Carbon dioxide fertilization offsets negative impacts of climate change on Arabica coffee yield in Brazil

by

Fabian Yoltic Francisco Verhage

Thesis report for the

Master of Science Climate Studies

Piracicaba, São Paulo, Brazil

February 2017

WAGENINGEN UNIVERSITY & RESEARCH

ESALQ Escola Superior de Agricultura "Luiz de Queiroz"

Abstract

Arabica coffee production provides a livelihood to millions of people worldwide. Climate change impact studies consistently project a drastic decrease of Arabica yields in current production regions by 2050. However, none of these studies incorporated the beneficial effects that elevated CO_2 concentrations are found to have on Arabica coffee yields, the so-called CO2 fertilization effect. To assess the impacts of climate change and elevated CO_2 concentrations on the cultivation of Arabica coffee in Brazil, a coffee yield simulation model was extended with a CO_2 fertilization and irrigation factor. The model was calibrated and validated with yield data from 1989 to 2013 of 42 municipalities in Brazil, and found to perform satisfactorily in both the calibration (R^2 = 0.91, d = 0.96, MAPE = 8.58%) and validation phase (R^2 = 0.96, d = 0.95, MAPE = 11.16%). The model was run for the 42 municipalities from 1980 to 2010 with interpolated climate data, and from 2040 to 2070 with climate data projected by five global circulation models according to the RCP 4.5 scenario. The model projects that yield losses due to high air temperatures and water deficit will increase, while losses due to frost will decrease. Nevertheless, extra losses are offset by the CO_2 fertilization effect, resulting in a net increase of the average Brazilian Arabica coffee yield of 0.8% to 1.48 t ha^{-1} in 2040-2070, assuming growing locations and irrigation use remain the same. Simulations further indicate that future yields can reach up to 1.81 t ha^{-1} if irrigation use is expended.

Keywords

simulation model, productivity, irrigation, global warming, elevated CO_2 concentration

Highlights

- Proposed Arabica coffee model represents historic yields with high accuracy.
- Yield losses due to high temperatures and water deficit will increase by 2040-2070.
- CO_2 fertilization will increase Arabica coffee's potential yield 8.6% by 2040-2070.
- Climate change will overall benefit yields in Brazilian Arabica coffee regions.
- Under full irrigation average Brazilian yield can reach up to 1.81 t ha^{-1}.

Student

Fabian Y. F. Verhage

Student number: 911010-873-110

Master of Science Climate Studies, specialization: Crop and Weed Ecology

Wageningen University, Wageningen, Netherlands

Thesis course code: CSA80436

Supervisor chair group and examiner

Niels P.R. Anten

Centre for Crop Systems Analysis, Wageningen University, Wageningen, Netherlands

Supervisor outside chair group

Paulo C. Sentelhas

Department of Biosystems Engineering, ESALQ, University of São Paulo, Piracicaba, Brazil

Contents

1. Introduction

Climate conditions strongly determine Arabica coffee (*Coffea arabica* L.) yield, as soil water availability and air temperature govern its physiological processes and phenological phases along its two-year growing cycle (Camargo 2010). Moreover, climate conditions control the intensity of coffee's major pests and diseases, such as the coffee berry borer (*Hypothenemus hampei* Ferrari) and coffee rust (*Hemileia vastatrix* Berkeley & Broome) (Ghini et al. 2011; Jaramillo et al. 2011). Additionally, as coffee plants have an average lifespan of 30 years and can be productive for over 50 years they are especially susceptible to changes in climate (Bunn et al. 2015). These characteristics make climate change a clear threat to the production of coffee, its 25 million farmers (Jaramillo et al. 2011) and millions of daily consumers worldwide (Butt & Sultan 2011).

