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Agroforestry systems can mitigate the impacts of climate change on coffee production: A spatially explicit assessment in Brazil

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ABSTRACT

Climate change may impose severe challenges to farmers to maintain agricultural production levels in the future. In this study we analysed the effect of projected changes in climate on the area suitable for coffee production in 2050, and the potential of agroforestry systems to mitigate these effects in a major coffee production region in southeast Brazil. We conducted a spatially explicit analysis with the bioclimatic model MaxEnt to explore the area that is suitable for coffee production in 2050 when coffee is grown in unshaded plantations and in agroforestry systems. The projected climate in 2050 was assessed using 19 global circulation models, and we accounted for the altered microclimate in agroforestry systems by adjusting the maximum and minimum air temperature. The climate models indicated that the annual mean air temperature is expected to increase 1.7 °C ± 0.3 in the study region, which will lead to almost 60 % reduction in the area suitable for coffee production in unshaded plantations by 2050. However, the adoption of agroforestry systems with 50 % shade cover can reduce the mean temperatures and maintain 75 % of the area suitable for coffee production in 2050, especially between 600 and 800 m altitude. Our study indicates that major shifts in areas suitable for coffee production may take place within three decades, potentially leading to land conflicts for coffee production and nature conservation. Incentives that contribute to the development of coffee agroforestry systems at appropriate locations may be essential to safeguard coffee production in the southeast of Brazil.

1. Introduction

Climate change is expected to impose severe challenges to farmers to maintain agricultural production levels in the future (IPCC, 2019; Schroth et al., 2009). This is particularly the case for producers of coffee, which is an important cash crop for approximately 25 million smallholder farmers and 100 million livelihoods in many countries in Africa, Mesoamerica, and South America (Pendergrast, 2010; Waller et al., 2007). *Coffea arabica* is highly sensitive to changes in climate and global projections indicate a reduction in the area that is suitable for coffee production due to changing temperature and precipitation regimes (DaMatta, 2004; DaMatta and Cochicho Ramalho, 2006; Ovalle-Rivera et al., 2015). This may force coffee production to move to other regions with more favourable climatic conditions. Alternatively, farmers may adapt by switching to coffee varieties that are better adjusted to future climate conditions or by changing the management of coffee systems to mitigate the effects of climate change (Baca et al., 2014; Schroth et al., 2009). Relocation of production areas, switching coffee varieties or to other crops types are challenging, and entail many complexities, including the availability of suitable areas, availability of new *C. arabica* varieties resistant to higher temperatures and cultural adaptation to another crop species (Eskes and Leroy, 2009). On the other hand, changing coffee management systems may be easier to implement. For instance, agroforestry management systems have been identified as a promising way to maintain coffee production in the future under scenarios of climate change (Lin, 2007; IPCC, 2014).

Agroforestry coffee systems consist of coffee plants intercropped with shade trees, which can increase nutrient cycling, biodiversity, carbon storage, and provide a moderate microclimate (Bhagwat et al., 2008; Duarte et al., 2013; Nair, 1997; Soto-Pinto et al., 2009). The microclimate created by the trees results in lower mean air temperatures and higher soil moisture in coffee agroforestry systems than in

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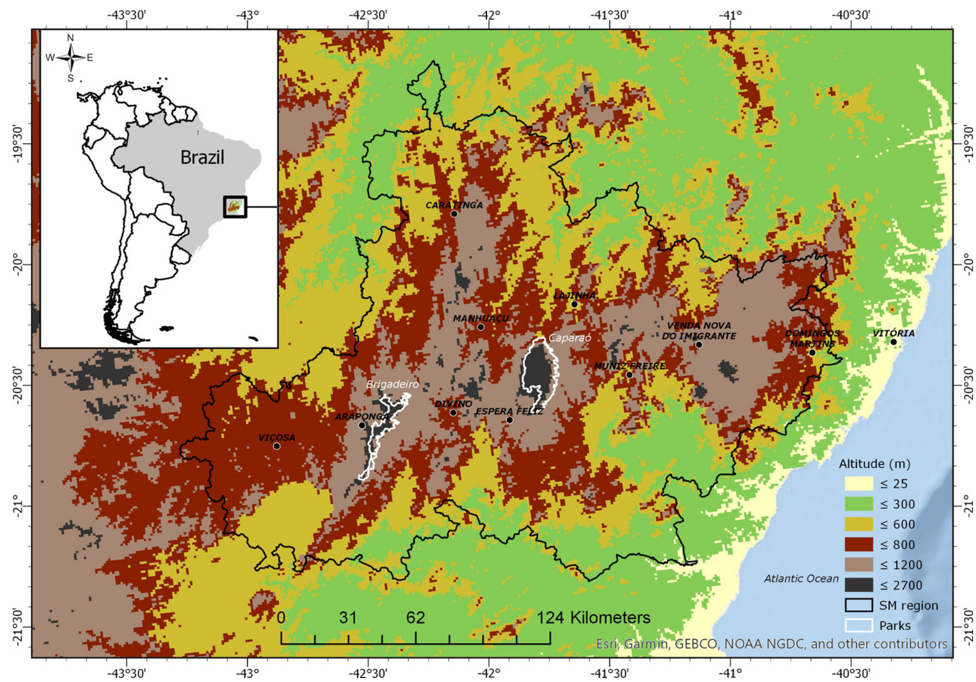

Fig. 1. The Southeast Mountains region (SM) and the digital elevation model (m) in the Atlantic Forest Biome, Brazil. The National Caparaó Park (Caparaó) and the Serra do Brigadeiro State Park (Brigadeiro) are represented in white colour.

unshaded coffee systems (Lin, 2010; Moreira et al., 2018; Souza et al., 2012a,b,c). However, increasing shade can also affect the physiology of coffee plants, stimulating the vegetative growth instead of flower buds, reducing the number of nodes per branch and coffee yield (Cannell, 1976). While shade levels above 50 % in coffee plantations are associated with a decrease in coffee productivity, shade levels below 50 % do not seem to compromise yield (Moreira et al., 2018). In unshaded systems, the coffee flowering shows strong yearly fluctuations, resulting in a biennial production pattern with alternating years with high and low productivity (DaMatta, 2004). These fluctuations can compromise income security for farmers and decrease the lifespan of coffee plants due to exhaustion during heavy production years. In contrast, the productivity of coffee under shade tends to be more stable across years than in unshaded coffee systems (DaMatta, 2004). Therefore, agroforestry coffee systems, when properly managed, may alleviate the effects of projected climate change by modifying the microclimate without decreasing coffee productivity. Yet, although several studies have shown the benefits of agroforestry systems on microclimate at specific locations, the effectiveness of agroforestry systems to mitigate the effects of climate change may differ along geographic location and altitude (Akpo et al., 2005; Lin, 2007; Souza et al., 2012a,b,c). Therefore, the assessment of areas where agroforestry systems may have most potential to mitigate climate change can inform climate adaptation management to safeguard future coffee production.

