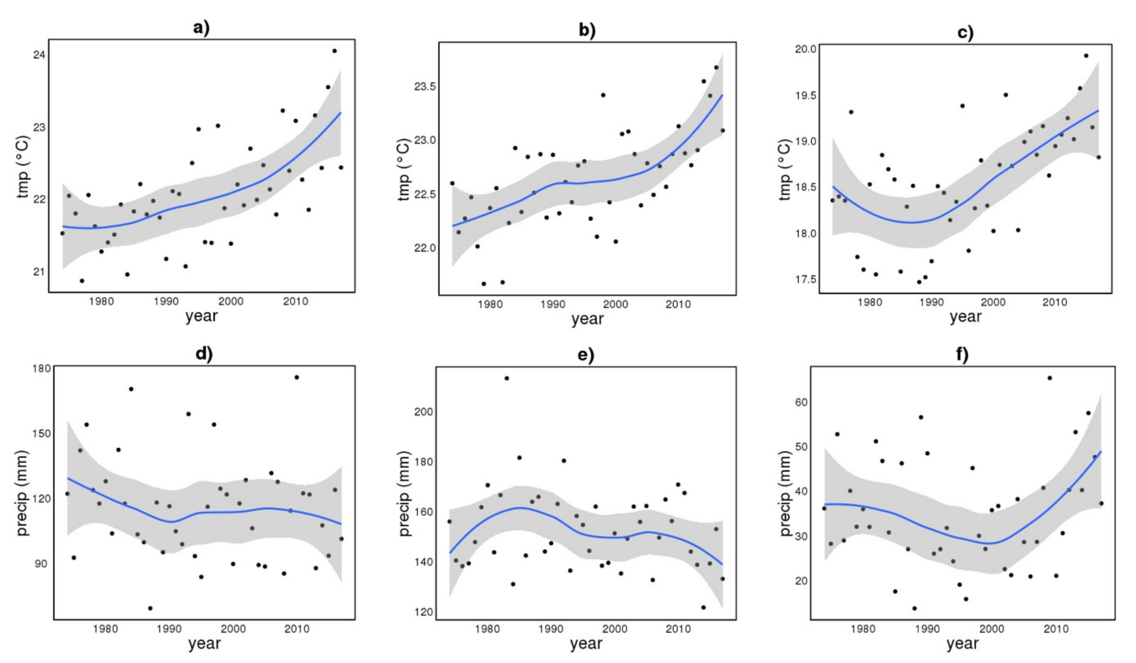

Figure 2. Historical temperature (top panel, a-c) and precipitation (bottom panel, d-f) trends for the blooming period (a), (d), ripening, (b), (e), and harvesting period (c), (f) between 1974 and 2017. The regression line for the point data is indicated in blue, with a confidence band of 95% in grey shading.

the unobserved factors that influence yield are controlled. Additionally, the model estimators of the fixed effects enable consistent estimation of the effect of independent variables. Likewise, a year fixed effect is added to control for time-varying shocks, such as macroeconomic factors. After conducting a joint test to find whether the dummies for all years are equal to 0, the F test was significant at 99.9% confidence level, suggesting that year fixed effects are needed. Lastly, a state- trend is used to control the broad regional productivity improvements that may be occurring due to technological change or changes in economic policies. The state-specific technological trends control the long-term trends in yields unrelated to weather variability.

The climate hazard of each municipality is then defined by combining our coffee yield model with historical trends in climate, following existing approaches to calculate the impacts of historical climate trends on yield (Lobell *et al* 2011, Butler *et al* 2018). First, for each municipality, we calculated the temporal trends in temperature and precipitation within each phenological stage using a linear regression. We then identify the net yield impacts of these climate trends by using Eq. 2 to model yields at the beginning and end of our 44-year period, given state-year yield trends. The difference in predicted yields due to climate is defined as the climate hazard, with more negative yield impacts indicative of a greater climate hazard. A limitation of this approach is that it relies on a deterministic model of climate-yield impacts, which may not be as suitable as a flexible time series approach for capturing climate-yield relationships, given the heterogeneity in coffee yield trends and variability across Brazilian states (figure S1 (available online at stacks.iop.org/ERL/15/104015/mmedia)) (Agnolucci and De Lipsis 2020).

3.2.2. Climate exposure

Our definition of climate exposure focuses on the presence of rural livelihoods in places that are likely to incur climate hazards. In case of rural coffee producing communities in Brazil, their exposure to climate hazards is proxied by the prevalence of coffee production in that region. As a whole, municipalities with a large coffee cultivation area as a proportion of their total area are likely to be more exposed to changes in climate that impact coffee yields than municipalities where coffee production occupies only a small proportion of the agricultural area. To map exposure, we generated a variable called coffee prevalence, defined by the percentage of agricultural area that is in coffee production using agricultural census data from the Brazilian Institute for Geography and Statistics for both 2006 and 2017.