1.1 Habitat and growth cycle

Coffea arabica, hereafter referred to as Arabica, originates as an under-story shrub from the southwestern Ethiopian highlands (Bote 2016). This area has a mean annual air temperature between 18 and 22°C with little seasonal variability, more than 1,600 mm of annual rainfall and a dry season of three months (Camargo 2010). Arabica provides 75% of the world's coffee, while Robusta (*Coffea canephora Pierre ex A. Froehner*) provides almost all the remaining 25% (Davis et al. 2012). The optimal mean annual air temperature for Arabica ranges between 18 and 21°C (DaMatta 2004). Higher temperatures accelerate Arabica fruit development, which leads to a loss of quality, while at lower mean annual air temperatures growth is depressed (Davis et al. 2012). Temperatures below 0°C for short periods can nullify the harvest, while frosts for prolonged periods can damage the plants irreversibly (Santos 2005). The optimal annual rainfall for Arabica is 1,800 mm (Chemura et al. 2016). Despite the importance of the climate to define the yield of Arabica, the vulnerability of coffee plants to sub-optimal and supra-optimal temperatures and water deficits depends on the phenological phase when they occur.

Arabica plantations pass through six phenological phases along their two-year production cycle, as described by Camargo & Camargo (2001) for the Catuaí and Mundo Novo cultivars in Brazil. In the first phase the vegetative buds are formed. This phase runs under long-day conditions from September until March. In the second phase, these vegetative buds are induced to floral buds. This happens from April to August, when days are shortening. In the third phase the coffee flowers and the young green coffee cherries are formed (Camargo & Camargo, 2001). The start of this phase, the anthesis, is triggered by rainfall or irrigation greater than 7 mm within 10 days once the growing degree days accumulate 1579°C day or the potential evapotranspiration accumulates 335 mm since the beginning of April (Zacharias et al. 2008). This third phase usually occurs from September until December. In the fourth phase, which runs from January until March, the beans are formed. In the fifth phase the beans ripen, which usually occurs from April to June. In the last and sixth phase the coffee plants senesce their tertiary branches (Camargo & Camargo, 2001). The harvesting period generally takes place between May and August (Cardenas 2015), during the dry season. The weather conditions to obtain a maximum yield and quality differ per phenological phase. In the first, third and fourth phases sufficient rainfall or irrigation is very important. If there is a water deficit during these phases, fewer buds are formed, the anthesis is delayed, flowers might abort and beans remain underdeveloped (Cardenas 2015). Contrarily, in the second, fifth and sixth phases, Arabica requires a moderate water deficit. If there is too much rainfall during these phases, floral buds do not mature evenly, beans do not ripe steadily and beans fermentation promoted by microorganisms is more vigorous, negatively affecting the quality. An important consequence of the two-year production cycle of coffee is the alternating quantity of its production, referred to as the biennial bearing effect (Bote & Vos 2016).

The dependency of Arabica yield on specific climate conditions has been confirmed by almost a dozen agro-ecological zoning studies, which all conclude that the area suitable for Arabica cultivation in their region of study will decrease by 2050 due to climate change. The majority of these studies infer the bioclimatic requirements for Arabica cultivation from current production locations, for example with the Maximum Entropy (MaxEnt) methodology (Sachs et al. 2015). Three of these agro-ecological zoning studies project that under the Special Report on Emissions Scenario (SRES) A2 the suitable area for Arabica worldwide will have decreased by respectively 19 (Ovalle-Rivera et al. 2015), 50 (Bunn et al. 2015) and 56% (Sachs et al. 2015) in 2050. This global trend reflects itself on specific predictions for individual countries, either with a smaller production, such as Haiti (Eitzinger et al. 2013), Kenya (CIAT - International Center for Tropical Agriculture 2010), Nicaragua (Eitzinger et al. 2013), Tanzania (Craparo et al. 2015), Uganda (Jassogne et al. 2013) and Zimbabwe (Chemura et al. 2016), as well as with a greater production, such as Indonesia (Schroth et al. 2014), Mexico (Eitzinger et al. 2013) and Brazil (Assad et al. 2004). Brazil is the largest Arabica producer in the world, responsible for over 33% of the production (Sachs et al. 2015). However, projections of suitable land lost in 2050 to climate change range from 25% under SRES A2 (Ovalle-Rivera et al. 2015) to 85% under Representative Concentration Pathway (RCP) 8.5 (Bunn et al. 2015). If these projections materialize, millions of people worldwide who depend on coffee for their livelihoods would be at risk (Bunn et al. 2015).