Brazil is the world's largest producer of coffee, with mostly unshaded coffee systems and only limited agroforestry coffee systems. The dominance of unshaded coffee systems makes coffee production in Brazil vulnerable for impacts of climate change with potential serious socio-economic repercussions. There are three main regions of coffee production in Brazil: Savannah areas in the Minas Gerais (Cerrado), south of Minas Gerais (Sul de Minas) and the Southeast Mountains (Matas de Minas Gerais and Montanhas do Espírito Santo). These regions have contrasting characteristics. Savannah areas in the Minas Gerais are characterized by flat areas and mechanized and irrigated sun coffee systems, while the south of Minas Gerais and the Southeast Mountains are mountainous areas. The Southeast Mountains cover almost one-third of all coffee production areas in Brazil, being managed mainly by smallholder family farmers. In this region, a group of family farmers in partnership with a non-governmental organization and the Federal University of Viçosa implemented agroforestry systems following participatory methodologies, aiming to restore soil quality and biodiversity in the 1990's (Cardoso et al., 2001). From this experience, the family farmers and researchers identified the criteria to identify best trees species for intercropping with coffee (Souza et al., 2010). They also indicated several tree species to be intercropped and several benefits associated to these trees (Souza et al., 2010), including natural pest suppression (Rezende et al., 2014), increased soil quality and biodiversity (Duarte et al., 2013; Souza et al., 2012a,b,c), diversification of agricultural production (Souza et al., 2012a,b,c) and climate regulation (Gomes et al., 2016). These findings underline the potential of coffee agroforestry systems in the Southeast Mountains region in Brazil.

Because of its mountainous terrain and heterogeneous landscapes, the projected changes in temperature and precipitation regimes may vary locally in Southeast Mountains, potentially impacting coffee production differentially in distinct locations. While field experiments in the Southeast Mountains show that agroforestry systems can reduce the daily maximum temperatures by up to 5 °C (Souza et al., 2012a,b,c), it is not clear how this will play out in different locations and what the implications are for coffee production. The identification of areas with high to low risk can inform spatial planning and management actions to mitigate effects of climate change. This study aimed to explore potential effects of climate change on the area suitable for coffee production, and the potential of agroforestry system to mitigate impacts of climate change at the regional scale. More specifically, the study aimed to (i) assess the projected monthly temperature and precipitation in the Southeast Mountains for 2050, (ii) assess how these climate conditions may affect the suitability for coffee production, and (iii) identify the potential of agroforestry systems to mitigate the impacts of climate change.

2. Material and methods

2.1. Study area

The Southeast Mountains region (40.5 °W, 43.3 °W, 19.15S, 21.30S) is located in the southeast of Brazil, and is part of the Atlantic Forest

Biome, which is an important biodiversity hotspot (Fig. 1; Myers et al., 2000). The main part of this area is characterized by mountains with elevations varying between 400–2700 meters above sea level. The region covers 31,700 km^2 and includes 107 municipalities, where approximately 383,000 ha consists of coffee plantations, producing on average 484,000 tons coffee per year, corresponding to almost 22 % of the total *C. arabica* production in Brazil (IBGE, 2019). The areas over 1200 m altitude are mainly located in the Caparaó National Park and the Serra do Brigadeiro State Park, which are protected areas for nature conservation and tourism.

2.2. Coffee production areas and climate data

The current coffee production areas in the Southeast Mountains region were identified by the analysis of land use maps, annual yearbooks of statistical agricultural production from the municipalities (IBGE, 2019), and by checking Google Earth maps. First, we selected 3000 random sample points with coffee production from a land use map (Gomes et al., 2020; *in review*) and 2000 additional sampling points from Google Earth maps in the municipalities that currently produce coffee, resulting in 5000 sampling points in total. Then, we checked each sampling point to confirm the presence of *C. arabica* and for overlapping sampling points, which reduced the number of suitable sampling points to 4200 (Appendix A, Supplementary material). To assess the historical climate data in the study region between 1960–1990 and the projected climate in 2050 we used the WorldClim database version 1.4, which contains maps of monthly precipitation and mean, minimum and maximum temperatures at a spatial resolution of approximately 1 × 1 km (Hijmans et al., 2005). The WorldClim database 1.4 also includes maps of historic and projections of 19 bioclimatic variables (Table 1) that represent annual trends of temperature and precipitation, seasonality, and crop growth limiting factors, such as temperature of the coldest and warmest month, and precipitation during the wettest and driest month (Hijmans et al., 2005).

To study the changes in the spatial distribution of areas suitable for coffee production in the Southeast Mountains in 2050, we used projections of precipitation, temperature and bioclimatic variables from 19 different Global Circulation Models (GCMs) for the Representative Concentration Pathway 4.5 scenario for 2050 (RCP 4.5), which is considered the reference and therefore the most plausible climate scenario (Hijmans et al., 2005).

2.3. Coffee suitability analysis

We used the MaxEnt model (Phillips et al., 2019) to predict the current and the future coffee suitability in 2050 under the RCP 4.5 scenario climate change. The MaxEnt model has been applied for species distribution/environmental modelling (Merow et al., 2013; Phillips et al., 2006), and has been used to analyse the impact of climate change on coffee suitability from regional to global scales (Bunn et al., 2015; Läderach et al., 2017; Ovalle-Rivera et al., 2015). In MaxEnt we used the actual location of the 4200 coffee plantations as input data and the bioclimatic variables as environmental predictors. To avoid model-overfitting, we applied a Pearson correlation analysis ($r < 0.8$) on the 19 maps of bioclimatic variables and this resulted in six relatively uncorrelated bioclimatic variables (Bio 3, 4, 10, 12, 13 and 19), which were used for further analysis. We restricted the analysis to bioclimatic variables as predictor variables because no soil data at sufficiently fine resolution are available for the study region. We applied a multiple logistic regression in MaxEnt to create a predictive model for the probability of the presence of coffee plantations in each pixel with values ranging from zero to one (Ovalle-Rivera et al., 2015). In order to assess the changes in the percentage of area suitable for coffee production from current situation to 2050, we used a coffee suitability threshold of 0.25, which corresponds with the coffee suitability of marginal areas for current coffee production (Fig. 3a).