3.2.3. Climate vulnerability

Here we develop a Vulnerability Index (VI) to characterize spatial variability in factors likely to influence communities' propensity to be negatively affected by climate change, following several prior studies (Cutter *et al* 2003a, 2010, Cutter and Finch 2008, Hahn *et al* 2009, Gbetibouo *et al* 2010, Pandey and Jha 2012, Shah *et al* 2013, Ahsan and Warner 2014). Prior social VIs have included age, race, health, income, type of dwelling unit, employment of people living within a region, but are not specific to rural or agricultural vulnerability. In our study, we develop a VI that focuses on variables for which there is a clear causal pathway linking the condition to the ability of people in rural communities to prepare for, respond to, or adapt to climate stresses. Due to data availability, our analysis focuses on average levels of vulnerability at the municipality level (aggregate statistics of individual households within each municipality) in regions where coffee is grown.

The factors considered in our VI include average household and property conditions (age, knowledge and social capital, technology, and household and farm economy), as well as regional conditions (infrastructure and yields) in 2006 and 2017. The data source for the household and property conditions is the Brazilian Agricultural Census (table S2), while infrastructure comes from OpenStreeMap and yields from the Brazilian Agricultural Municipal Surveys. Variables included in the VI were selected based on their theoretical and empirical impacts on vulnerability or its sub-components, from previous studies (Kellerman 1983, Hahn *et al* 2009, Pandey and Jha 2012, Shah *et al* 2013, Garrett *et al* 2013). Specific justifications for each variable in the index are included in the SI.

To generate the VI from these six groups of variables, we use a composite index approach, whereby sub-components are first normalized and then averaged at the group level (i.e. major component) and then each group is averaged into a single index value. The composite approach is a standard way of achieving a single numerical value when the amount of data per group is unbalanced. It also allows the user to weight each group differently based on their theoretical importance. This approach was chosen over a PCA approach due to the small number of candidate variables and the low correlation between them. The SI discusses the justifications for the weightings used in the main text results, as well as the results of a sensitivity analysis using different weightings. The sensitivity analysis indicates that both weightings produce the same distribution of relative vulnerability over space, except that municipalities in Rio de Janeiro have an even higher relative vulnerability using an equal weights method over an approach that more heavily weights baseline yields and household assets (figure S3).

3.3. VI validation

To assess how well the VI is picking up important socioeconomic variability for coffee production in each municipality we examined its relationship to the unexplained variance in the yield model (after controlling for climatic factors). The results, which indicate a moderate positive relationship between the VI and unexplained yield variance, are explained in the SI.

4. Results

4.1. Climate hazard

Since 1974, temperatures in Brazilian coffee growing municipalities have been increasing by ~0.25 °C per decade (figures 2 (a)–(c)). Annual precipitation has been decreasing during the blooming and ripening period, and until 2002 during the harvesting period as well (figures 2 (d)–(f)). However, since 2002 precipitation during the harvesting period has been increasing (figure 2(f)). This recent trend may help offset the increasing temperature, sustaining the development of coffee beans and preventing cherries from ripening too soon during the dry season.

Municipalities in the north of the study region (Bahia, northern Goiás, and Minas Gerais) have the highest mean temperature. Since 2010 mean temperatures in this region have frequently exceeded the optimal range for Arabica coffee (>23 °C). During the flowering period temperatures in all states increased by more than 1.2 °C. In Bahia, Minas Gerais, and São Paulo these large increases in temperature were coupled with large decreases in rainfall (>10% decrease).

Like past studies of annuals, we found that temperature and precipitation increase yields up to a point, but then detrimentally influence yields (table S1). This concave relationship is constrained to the blooming and ripening period. This supports the hypothesis that excessively high temperatures coupled with a lack of rainfall can inhibit both the initial flower budding and the development and maturing of ripening beans. During the harvest period, temperatures had a weakly convex relationship with yields (the linear term was significant, large and negative, while the squared term was significant and positive, but very small). This suggests non-linearly increasing benefits to cooler temperatures during the coffee harvest period, which contradicts established agronomic understanding of temperature-yield relationships and may reflect a limitation of the model's structural form. Precipitation had a monotonically positive relationship with yields.

The net impact of climate trends since 1974 have been negative overall, with the biggest impacts concentrated in Minas Gerais. The average yield loss ranged from 9% to 29% across the study region. The differences in climate hazard across individual municipalities within each state are separated into quantiles and mapped in figure 3 for climate trends from 1974 to 2006 and 1974 to 2017.