1.2 CO_2 fertilization and plant acclimation

All these aforementioned agro-ecological zoning studies project a grim future for Arabica cultivation around the world, but none of them incorporated the effects of CO_2 fertilization and plant acclimation in their assessments (Martins et al. 2016). The atmospheric CO_2 concentration is projected to increase from the pre-historic ~280 ppm to between 421 and 936 ppm by the end of the XXI century (Stocker et al. 2015). It is clear that augmented CO_2 concentrations raise photosynthetic rates and there are indications that they enhance the water-use efficiency of tropical trees, such as coffee (van der Sleen et al. 2015). However, it remains unclear under which conditions augmented CO_2 concentrations stimulate biomass growth (Sterck et al. 2016). Analysis of growth rings of tropical trees in Bolivia, Cameroon and Thailand indicated, for example, that augmented CO_2 concentrations in the past 150 years enhanced their water-use efficiency, but did not stimulate stem growth (van der Sleen et al. 2015). There are several possible explanations for this. Elevated CO_2 concentrations come with increased air temperatures. This can cause plant stress which offsets additional stem growth. Trees might not allocate the additional assimilated carbon to growth, but instead to fruit production or roots biomass. And last but not least, other factors such as nutrients can limit additional growth (van der Sleen et al. 2015). Other studies suggest that tropical trees can acclimatize to increased air temperatures, drought and under certain conditions to elevated CO_2 concentrations, but it remains unclear to which degree (Sterck et al. 2016).

Experiments in which coffee was cultivated under elevated CO_2 conditions suggest that augmented CO_2 concentrations stimulate plant growth and increase tolerance to higher air temperatures (DaMatta et al. 2016; Ghini et al. 2015; Rodrigues et al. 2016). Arabica cultivars Icatu and IPR108 grown under elevated air CO_2 concentrations of 700 ppm improved carbon assimilation and biochemical functioning under different day/night air temperatures ranging from 25/20 to 42/34°C. At an air temperature of 31/25°C the elevated air CO_2 conditions promoted higher water-use efficiency as well (Rodrigues et al. 2016). These effects can lead to higher coffee yields as demonstrated by an experiment with the Arabica Catuaí Vermelho IAC 144 and Obatã IAC 1669–20 cultivars grown for two years under free-air CO_2 enrichment of 550 ppm. Compared to Arabica plants grown under actual CO_2 concentrations, but with similar climate conditions, this study showed that yields increased 14.6 and 12% respectively (Ghini et al. 2015). It is likely that these yield increases will be sustained under higher CO_2 concentrations, as Arabica plants do not demonstrate downregulation of photosynthesis under these conditions (Rodrigues et al. 2016). Photosynthesis of coffee is strongly limited by diffusional constraints at the stomatal level, instead of biochemical constrains (DaMatta et al. 2016). Coffee can therefore benefit significantly from the additional assimilated carbon. Furthermore, different to tropical forest trees, the CO_2 fertilization effect will not be limited by nutrient-deficiencies in most plantations, as coffee plants are well fertilized in the countries responsible for most of the coffee production (Sachs et al. 2015). In addition, coffee might allocate part of the additional assimilated carbon to the root system and vegetative growth, instead of the fruits, but this will still benefit the potential yield. However, similar to tropical forest trees, increasing temperatures and changing rainfall patterns might still offset the benefit of additional assimilated carbon and increased water-use efficiency for coffee. As augmented CO_2 concentrations have such a significant effect on the photosynthetic rates and heat tolerance of coffee, these effects have to be incorporated in models to correctly assess the impact of the climate change on Arabica production. These effects cannot be incorporated in agro-ecological zoning methods, because these do not simulate the biological processes of coffee, on which the augmented CO_2 concentrations have their effect.