We split the 4200 locations in datasets for model training and validation. Eighty percent of the data were randomly assigned for model training and the remaining twenty percent was used for validation using the default setting in MaxEnt (Läderach et al., 2017). We used a fixed background area from which we drew 10,000 random locations for pseudo-absences of coffee (Läderach et al., 2017; VanDerWal et al., 2009). Then we ran the MaxEnt 25 times to map the current coffee suitability and also for each of the 19 GCMs, resulting in a total of 25 suitability maps for the current situation, and 475 suitability maps for 2050. For each of the 25 replicate runs new random training and validation datasets were drawn. To assess the uncertainty of the MaxEnt estimations and the predictions of the GCMs, we generated maps with the mean and coefficient of variation of the suitability predictions for 2050 of the 19 GCMs. The accuracy of the model to predict the suitability for coffee production was assessed using the Area Under the Curve (AUC) index (Peterson et al., 2008; Schroth et al., 2015). The model presented median AUC values of 0.77 for training and validation indicating satisfactory performance (Appendix B).

Table 1
Overview of values of bioclimatic variables (BIO) for 4200 locations with coffee production in the Southeast Mountains region in Brazil for the period between 1960 and 1990, and projected for 2050. The data for 2050 are generated with 19 Global Circular Models under the Representative Concentration Pathway 4.5 scenario (RCP 4.5). Variables Bio 3, 4, 10, 12, 13 and 19 were used for the MaxEnt modelling. Means and standard deviation are presented.

Code	Bioclimatic variables	Current	2050
BIO1	Annual Mean Temperature	19.61 ± 1.15	21.35 ± 1.13
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	12.39 ± 0.70	12.5 ± 0.70
BIO3	Isothermality (BIO2/BIO7) (x 100)	64.84 ± 0.90	65.24 ± 0.87
BIO4	Temperature Seasonality (standard deviation *100)	193.1 ± 8.99	197 ± 8.64
BIO5	Max Temperature of Warmest Month	28.38 ± 1.10	30.17 ± 1.08
BIO6	Min Temperature of Coldest Month	9.43 ± 1.48	11.04 ± 1.43
BIO7	Temperature Annual Range (BIO5-BIO6)	18.95 ± 0.93	19.1 ± 1.10
BIO8	Mean Temperature of Wettest Quarter	21.29 ± 1.14	23.06 ± 1.13
BIO9	Mean Temperature of Driest Quarter	17.19 ± 1.17	18.88 ± 1.14
BIO10	Mean Temperature of Warmest Quarter	21.77 ± 1.17	23.40 ± 1.15
BIO11	Mean Temperature of Coldest Quarter	16.91 ± 1.17	18.59 ± 1.14
BIO12	Annual Precipitation	1296 ± 59.20	1235 ± 58.42
BIO13	Precipitation of Wettest Month	230.48 ± 12.69	239.2 ± 15.35
BIO14	Precipitation of Driest Month	21.10 ± 5.46	19.42 ± 4.88
BIO15	Precipitation Seasonality (Coefficient of Variation)	68.10 ± 5.81	72.16 ± 5.96
BIO16	Precipitation of Wettest Quarter	651.46 ± 35.35	634.2 ± 38.98
BIO17	Precipitation of Driest Quarter	80.29 ± 18.98	73.74 ± 13.36
BIO18	Precipitation of Warmest Quarter	492.52 ± 37.27	494.6 ± 38.11
BIO19	Precipitation of Coldest Quarter	96.40 ± 20.21	90.9 ± 18.72

2.4. Potential of agroforestry systems to mitigate the effect of climate change

Shade trees affects the maximum and minimum daily temperature, and can decrease the mean daily temperature by up to 4 °C (Beer et al., 1998). More specifically, shade levels of 50 % can decrease the mean daily temperature by 2 − 3 °C (Barradas and Fanjul, 1986; Rahn et al., 2018; van Oijen et al., 2010), decrease the maximum air temperature by 3 °C, and increase the minimum temperature by 1 °C without compromising coffee yield (Moreira et al., 2018; Souza et al., 2012a,b,c). To assess the spatial distribution of areas suitable for coffee production under agroforestry systems in 2050, we adjusted the maps of monthly minimum and maximum temperature from the RCP 4.5 scenario. First, we derived maps of the averages of the 19 GCMs for minimum and maximum temperature maps for each month in 2050. This resulted in twelve maps of monthly minimum and maximum temperatures in 2050. Then we subtracted 3 °C from the monthly maximum temperature maps and added 1 °C for monthly minimum temperature maps to mimic the effect of shade on the microclimate in coffee agroforestry systems. With the adjusted maps of temperature we recalculated new bioclimatic variables (BIO 3, 4, and 10) that account for shade effects (Appendix C; O'Donnell and Ignizio, 2012), which were used as input for MaxEnt (Section 2.3) to explore the spatial distribution of areas suitable for coffee production in agroforestry systems.

3. Results

3.1. Projected climate changes

The 19 global circulation models show a trend of increasing temperature and decreasing precipitation for 2050 in coffee production areas in the Southeast Mountains, Brazil (Fig. 2 and Table 1). The mean annual temperature is projected to increase 1.71 ± 0.3 °C, with the highest increase from October to December, when the temperature can increase by up to 2.3 °C. The total annual precipitation is projected to decrease from 1257 to 1199 mm, with the largest decrease from September to December.

3.2. Environmental factors and coffee suitability

Temperature of wettest quarter (Bio 10) explained 63.2 % and precipitation of the coldest quarter (Bio 19) explained 21.4 % of the variation in suitability for coffee production (Appendix D). Under the current conditions, the highest suitability for coffee production occurred between altitudes of 800 and 1200 m, with an average of 0.50 and maximum values of up to 0.66 (at a scale ranging from 0 to 1; Fig. 3a). Areas at altitudes between 600 and 800 m had a mean of 0.39 for suitability for coffee production, while the areas under 600 m had the lowest values with a mean of 0.13. The area suitable for coffee production in 2050 is expected to decrease by 60 % when using the criterion that suitable coffee production areas should have a higher suitability than 0.25. For 2050, the maximum suitability values were 0.46 and occurred in the regions between 800 and 1200 m (Fig. 3b). The strongest reduction in suitability for coffee production is expected to occur between 600 and 800 m, with a decrease in coffee suitability of up to −0.48 (Fig. 3d). However, the suitability for coffee production is projected to increase slightly in an area covering approximately 1069 km^2, located mainly between 1200 and 1800 m (Fig. 3d).