4.2. Climate exposure

Municipalities with the highest coffee climate exposure are clustered in Minas Gerais (figure 3). This state has the highest ratio of coffee area as a proportion of crop area. Between 2006 and 2017, climate exposure

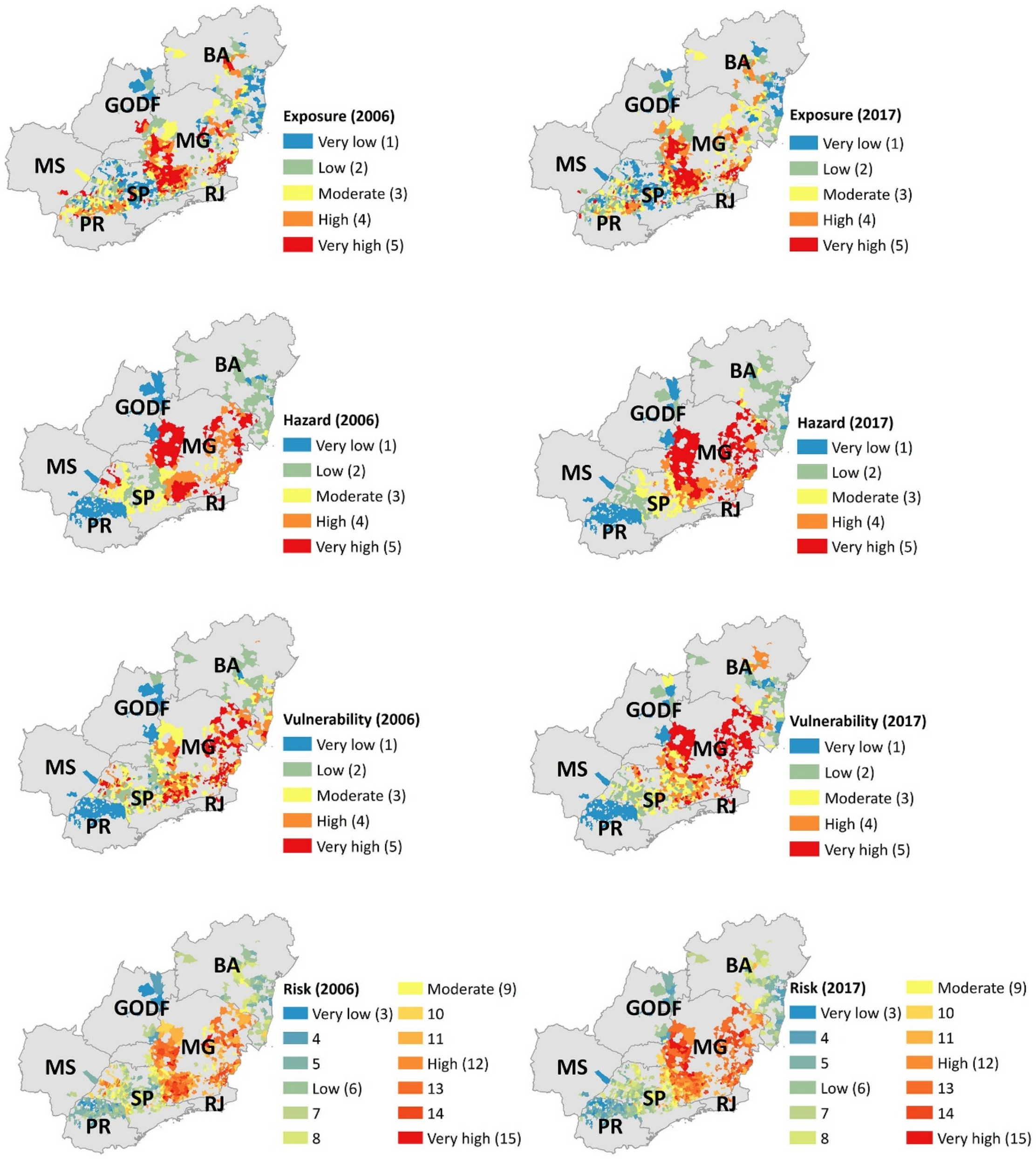

Figure 3. Climate risk by component (top three panels) and cumulative risk (bottom panel) for each coffee producing municipality in 2006 (left) and 2017 (right). There are 935 municipalities in the study region with data for all variables across both time periods. Grey areas indicate municipalities that do not produce coffee or were missing data and were not included in the study. BA = Bahia, DF = Federal District of Brazil, GO = Goiás, MG = Minas Gerais, MS = Mato Grosso do Sul, PR = Paraná, RJ = Rio de Janeiro, SP = São Paulo. The classes (and associated scores) presented here were created using quantiles to transform the continuous data for each component. The use of quantiles was more illustrative then other methods, e.g. Jenks natural breaks and equal length intervals, as quantiles maximized the variation across municipalities.

in the southern region of Brazil, including Paraná and São Paulo, decreased because these states have been diversifying their cropping systems and reducing their reliance on coffee.