Unfortunately, models that can simulate these biological processes for coffee plants are still in their early stages of development (Sachs et al. 2015). The model developed by Camargo et al. (2005) estimates coffee yield at plant, field, farm or municipal level for Brazilian growing conditions on the basis of mean and minimum air temperatures and water deficit data, distinguishing between the physiological phases of the plant (Camargo et al. 2005). Differently, the model developed by Rodríguez et al. (2011; 2013) incorporates solar radiation, air temperature and rainfall to estimate the effect of the coffee berry borer on yields in Brazilian and Colombian municipalities. The econometric model by Estrada et al. (2012) incorporates mean summer and winter air temperatures, rainfall and minimal salary data to estimate the impact of climate change on the production of coffee in the Veracruz region in Mexico. Another statistical coffee model was developed by Sachs et al. (2015) and incorporates air temperature and rainfall data, but does not distinguish between the physiological phases of coffee. A model with mechanistic components was developed by Maro et al. (2014), incorporating soil fertility data to estimate yields in Northern Tanzania, but is not publically available. Incorporating the effects of augmented CO_2 concentrations into one of these models to quantitatively assess the impact of climate change on Arabica yields, would greatly assist farmers, researchers and policy makers to take adaptation measures (Craparo et al. 2015).

Among the quantitative coffee models that are publically available, the model proposed by Camargo et al. (2005) has several characteristics which make it especially suitable to assess the impact of climate change with incorporation of the CO_2 fertilization effect. First of all, it estimates Arabica yield in reference to the potential yield, which can be increased to incorporate the effect of the CO_2

fertilization. Furthermore, the model takes into account the differing vulnerability of sub- and supra-optimal temperatures and water deficit during the different phenological phases. Last but not least, the model has been calibrated for commercial cultivars of Brazil, for which the experiments of augmented CO_2 concentrations have been carried out, and for which there is historic yield data available at municipal level (IBGE 2016), which facilitates the calibration and validation of the model for climate change studies.

1.3 Objectives

Therefore, the main purpose of this study was to assess the impact of climate change on Arabica yield in Brazil by applying the Camargo coffee simulation model enhanced by incorporating the effect of CO_2 fertilization. Thereby we hypothesize that CO_2 fertilization will offset a substantial part of the negative impacts of climate change on Arabica yield, caused by higher air temperatures and water deficit.

The assessment of the impact of changed rainfall patterns, air temperature increases and augmented CO_2 concentrations on the Arabica yield in Brazil serves several goals. First of all, understanding the impact of climate change on the Brazilian coffee production can motivate mitigation and adaptation strategies. Secondly, the adapted model can assist climate change impact assessments in other countries, once it is calibrated for these regions. Thirdly, it contributes to the development of coffee growth models, which can ultimately be used to provide decision support to coffee producers, researchers and policy makers. To this end four specific objectives were formulated:

1. To incorporate the effect of CO_2 fertilization and irrigation into the Arabica coffee simulation model proposed by (Camargo et al. 2005);
2. To calibrate and validate the model for the Arabica production regions in Brazil;
3. To assess the model's sensitivity to changes in air temperature and rainfall;
4. To apply the model to estimate the impacts of climate change on Arabica yield and production in Brazil by 2040-2070.

2. Material and methods

2.1 Data

Climate, coffee yield and irrigation data of 42 municipalities was used to calibrate, validate and run the model of Camargo et al. (2005). The 42 municipalities were selected to represent the main Arabica producing regions in Brazil (Fig. 1, Table 1). The municipalities were selected dispersed over each state where Arabica is produced, and that had: 1) only reported production of Arabica (and no Robusta); 2) more than 500 hectares planted with coffee; 3) yield data available from 1989 to 2013. Afterwards 2/3 of the municipalities per state were selected for calibration and 1/3 for validation.