3.3. Potential of agroforestry systems

MaxEnt simulations show that agroforestry systems have potential to partly mitigate the impact of climate change on coffee suitability for the Southeast Mountains region in 2050 (Fig. 4). Under the agroforestry systems scenario with 50 % shade cover, 75 % of the currently suitable area for coffee production will remain suitable for coffee production in 2050 with suitability values ranging from 0.25 to 0.59 (Fig. 4a, c). Yet, the potential of agroforestry systems to mitigate the effects of climate change depends strongly on altitude: in areas between 600 and 800 m, agroforestry systems have the potential to increase coffee suitability by up to +0.45 in 2050 compared to unshaded coffee systems, especially in the region of the Caparaó National park (Fig. 4b). In areas between 800 and 1200 m, agroforestry systems with 50 % shade cover are expected to have a similar positive effect of up to +0.45 (Fig. 4b) but can also have negative effects of up to -0.29.

4. Discussion

We explored the impact of climate change on coffee suitability in the Southeast Mountains region in Brazil using a bioclimatic modelling approach. We found that i) substantial increases in the temperature and changes in precipitation regimes may be anticipated throughout the year in 2050; ii) the projected changes in temperature and precipitation may lead to a strong decrease in the suitability for coffee production in this region, and iii) agroforestry systems can mitigate some of the impacts of these changes in climate on the suitability for coffee production.

The projected changes in the annual mean temperature (+1.7 °C) and changes in precipitation regimes (almost 60 mm less) under the RCP 4.5 scenario can affect the physiology of coffee plants and the associated coffee yields. In the coldest months (April to July), the

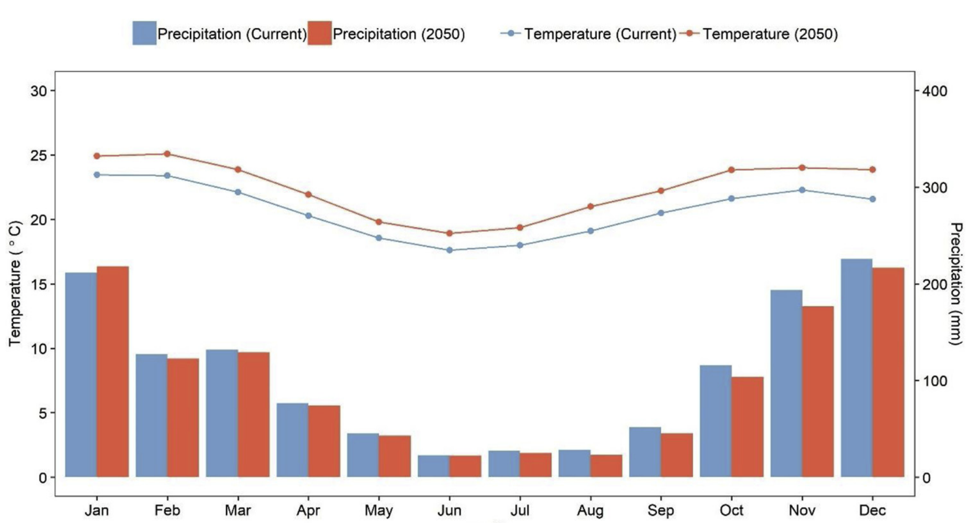

Fig. 2. Annual variation of temperature (lines) and precipitation (bars) between 1960 and 1990 (Current, blue) and projected for 2050 (red) for coffee production areas in the Southeast Mountains region, Brazil. Projections for 2050 are based on the average of 19 Global Circulation Models for the Representative Concentration Pathways 4.5 scenario (RCP 4.5) from the Intergovernmental Panel on Climate Change (IPCC). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

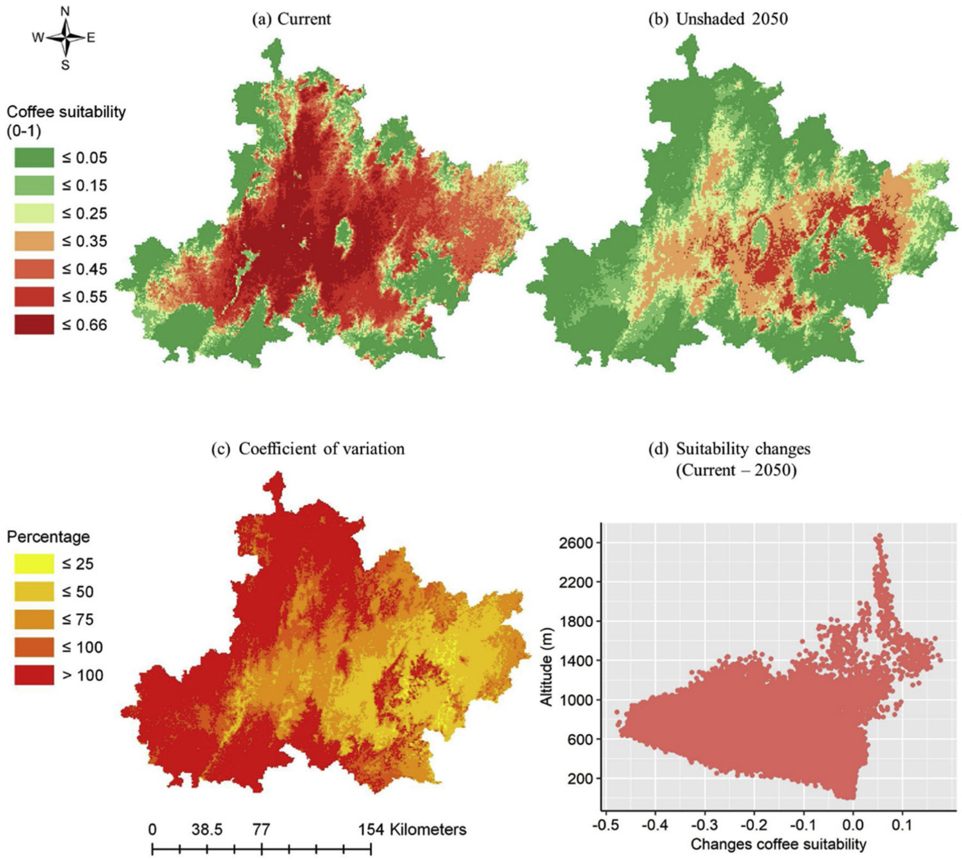

Fig. 3. Suitability for coffee production for the current situation (a) and for 2050 under unshaded coffee management systems based on the Representative Concentration Pathways scenario 4.5 from 19 Global Circulation Models (b). Model uncertainty is indicated by the coefficient of variation (%) based on 475 suitability maps for 2050 (19 models x 25 replications) (c). Relationship between altitude and the change in suitability for coffee production from the current situation and 2050 (d).