4.3. Climate vulnerability

On average, we observe that northern municipalities in Minas Gerais, and Rio de Janeiro have the highest vulnerability due to lower baseline coffee yields, knowledge and social capital, and access to technical assistance, as well as poor transportation infrastructure (figure 3) (see SI, figure S2 for more details). These results are largely robust to an alternate component weighting method that treats weights for household age structures and local infrastructure as equal to social, knowledge, and financial household assets and yields. Only the relative vulnerability of Rio de Janeiro is systematically different under the two methods (figure S3). Under the equal weighting scheme, the relative vulnerability in Rio de Janeiro would be lower.

4.4. Overall risk (overlap of climate hazard, exposure, and vulnerability)

We find that Minas Gerais and Rio de Janeiro have the highest mean risk under all classification systems

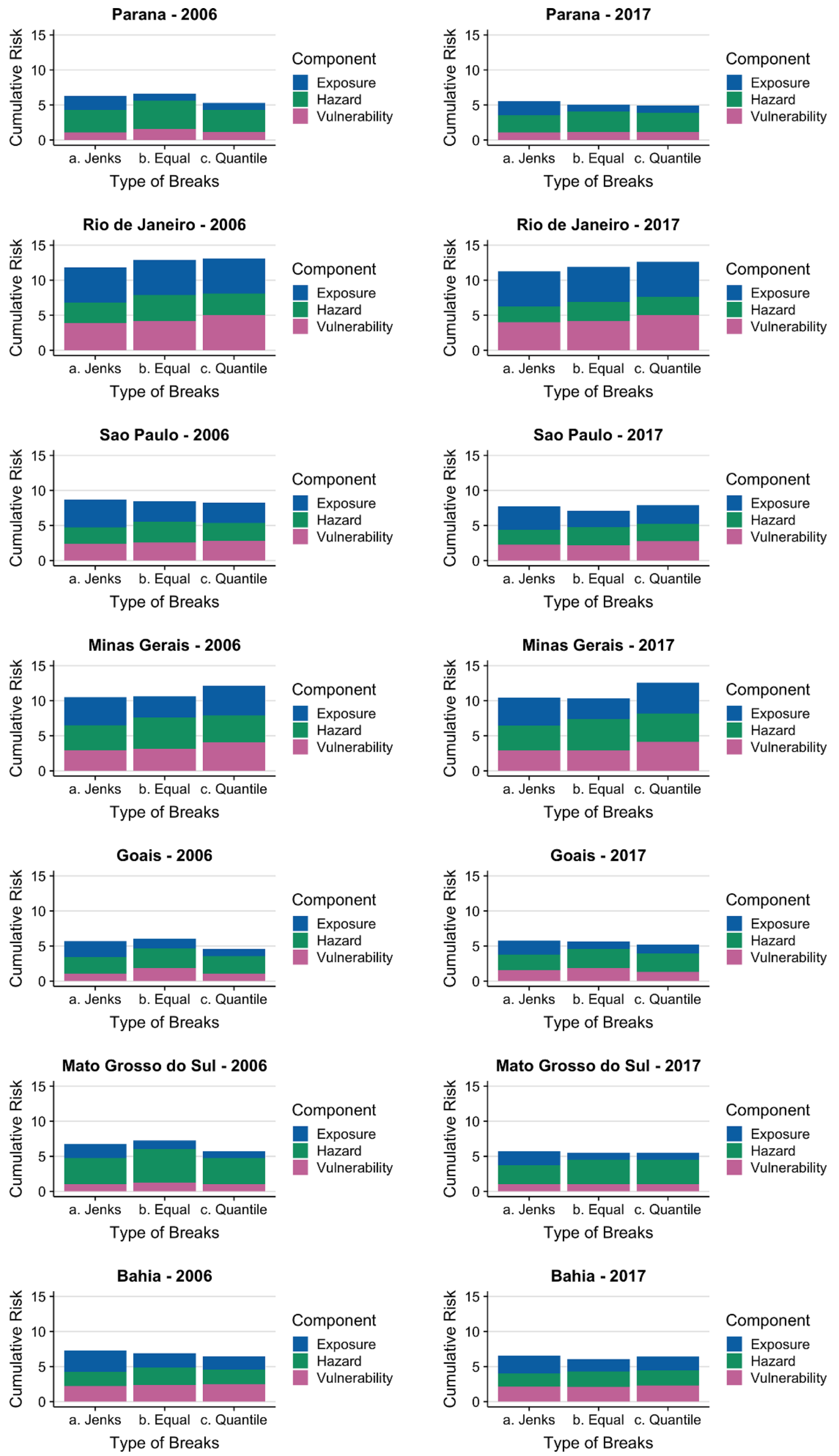

Figure 4. Mean state climate risk in 2006 and 2017 by classification method (Jenks natural breaks, equal intervals, and quantiles) and component (hazard, exposure, and vulnerability). Overall risk declined between 2006 and 2017 in nearly all regions, largely due to decreases in exposure (reduced dependence on coffee production as a rural livelihood).