The coffee yield of each municipality was calculated with data of harvested coffee and cultivated coffee area per municipality published annually by the Brazilian Institute of Geography and Statistics (IBGE 2016). The IBGE data does not differentiate between Arabica and Robusta from 1989 until 2011, but from 2012 until 2014 specific production data for Arabica and Robusta was available. To solve this limitation, only municipalities were selected that had exclusively Arabica production from 2012 until 2014, assuming their historic production was also solely Arabica. The percentage of coffee area with irrigation per municipality was obtained from the 2006 agricultural census held by the IBGE

(2006). This data was not available for 5 municipalities, as can be seen in Table 1, so these gaps were filled with the percentage of coffee farms with irrigation per municipality from the before mentioned IBGE (2006).

Daily maximum and minimum air temperatures and rainfall data were obtained from Xavier et al. (2015). Xavier et al. (2015) interpolated temperature data from a total of 735 weather stations and rainfall data from 3625 rain gauges throughout Brazil from 1980 to 2013 to a gridded resolution of 0.25° × 0.25°. The climate data was downloaded for the coordinates of each municipality's main city center. For three municipalities (Barreiras, Mucugê, Rio Pardo de Minas) this data was corrected to account for the substantial difference in altitude between the municipality's main city and its highlands, where the coffee is cultivated. The climate classification of each municipality according to the Köppen system, mapped by Alvares et al. (2013), is presented in Fig. 1.

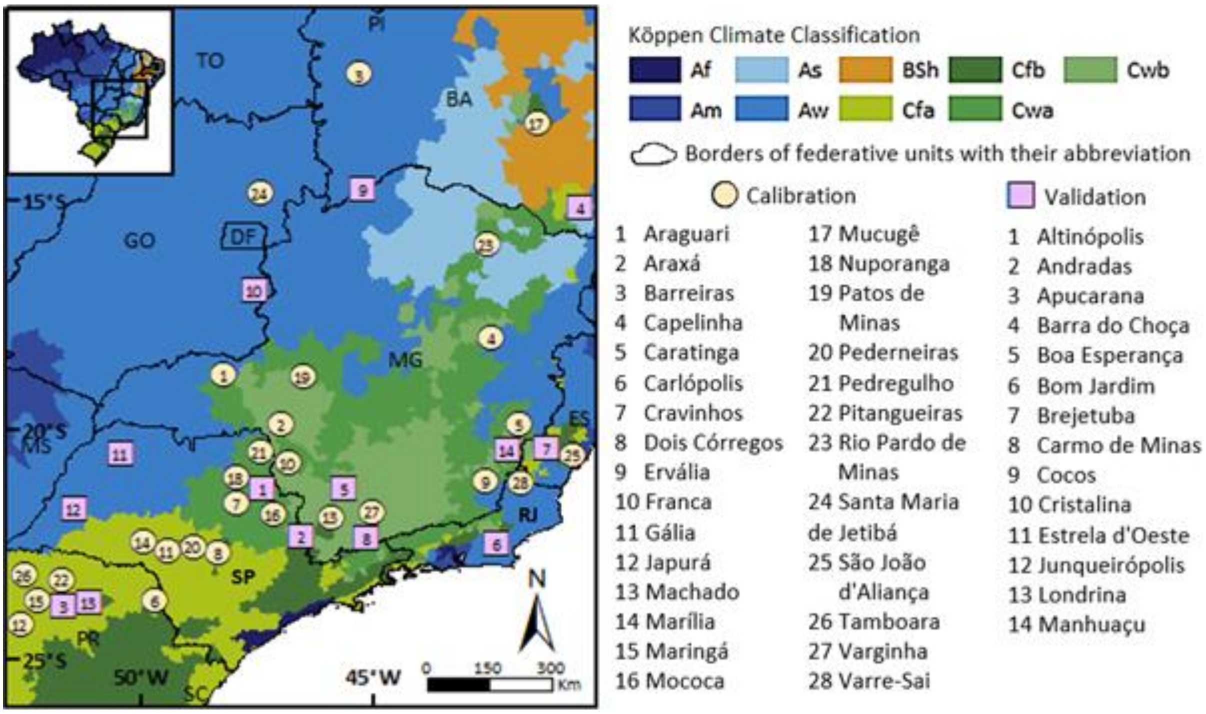

Fig. 1. Location of the 28 calibration and 14 validation municipalities displayed on a map with the climate classification according to Köppen system (Alvares et al. 2013), whereby: Aw = tropical zone with dry winter; Cfa = oceanic climate without dry season with hot summer; Cfb = oceanic climate without dry season with temperate summer; Cwa = humid subtropical zone with dry winter and hot summer; and Cwb = humid subtropical zone with dry winter and temperate summer.