projected temperature is expected to increase by about 1.3 °C, while in the warmest months (October to November) the mean temperature may increase by 2.1 °C followed by decrease in precipitation of almost 60 mm (Fig. 2). The changes in temperature and precipitation vary across the year (Fig. 2), which deviates from projections for other countries in Mesoamerica, where temperature is expected to consistently increase throughout the year (Läderach et al., 2017). The predicted increase of temperature from October to November combined with the decrease in precipitation will increase the potential evapotranspiration and decrease the water availability, resulting in a longer dry season (Fig. 2). Since the seasonal water cycle influences the growth and development of coffee plants, including the flowering and fruiting stages (Carr, 2001), the projected changes in temperature and precipitation may reduce coffee productivity. Indeed, the increase of temperature associated with a prolongated dry season can alter coffee plant photosynthesis, cause abortion of flowers, thus compromising coffee yields (Camargo, 1985; DaMatta and Cochicho Ramalho, 2006).

The projected change in climate in the study area in 2050 may lead to an 60 % decrease in the area suitable for coffee production, particularly affecting coffee plantations in altitudes ranging from 600 to 800 m. Currently, the areas suitable for coffee production range from 600 to 1200 m, but due to climate change, these areas are expected to be restricted to altitudes higher than 800 m by 2050 (Fig. 3). The decline and shifts in areas suitable for coffee production have also been reported in global and regional studies. In Nicaragua, the area suitable for coffee production is expected to decrease by 90 % in 2050 (Bunn et al., 2015; Läderach et al., 2017; Ovalle-Rivera et al., 2015). Similar to our findings, a global study identified that coffee production will need to be relocated to higher elevations, where the climate will become suitable for coffee production in the future (Magrach and Ghazoul, 2015). However, in our study region the land at elevated areas consist of national parks, which could potentially lead to competing claims for land use for coffee production and nature conservation. However, such potential conflict could be limited or avoided with adapted climate management with agroforestry coffee systems.

Our study shows that the adoption of agroforestry coffee systems is a promising strategy to mitigate the negative impact of climate change and maintain 75 % of current area that is suitable for coffee production in the study region in 2050. Agroforestry systems with 50 % shade cover can especially mitigate the impact of climate change at altitudes between 600 and 800 m (Fig. 4). This altitude range covers a large area of coffee production, where the coffee suitability can decrease by -0.48, but with agroforestry systems the coffee suitability could increase up to +0.45 under the projected climate change scenario for 2050. Farmers may further mitigate of climate change impacts on coffee production by increasing the shade cover of agroforestry systems to more than 50 %. This will require tailored shade management throughout the year, with reduced shade cover after harvesting (Souza et al., 2010), when the coffee plants need more solar energy to develop the nodes. In contrast, coffee plants at altitudes exceeding 1000 m may benefit from higher temperatures in the future, and coffee agroforestry systems at this altitude should have shade levels below 50 %. The incorporation of shade trees in coffee systems may influence the productivity of coffee plants in different ways. Positive effects include reduced temperatures under shade that slow down the maturation of fruit, leading to larger coffee beans of better quality (Muschler, 2001; Bote and Struik, 2011). In addition, the presence of trees in coffee systems can lead to more birds and bees, which contribute to pollination and pest control (Chain-Guadarrama et al., 2019). On the other hand, increasing shade cover in coffee systems may favour diseases, such as coffee leaf rust (López-bravo et al., 2012), and increase competition for water and nutrients, which reduce coffee yield (DaMatta, 2004).

Careful selection of shade trees and tailored pruning management may limit the competition between coffee plants and shade trees (Souza et al., 2010). This is particularly relevant for competition for water, nutrient and light, limiting factors for coffee production. Compared