due to the combination of high exposure, hazard, and vulnerability (figures 3 and 4). Paraná and Goaís have the lowest mean climate risk due to a combination of low exposure, hazard, and vulnerability.

Cumulative risk decreased in all states except for Goiás and Minas Gerais, largely due to decreases in exposure. This decline in risk is accentuated when equal length intervals are used (shown in

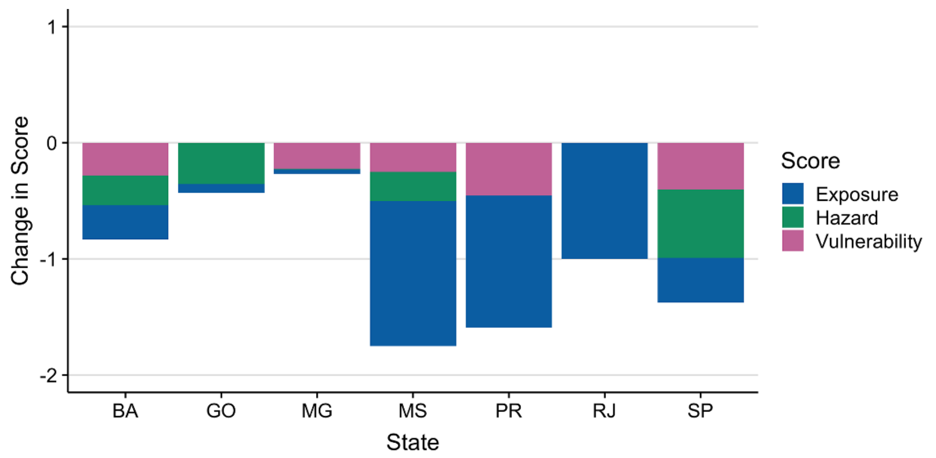

Figure 5. Change in mean state climate risk between 2006 and 2017 by component (hazard, exposure, and vulnerability) using the equal length interval classification. Equal length intervals are displayed because they produced the greatest changes between 2006 and 2017. BA = Bahia, DF = Federal District of Brazil, GO = Goiás, MG = Minas Gerais, MS = Mato Grosso do Sul, PR = Paraná, RJ = Rio de Janeiro, SP = São Paulo.

figure 5). Since each component of risk is a relative score, this means that the number of municipalities that fell into moderate to very high vulnerability and hazard classes in most states decreased over time. Decreases in mean climate exposure were partially offset by increases in vulnerability in several states. Risk decreased the most in Mato Grosso do Sul and Paraná through reductions in exposure.

5. Discussion and limitations

While prior climate zoning studies forecast major reductions in the area suitable for Arabica coffee production in Brazil by 2050 (Zullo *et al* 2006, 2011), our study shows that historical climate change is already having a substantial negative impact on yields. However, this climate hazard is not evenly distributed. Worryingly, it is concentrated in the Southeast of Brazil, including Minas Gerais, the region with the highest Arabica coffee production. Little adaptation has occurred in the form of reducing exposure by diversifying away from coffee production. In contrast, the states in Brazil that had the *lowest* climate hazard did reduce their exposure to climate hazards via agricultural diversification.

Differences in all aspects of climate risk mirror biophysical conditions and rural development levels. Many of the mountainous regions in Brazil, which have the highest climate risk, rely heavily on coffee production as a farming activitiy due to the high slope, lack infrastructure and rural services, and lack of other economic development opportunities (Watson and Achinelli 2008). Mountainous regions also tend to experience more dramatic shifts in climate than flatter areas, explaining higher climate hazards (Diffenbaugh and Giorgi 2012).

Yet, our municipality-level estimates of climate hazards and vulnerability may not accurately represent the conditions for all farms in each region. Across all data sources, the mismatch between sub-municipal areas and municipal averages is likely to be larger in regions with greater variation in altitude, orientation, slope, road density, and distance to municipal centers. Additionally, measurement error, particularly with respect to the agricultural censuses, may be larger in more remote regions where it may not be possible to interview all farmers. Another limitation of this work is that it relies heavily on existing understanding of the correlates of climate vulnerability in rural regions to construct the vulnerability index. In much of Brazil, and for coffee specifically, the causes of climate vulnerability are poorly understood. Future studies should supplement this research by analyzing the mechanisms underlying coffee farmers' vulnerability, including through in-depth field interviews.