Table 1. Municipality, federative unit of the state, climate classification according to the Köppen system, latitude and longitude in decimal degrees, altitude, percentage of coffee area with irrigation in 2006 (or percentage of coffee farms with irrigation that year in case of a *), number of years with yield data from 1989 to 2013, and weighted observed yields over that period (avg. obs. yield).

Municipality name / Climate classification	State	Lat. S	Long. W	Alt. (m)	Irrigated area (%)	Years with data	Avg. obs. yield (t ha^{-1})
Andradas	MG	22.07	46.57	887	2	23	1.45
Araxá	MG	19.59	46.94	990	3*	23	1.63
Boa Esperança	MG	21.09	45.57	790	5	23	1.26
Bom Jardim	RJ	22.16	42.43	575	37	23	1.62
Capelinha	MG	17.69	42.52	935	12	23	1.21
Carmo de Minas	MG	22.12	45.13	906	1*	23	1.47
Ervália	MG	20.84	42.65	740	0	23	0.98
Franca	SP	20.54	47.40	953	8	23	1.34
Machado	MG	21.68	45.92	853	2	23	1.44
Manhuaçu	MG	20.26	42.03	653	1	23	1.17
Varginha	MG	21.55	45.43	933	3	23	1.21
Cwb				838	7	23	1.34
Altinópolis	SP	21.02	47.37	895	4	22	1.75
Caratinga	MG	19.79	42.14	630	5	23	1.12
Cravinhos	SP	21.34	47.74	791	82	23	1.81
Mococa	SP	21.47	47.01	641	18	23	1.06
Nuporanga	SP	20.71	47.74	778	82	23	2.02
Patos de Minas	MG	18.59	46.51	832	49	23	2.13
Pedregulho	SP	20.26	47.48	1024	18	23	1.50
Rio Pardo de Minas	MG	15.62	42.54	1263	74	23	1.37
Cwa				857	42	23	1.60
Apucarana	PR	23.55	51.46	863	2	22	1.28
Barra do Choça	BA	14.87	40.58	880	17	23	0.89
Carlópolis	PR	23.48	49.73	504	7	23	1.72
Dois Córregos	SP	22.37	48.39	696	4	23	1.75
Gália	SP	22.29	49.55	567	26	23	1.21
Japurá	PR	23.47	52.55	470	2*	23	1.07
Londrina	PR	23.31	51.16	564	4	23	1.34
Marília	SP	22.21	49.95	675	31	22	1.05
Maringá	PR	23.43	51.94	564	10	23	1.04
Pederneiras	SP	22.35	48.78	520	99	23	1.56
Pitangueiras	PR	23.23	51.59	519	2	20	1.89
Tamboara	PR	23.20	52.50	460	2*	23	1.23
Varre-Sai	RJ	20.93	41.87	692	1	20	1.33
Cfa				613	16	22	1.34
Araguari	MG	18.65	48.19	922	75	23	1.79
Barreiras	BA	12.15	45.00	606	100	17	2.26
Cocos	BA	14.18	44.54	565	93	16	2.01
Cristalina	GO	16.77	47.61	1231	97	23	1.80
Estrela d'Oeste	SP	20.29	50.40	501	0*	22	0.98
Junqueirópolis	SP	21.51	51.43	429	17	23	0.74
São João d'Aliança	GO	14.44	47.37	1048	98	23	1.65
Aw				783	69	21	1.60
Brejetuba	ES	20.14	41.30	749	1	16	1.36
Mucugê	BA	13.01	41.37	1285	74	23	1.71
Santa Maria de Jetibá	ES	20.03	40.74	707	9	23	1.19
Cfb				914	28	21	1.42
Brazil				815	21	23	1.42