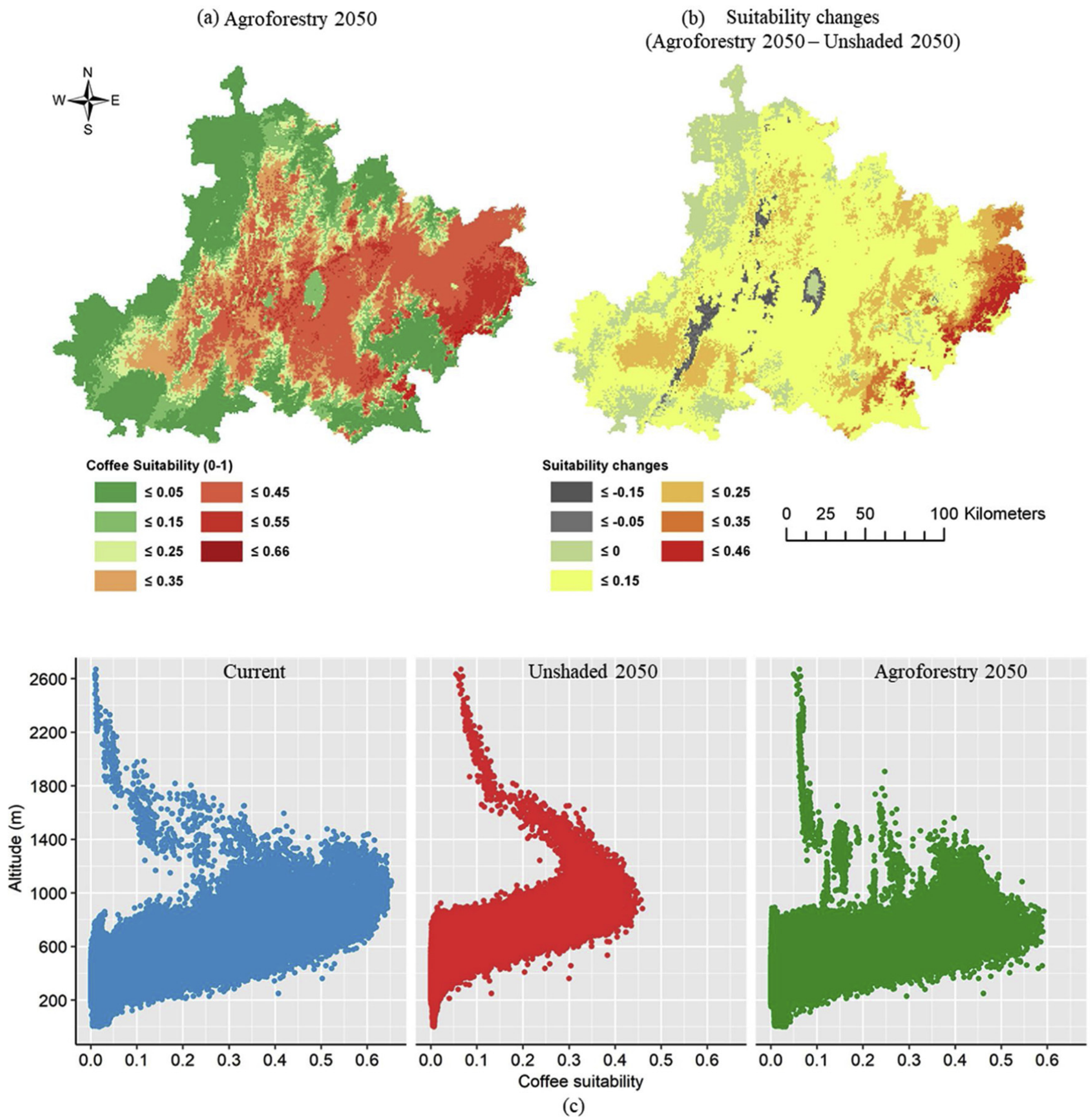

Fig. 4. Changes in coffee suitability from the current situation as compared to 2050 under unshaded and agroforestry coffee systems in the Southeast Mountains region, Brazil. Maps show the coffee suitability in the agroforestry (shaded coffee) scenario for 2050 (a), and the changes in coffee suitability between the Agroforestry and Unshaded scenario in 2050 (b). The bottom panels show the relation between altitude and suitability for coffee production for the current situation (left), unshaded coffee for 2050 (middle), and agroforestry coffee for 2050 (right).

with unshaded coffee, agroforestry coffee systems may maintain higher levels of soil water content due to decreased soil evaporation (Lin et al., 2010), but on the other hand shade trees also take up soil water (Padovan et al., 2018). Due to the complex interactions between tree species, coffee plants and the soil, the selection of shade trees species for agroforestry must consider several factors, including canopy structure, rooting pattern and depth, and leaf phenology (e.g., evergreen or deciduous). A list of suitable shade tree species for agroforestry coffee systems for the study region has been developed by a group of family farmer with more than 30 years of experience with agroforestry systems (Souza et al., 2010). The list includes, among others, *Aegiphila sellowiana* Cham. (papagaio), *Persea americana* Mill. (abacate) and *Solanum mauritianum* Scop. (capoeira-branca) (Appendix E). These shade tree species have rooting systems that limit the competition with coffee plants for water and nutrients and, moreover, improve recycling important nutrients such as P, Ca, Mg and N via litter fall (Duarte et al., 2013; Souza et al., 2010). The agroforestry systems have been successfully used in the region by some farmers (Cardoso et al., 2001; Souza et al., 2010, 2012a,b,c) and may be a viable option to mitigate the negative impact of climate change (Geertsema et al., 2016). However, the expansion of agroforestry systems in the region needs a joint effort of scientists and family farmers to improve the understanding about the effect of climate change and trees on coffee suitability. We recommend for future studies to integrate species distribution models, water balance and solar interception modelling for selected trees species under contrasting shade levels according to seasons and altitude ranges (Rahn et al., 2018). This could result in context-specific recommendations for the successful development of agroforestry coffee systems.

Our study indicates that a decline of 60 % in the area suitable for coffee production may be expected in the Southeast Mountains, which can impact millions of livelihoods. Yet, recent studies suggest that the projected negative impacts of increase of temperature and changes in precipitation patterns on coffee production can be compensated up to 13–21 % by the CO_2 fertilization effect associated with the emission of greenhouse gasses (Rahn et al., 2018; Ramalho et al., 2018). However, this beneficial effect of CO_2 fertilization is linked with highly intensified coffee systems, which may be not realistic for family farmers in mountainous areas (Rahn et al., 2018). In this context, the implementation of shade trees may be a more promising alternative for smallholder farmers. Moreover, agroforestry systems may reconcile coffee production with conservation of nature, and act as a frontier buffer between more intensively managed agricultural areas and nature conservation areas. Since coffee production is at the heart of social, economic and cultural development in the region, smallholder farmers, government, NGOs, scientific community and policy makers should join forces to implement agroforestry systems in the region to counteract the threat posed by climate change and safeguard the future of coffee production in the Southeast Mountains. Our assessment of the impacts of climate change on the area suitable for coffee production may be useful for identifying coffee production areas that are vulnerable to climate change and may benefit from direct targeted management actions.