Since livelihood risks are not constrained to a single crop, future work should examine climate risks across the whole livelihood portfolio of rural households, including off-farm activities. Climate hazards may damage people's ability to maintain or secure material assets and resources, as well as their ability to live a 'good life' in other ways, including non-material goals (Chambers 2013). However, it is also possible that climate change could create new opportunities for regions that become more favorable for coffee farming or new crops, such as cocoa (de Sousa *et al* 2019). Further in-depth fieldwork is urgently needed to investigate these issues in the Brazilian context.

6. Conclusion

In this study we sought to quantitatively assess the spatial and temporal variation in the climate risk of coffee communities in Brazil. Unlike past work, we measure climate hazard, exposure, and vulnerability independently and then identify where they overlap to increase overall risk. This approach allows us to assess which regions have the highest overall risk, as well as the major sources of that risk.

Our study finds that since 1974, temperatures in Brazilian coffee growing municipalities have been increasing by ~0.25 °C per decade and annual precipitation has been decreasing during the blooming and ripening periods. This historical climate change has already resulted in reductions in coffee yield by more than 20% in the Southeast of Brazil. The Southeast, particularly Minas Gerais, is the largest coffee producing region in Brazil, so this high climate hazard translates into high overall climate risk for much of the country's core coffee producing regions. In the mountainous Brazilian highlands, where farmers are generally poorer and more disconnected from markets, the risk posed by high climate hazards and exposure is exacerbated by high vulnerability.

Our results provide useful information for the targeting of agricultural policies and climate planning. They indicate that federal and civil society efforts to prepare for climate change in coffee production regions should focus on Minas Gerais, where a majority of production occurs, rural economic dependence on coffee is very high, and climate hazards and vulnerability are the highest. Minas Gerais has already experienced high climate hazards from rising temperatures and declining precipitation in the blooming and ripening period. Improved coffee varieties, agricultural loans for irrigation and agroforestry might enable coffee farmers to maintain or improve their yield under climate hazard, while infrastructure development and capacity building within existing cooperatives could help increase access to higher value marketing opportunities to offset lower yields. Given its high climate vulnerability, but lower hazard, climate adaptation strategies for the more mountainous Eastern Minas Gerais could focus on broader development interventions, such as improved services, infrastructure, and market access. In contrast, climate adaptation strategies in Southwestern Minas Gerais would be better off focusing on diversifying production, off-farm income diversification, increasing access to irrigation, or expanding climate-related crop insurance.

Acknowledgments

We thank the three anonymous reviewers for their careful comments, which substantially improved the manuscript. This work would not have been possible without the generous contributions of our co-author Anthony Janetos, who sadly passed away earlier this year. We further thank Mark Friedl, Anne Short Gianotti, Robert Kaufmann, and Ian Sue Wing for their suggestions and comments on earlier versions of this research. This research was supported by the Fulbright Foundation NEXUS Program for the Western Hemisphere, the Summer Fellows program at the Boston University Fredrick S. Pardee Center for the Study of the Longer-Range Future and the Boston University Global Development Policy Center Land Use and Livelihoods Initiative.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID iDs

Rachael Garrett https://orcid.org/0000-0002-6171-263X
Nathaniel D Mueller https://orcid.org/0000-0003-1857-5104

References

Agnolucci P and De Lipsis V 2020 Long-run trend in agricultural yield and climatic factors in Europe *Clim. Change* **159** 385–405

Ahsan M N and Warner J 2014 The socioeconomic vulnerability index: a pragmatic approach for assessing climate change led risks–a case study in the south-western coastal Bangladesh *Int. J. Disast. Risk Reduct.* **8** 32–49

Akiyama T 2001 Coffee market liberalization since 1990 *Commodity Market Reforms: Lessons of Two Decades* pp 83–120

Bacon C 2005 Confronting the coffee crisis: can fair trade, organic, and specialty coffees reduce small-scale farmer vulnerability in Northern Nicaragua? *World Dev.* **33** 497–511

Baker P and Haggar J 2007 Global warming: the impact on global coffee; presentation handout (SCAA)

Barros R S, Maestri M and Ab R 1999 Physiology of growth and production of the coffee tree-a review *J. Coffee Res.* **27** 1–54

Blanc E and Schlenker W 2017 The use of panel models in assessments of climate impacts on agriculture *Rev. Environ. Econ. Policy* **11** 258–79

Bunn C, Läderach P, Jimenez J G P, Montagnon C and Schilling T 2015 Multiclass classification of agro-ecological zones for Arabica coffee: an improved understanding of the impacts of climate change *PLoS One* **10** e0140490

Butler E E and Huybers P 2015 Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase *Environ. Res. Lett.* **10** 034009

Butler E E, Mueller N D and Huybers P 2018 Peculiarly pleasant weather for US maize *Proc. Natl. Acad. Sci.* **115** 11935–40

Camargo A D 1985a O clima ea cafeicultura no Brasil *Inf. Agropec.* **11** 13–26

Camargo Â P 1985b Florescimento e frutificação de café arábica nas diferentes regiões (cafeeiras) do Brasil *Pesqui. Agropec. Bras.* **20** 831–9

Camargo M B P D 2010 The impact of climatic variability and climate change on arabic coffee crop in Brazil *Bragantia* **69** 239–47

Chambers R 2013 *Ideas for Development* (London: Routledge) (https://doi.org/10.4324/9781849771665)

Coltri P P, Zullo J, Rrv G, Romani L A S and Pinto H S 2012 Carbon stock estimation in coffee crops using high resolution satellites *2012 IEEE Int. Geoscience and Remote Sensing Symp.* pp 6657–60

Craparo A C W, Pja V A, Läderach P, Jassogne L T P and Grab S W 2015 Coffea arabica yields decline in Tanzania due to climate change: global implications *Agric. For. Meteorol.* **207** 1–10
Cutter S L 1996 Vulnerability to environmental hazards *Prog. Hum. Geogr.* **20** 529–39
Cutter S L, Boruff B J and Wl S 2003 Social vulnerability to environmental hazards *Soc. Sci. Q.* **84** 242–61
Cutter S L, Burton C G and Emrich C T 2010 Disaster resilience indicators for benchmarking baseline conditions *J. Homel. Secur. Emerg. Manage.* 7
Cutter S L and Finch C 2008 Temporal and spatial changes in social vulnerability to natural hazards *Proc. Natl. Acad. Sci.* **105** 2301–6
Cutter S L, Boruff B J and Wl S 2003 Social vulnerability to environmental hazards *Soc. Sci. Q.* **84** 242–61
da Silva Tavares P, Giarolla A, Chou S C, de Paula Silva A J and de Arruda Lyra A 2018 Climate change impact on the potential yield of Arabica coffee in southeast Brazil *Reg. Environ. Change* **18** 873–83
Davis A P, Gole T W, Baena S and Moat J 2012 The impact of climate change on indigenous Arabica coffee (*Coffea arabica*): predicting future trends and identifying priorities *PLoS One* **7** e47981
de Sousa K, van Zonneveld M, Holmgren M, Kindt R and Jc O 2019 The future of coffee and cocoa agroforestry in a warmer Mesoamerica *Sci. Rep.* **9** 8828
Diffenbaugh N S and Giorgi F 2012 Climate change hotspots in the CMIP5 global climate model ensemble *Clim. Change* **114** 813–22
FAO 2013 FAOSTAT Online Statistical Service
FAO 2018 *Statistical Yearbook of the Food and Agriculture Organization* (Rome, Italy: United Nations Food and Agriculture Organization)
Garrett R D, Lambin E F and Naylor R L 2013 The new economic geography of land use change: supply chain configurations and land use in the Brazilian Amazon *Land Use Policy* **34** 265–75
Gay C, Estrada F, Conde C, Eakin H and Villers L 2006 Potential impacts of climate change on agriculture: a case of study of coffee production in Veracruz, Mexico *Clim. Change* **79** 259–88
Gbetibouo G A, Ringler C and Hassan R 2010 Vulnerability of the South African farming sector to climate change and variability: an indicator approach *Nat. Resour. Forum* **34** 175–87
Haggar J 2016 Coffee and climate change desk study: impacts of climate change in the Pilot Country Vietnam the coffee & climate initiative http://dspace.agu.edu.vn:8080/handle/AGU_Library/5347
Hahn M B, Riederer A M and Foster S O 2009 The Livelihood Vulnerability Index: a pragmatic approach to assessing risks from climate variability and change—a case study in Mozambique *Glob. Environ. Change* **19** 74–88
Harlan S L, Brazel A J, Prashad L, Stefanov W L and Larsen L 2006 Neighborhood microclimates and vulnerability to heat stress *Soc. Sci. Med.* **63** 2847–63
Hong C, Mueller N D, Burney J A, Zhang Y, Aghakouchak A, Moore F C, Qin Y, Tong D and Davis S J 2020 Impacts of ozone and climate change on yields of perennial crops in California *Nat. Food* **1** 166–72
IBGE 2017a *Agriculture and Livestock Census* (Instituto Brasileiro de Geografia e Estatística) (http://sidra.ibge.gov.br)