Declaration of Competing Interest

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

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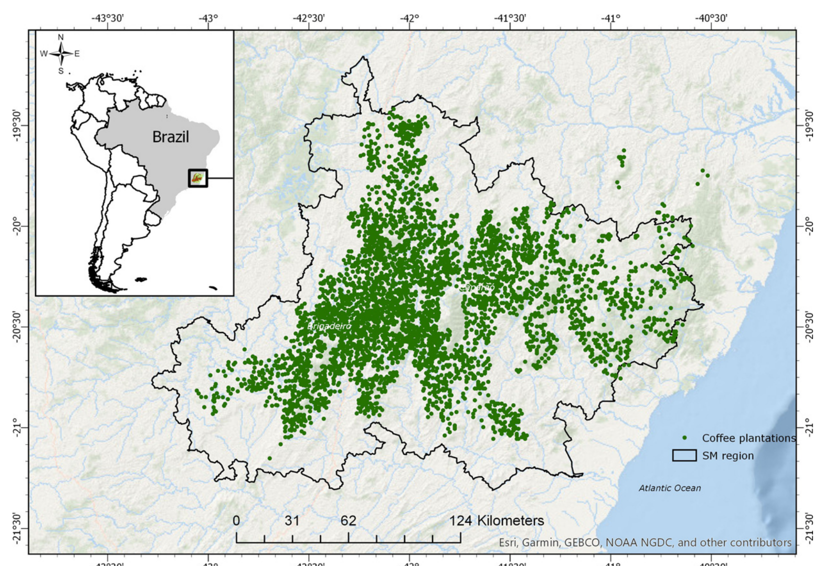
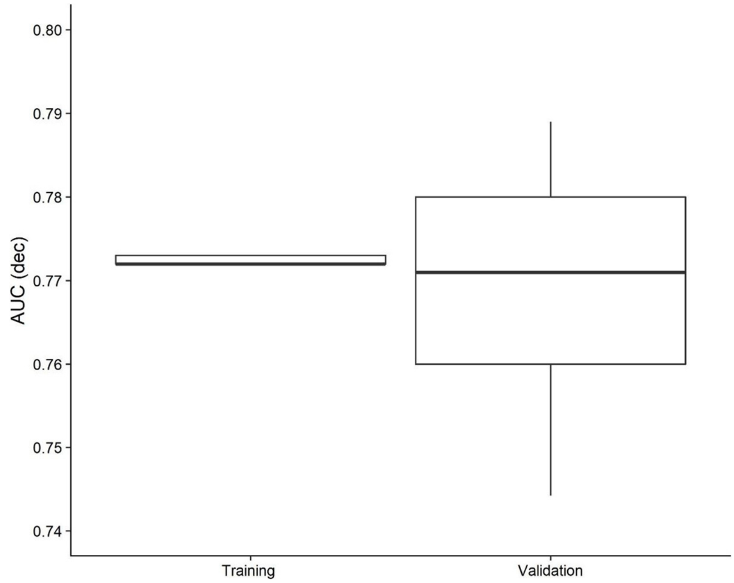
Appendix A. Geographical location of the current coffee plantations used to model the coffee suitability in the Southeast Mountains region (SM), Brazil. The geographical coordinates from each coffee plantation are presented in the supplementary material



Appendix B. Boxplots of AUC values of 25 MaxEnt model runs for training and validation. The black horizontal line in the box shows the median, the box show 25th and 75th percentiles, and whiskers show 5th and 95th percentiles



Appendix C. Overview of mean and standard deviation of bioclimatic variables values in 2050 for 4200 locations for unshaded coffee (RCP 4.5 scenario 2050) and shaded coffee (Agroforestry 2050) in the Southeast Mountains, Brazil

Code	Bioclimatic variables	2050	Agroforestry 2050
BIO1	Annual Mean Temperature	21.35 ± 1.13	20.33 ± 1.14
BIO2	Mean Diurnal Range (Mean of monthly (max temp - min temp))	12.5 ± 0.70	8.73 ± 0.70
BIO3	Isothermality (BIO2/BIO7) (x 100)	65.24 ± 0.87	54.27 ± 1.68
BIO4	Temperature Seasonality (standard deviation *100)	197 ± 86.49	212 ± 104.7
BIO5	Max Temperature of Warmest Month	30.17 ± 1.08	27.36 ± 1.14
BIO6	Min Temperature of Coldest Month	11.04 ± 1.43	12.08 ± 1.44
BIO7	Temperature Annual Range (BIO5-BIO6)	19.1 ± 1.10	15.28 ± 0.99
BIO8	Mean Temperature of Wettest Quarter	23.06 ± 1.13	22.24 ± 1.13
BIO9	Mean Temperature of Driest Quarter	18.88 ± 1.14	17.25 ± 1.16
BIO10	Mean Temperature of Warmest Quarter	23.40 ± 1.15	22.24 ± 1.13
BIO11	Mean Temperature of Coldest Quarter	18.59 ± 1.14	17.25 ± 1.16
BIO12	Annual Precipitation	1235 ± 58.42	1235 ± 58.42
BIO13	Precipitation of Wettest Month	239.2 ± 15.35	239.2 ± 15.35
BIO14	Precipitation of Driest Month	19.42 ± 4.88	19.42 ± 4.88
BIO15	Precipitation Seasonality (Coefficient of Variation)	72.16 ± 5.96	72.16 ± 5.96
BIO16	Precipitation of Wettest Quarter	634.2 ± 38.98	634.2 ± 38.98
BIO17	Precipitation of Driest Quarter	73.74 ± 13.36	73.74 ± 13.36
BIO18	Precipitation of Warmest Quarter	494.6 ± 38.11	494.6 ± 38.11
BIO19	Precipitation of Coldest Quarter	90.9 ± 18.72	90.9 ± 18.72

Appendix D. Explained variance (%) of bioclimatic variables (BIO) used to predict the coffee suitability using the MaxEnt model in the Southeast Mountains, Brazil

Code	Bioclimatic variables	Contribution (%)
BIO3	Isothermality (BIO2/BIO7) (* 100)	6.76
BIO4	Temperature Seasonality (standard deviation *100)	5.90
BIO10	Mean Temperature of Warmest Quarter	63.24
BIO12	Annual Precipitation	0.08
BIO13	Precipitation of Wettest Month	2.59
BIO19	Precipitation of Coldest Quarter	21.41

Appendix E. Family, species and common Portuguese names of tree species used in agroforestry systems in the Zona da Mata, Minas Gerais, Atlantic Coastal Rainforest, Brazil (Adapted from Souza et al., 2010). Origin specifies whether tree species is native (N) or exotic (E) and the classification as Fruit is also highlighted. Local source (Yes) indicates whether tree species are present in nearby forest fragments (up to hundreds of metres)