IBGE 2017b *Municipal Agricultural Production Survey* (Instituto Brasileiro de Geografia e Estatística) (http://sidra.ibge.gov.br)
IPCC 2014 *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of theIntergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)
Jayakumar M, Rajavel M and Surendran U 2016 Climate-based statistical regression models for crop yield forecasting of coffee in humid tropical Kerala, India *Int. J. Biometeorol.* **60** 1943–52
Johnson D P and Wilson J S 2009 The socio-spatial dynamics of extreme urban heat events: the case of heat-related deaths in Philadelphia *Appl. Geogr.* **29** 419–34
Kellerman A 1983 Economic and spatial aspects of von Thunen's factor intensity theory *Environ. Plan.* A **15** 1521–30
Knox J, Hess T, Daccache A and Wheeler T 2012 Climate change impacts on crop productivity in Africa and South Asia *Environ. Res. Lett.* **7** 034032
Läderach M, Haggar J, Lau C, Eitzinger A, Ovalle O, Baca M, Jarvis A and Lundy M 2010 Mesoamerican coffee: building a climate change adaptation strategy *CITA Policy Brief No. 2* Centro Internacional de Agricultura Tropical (CIAT) (https://hdl.handle.net/10568/29001)
Lobell D B and Field C B 2007 Global scale climate–crop yield relationships and the impacts of recent warming *Environ. Res. Lett.* **2** 014002
Lobell D B, Schlenker W and Costa-Roberts J 2011 Climate trends and global crop production since 1980 *Science* **333** 616–20
Ovalle-Rivera O, Läderach P, Bunn C, Obersteiner M and Schroth G 2015 Projected shifts in Coffea arabica suitability among major global producing regions due to climate change *PloS One* **10** e0124155
Pachauri R K *et al* 2014 *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (hdl:10013/epic.45156)* (https://epic.awi.de/id/eprint/37530/)
Pandey R and Jha S 2012 Climate vulnerability index-measure of climate change vulnerability to communities: a case of rural Lower Himalaya, India *Mitig. Adapt. Strateg. Glob. Change* **17** 487–506
Pham Y, Reardon-Smith K, Mushtaq S and Cockfield G 2019 The impact of climate change and variability on coffee production: a systematic review *Clim. Change* **156** 609–30
Samberg L H, Gerber J S, Ramankutty N, Herrero M and West P C 2016 Subnational distribution of average farm size and smallholder contributions to global food production *Environ. Res. Lett.* **11** 124010
Schlenker W and Lobell D B 2010 Robust negative impacts of climate change on African agriculture *Environ. Res. Lett.* **5** 014010
Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to US crop yields under climate change *Proc. Natl. Acad. Sci.* **106** 15594–8
Schroth G, Läderach P, Cuero D S B, Neilson J and Bunn C 2015 Winner or loser of climate change? A modeling study of current and future climatic suitability of Arabica coffee in Indonesia *Reg. Environ. Change* **15** 1473–82
Schroth G, Laderach P and Dempewolf J 2009 Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico *Mitig. Adapt. Strateg. Glob. Change* **14** 605–25
Shah K U, Dulal H B, Johnson C and Baptiste A 2013 Understanding livelihood vulnerability to climate change: applying the livelihood vulnerability index in Trinidad and Tobago *Geoforum* **47** 125–37
Verhage F Y F, Anten N P R and Sentelhas P C 2017 Carbon dioxide fertilization offsets negative impacts of climate change on Arabica coffee yield in Brazil *Clim. Change* **144** 671–85
Watson D J 1963 Climate, weather and plant yield *Environmental Control of Plant Growth* ed L T Evans (New Year: Academic) pp 337–50
Watson K and Achinelli M L 2008 Context and contingency: the coffee crisis for conventional small-scale coffee farmers in Brazil *Geogr. J.* **174** 223–34
Welch J R, Vincent J R, Auffhammer M, Moya P F, Dobermann A and Dawe D 2010 Rice yields in tropical/subtropical Asia

exhibit large but opposing sensitivities to minimum and maximum temperatures *Proc. Natl. Acad. Sci.* **107** 14562–7

Zullo J, Hilton J, Pinto S, Delgado E, Maria A and Ávila H D 2011 Potential for growing Arabica coffee in the extreme south of Brazil in a warmer world *Clim. Change* **109** 535–48

Zullo J, Pinto H S and Assad E D 2006 Impact assessment study of climate change on agricultural zoning *Meteorol. Appl.* **13** 69–80