Family	Species (common names)	Origin	Fruit	Local source
Anacardiaceae	*Mangifera indica* L. (manga)	E	x	
	Schinus terebinthifolia Raddi (aroeirinha)	N		Yes
	Spondias lutea L. (cajá manga)	E	x	
Annonaceae	*Annona muricata* L. (graviola)	E	x	
	Annona squamosa L. (fruta-do-conde)	E	x	
	Rollinia dolabripetala A.St.-Hil. (araticum)	N	x	Yes
Apocynaceae	*Aspidosperma polyneuron* Müll. (guatambu)	N		Yes
Araucariaceae	*Araucaria angustifolia* (Bertol.) Kuntze (pinheiro-brasileiro)	N		
Arecaceae	*Bactris gasipaes* Kunth (pupunha)	E		
	Cocos nucifera L. (coco-da-bahia)	E	x	
	Euterpe edulis Mart. (palmito-jussara)	N		Yes
	Syagrus romanzoffiana (Cham.) Glassman (coco-babão)	N		Yes
Asteraceae	*Eremanthus erythropappus* (DC.) MacLeish (candeia)	N		Yes
Bignoniaceae	*Jacaranda macrantha* Cham. (caroba)	N		Yes
	Sparattosperma sp. (cinco-folhas)	N		
	Tabebuia impetiginosa (Mart. *ex* DC.) Standl. (ipê-roxo)	N		Yes
	Tabebuia chrysotricha (Mart. *ex* A. DC.) Standl. (ipê-mulato)	N		Yes
	Tabebuia serratifolia (Vahl) G. Nicholson (ipê-amarelo)	N		Yes
	Zeyheria tuberculosa (Vell.) Bureau (ipê-preto)	N		Yes
Bixaceae	*Bixa orellana* L. (urucum)	N		
Cannabaceae	*Trema micrantha* (L.) Blume. (crindiúva)	N		Yes
Caricaceae	*Carica papaya* L. (mamão)	E	x	
Casuarinaceae	*Casuarina equisetifolia* L. (casuarinas)	E		
Ebenaceae	*Diospyros kaki* L. f. (caqui)	E	x	
Elaeocarpaceae	*Muntingia calabura* L. (calabura)	E		
Euphorbiaceae	*Alchornea triplinervia* (Spreng.) Müll. Arg. (pau-de-bolo)	N		Yes
	Croton urucurana Baill. (adrago)	N		Yes
	Joannesia princeps Vell. (cotieira)	N		
	Hyeronima alchorneoides Allemao (liquerana)	N		Yes
	Mabea fistulifera Mart. (canudo-de-pito)	N		Yes
Lamiaceae	*Aegiphila sellowiana* Cham. (papagaio)	N		Yes
	Vitex montevidensis Cham. (maria-preta)	N		
Lauraceae	*Persea americana* Mill. (abacate)	E	x	
Leguminosae	*Anadenanthera peregrina* (L.) Speg. (angico-vermelho)	N		Yes
	Calliandra houstoniana (Mill.) Standl. (caleandra)	E		
	Caesalpinia pluviosa DC. (sibipiruna)	N		
	Cassia ferruginea (Schrad.) DC. (canafístula)	N		Yes
	*Erythrina verna*Vell. (pau-abóbora)	N		
	Erythrina speciosa Andrews (mulungu)	N		
	Hymenaea courbaril L. (jatobá)	N		
	Inga edulis Mart. (ingá)	N		Yes
	Dalbergia nigra (Vell.) Benth. (jacaranda-caviúna)	N		Yes
	Enterolobium contortisiliquum (Vell.) Morong (orelha-de-macaco)	N		Yes
	Machaerium stipitatum (DC.) Vogel (canela-de-velho)	N		Yes
	Machaerium nyctitans (Vell.) Benth. (jacarandá-bico-de-pato)	N		Yes
	Piptadenia gonoacantha (Mart.) J.F. Macbr. (jacaré)	N		Yes
	Schizolobium parahyba (Vell.) S.F. Blake (breu)	N		Yes
	Senna macranthera (Collad.) H.S. Irwin and Barneby (fedegoso)	N		Yes
Malpighiaceae	*Byrsonima sericea* DC. (massaranduva)	N		Yes
Malvaceae	*Bombax marginatum* (A. St.-Hil., Juss. and Cambess.) K. Schum. (castanha-mineira)	E	x	
	Ceiba speciosa (A. St.-Hil.) Ravenna (paineira)	N		Yes
	Luehea grandiflora Mart. (açoita-cavalo)	N		Yes
Melastomataceae	*Tibouchina granulosa* (Desr.) Cogn. (quaresmeira)	N		Yes
Meliaceae	*Cedrela fissilis* Vell. (cedro)	N		Yes
	Melia azedarach L. (cinamomo)	E		
	Toona ciliata M. Roem. (cedro-australiano)	E		
Moraceae	*Artocarpus heterophyllus* Lam. (jaca)	E	x	
	Morus nigra L. (amora)	E		
Moringaceae	*Moringa oleifera* Lam. (moringa)	E		
Musaceae	*Musa paradisiaca* L. (banana)	E	x	
Myrsinaceae	*Rapanea ferruginea* (Ruiz and Pav.) Mez (pororoca)	N		Yes
Myrtaceae	*Campomanesia xanthocarpa* (Mart.) O. Berg (gabiroba)	N	x	Yes
	Eugenia malaccensis L. (jamelão)	N	x	
	Eugenia uniflora L. (pitanga)	N	x	
	Myrciaria jaboticaba (Vell.) O. Berg (jaboticaba)	N	x	
	Psidium araca Raddi (araçá)	N	x	
	Psidium guajava L. (goiaba)	N	x	
	Syzygium jambos (L.) Alston (jambo)	E		
Pinaceae	*Pinus* sp. (pinus)	E		
Rhamnaceae	*Hovenia dulcis* Thunb. (ovenia)	E	x	
	Colubrina glandulosa Perkins (só-brasil)	N		Yes

Rosaceae	*Moquilea tomentosa* Benth. (oiti)	N		
	Eriobotrya japonica (Thunb.) Lindl. (ameixa)	E	x	
	Pyrus communis L. (pêra)	E	x	
	Prunus persica (L.) Batsch (pêssego)	E	x	
Rutaceae	*Citrus* sp. (limão-cravo)	E	x	
	Citrus sp. (mexerica)	E	x	
	Citrus sinensis (L.) Osbeck (laranja)	E	x	
	Citrus sp. (turanga)	E	x	
	Dictyoloma vandellianum A.H.L. Juss. (brauninha)	N		Yes
Sapindaceae	*Litchi chinensis* Sonn. (lichia)	E	x	
Solanaceae	*Solanum lycocarpum* A. St.-Hil. (lobeira)	N		Yes
	Solanum mauritianum Scop. (capoeira-branca)	N		Yes
Urticaceae	*Cecropia* sp. (embaúba)	N		Yes
Verbenaceae	*Citharexylum myrianthum* Cham. (pau-de-viola)	N		

Appendix F. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.106858.

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