2.2 Climate scenario

Five different global circulation models were used to generate the climate data for the years from 2040 to 2070 with global greenhouse gas emissions according to Representative Concentration Pathway (RCP) 4.5 (van Vuuren et al. 2011). RCP 4.5 was chosen because the pledges of national governments worldwide to reduce greenhouse gas emissions would lead to a temperature increase of 2.3 to 3.5°C by 2100, with 2.8°C as the most likely estimate (Climate Action Tracker 2016). A temperature increase of 2.8°C by 2100 would be in line with RCP 4.5 (Sanford et al. 2014). The five global circulation models were selected from the Coupled Model Intercomparison Project Phase 5 (CMIP5) on the ability to represent the spatial and seasonal distribution of rainfall in different regions of Brazil with highest correlation and lowest root-mean-square error. The models were selected for their ability to represent historic rainfall, because this variable is considered to be more complex to simulate then temperature (Gulizia & Camilloni 2015). The five CMIP5 models that were selected were: CNRM_CM5, GISS_E2R, HadGEM2-ES, MIROC4h and MRI-CGCM3. The CNRM_CM5 and GISS_E2R models best represented historic rainfall respectively in the La Plata Basin and Amazon region, in a comparative study of seven CMIP5 models by Silveira et al. (2013). The HadGEM-ES model was selected because it performed best for the Amazon and South American Monsoon System regions compared to ten other CMIP5 models in a study of Yin et al. (2013). And the MIROC4h and MRI-CGCM3 models were selected because they best represented historic rainfall in respectively South East and central Brazil in a comparative study conducted by Gulizia & Camilloni (2015). The climate data was generated according to these five CMIP5 models with the Climate Scenario Generation Tool for R from the Agricultural Model Intercomparison and Improvement Project (Hudson & Ruane 2013). The daily weather data of Xavier et al. (2015) from 1980 to 2010 was used as baseline. The daily weather data was grouped to 10-day periods in RStudio (RStudio Team 2015), such that the third 10-day period of each month had 8, 9, 10, or 11 days in accordance with the duration of the month.

2.3 Arabica coffee yield model

The model applied in this study is an adaptation of the agrometeorological coffee yield model developed by Camargo et al. (2005) and calibrated to plant, field and farm levels for the state of São Paulo by Santos (2005). Camargo et al. (2005) tested the model on a municipal level, estimating the yields in four municipalities in São Paulo state with historic weather data for the harvests from 2001 to 2005. A statistical analysis of the estimated and observed yields generated a coefficient of determination (R^2) of 0.74 with a random and systematic errors of respectively 0.3 and 0.4 t ha^{-1}. These results showed that the model has the capacity to estimate the yields of municipalities in São Paulo with good accuracy and reasonable precision. The model of Camargo et al. (2005) can be represented as:

$$\mathrm{Yest} = \mathrm{Yp}\left(1 - \mathrm{Kb}\frac{\mathrm{Ypre}}{\mathrm{Yp}}\right)\left(1 - \frac{\mathrm{Ltmin}}{100}\right)\left(1 - \frac{\mathrm{Ltmean}}{100}\right)\left(1 - \frac{\mathrm{Lwdef}}{100}\right) \quad (1)$$

where Yest is the estimated yield (t ha^{-1}) and Yp is the potential yield (t ha^{-1}). The Yp is set by Camargo et al. (2005) as the maximal observed yield incremented by 10%. This increment of the maximal observed yield is assumed to account for losses under sub-optimal crop management (Kanemasu 1983, as cited in Picini et al. 1999). Ypre is the yield of the previous year estimated by the model in t ha^{-1}, or for the first year the Yp divided by 2. Kb is the biennality coefficient and represents the tendency of coffee plants to alternate high and low bean production. Kb was set to 0.45 as determined in the calibration of the model for the municipal scale (Camargo et al. 2005). Ltmin, Ltmean and Lwdef are, respectively, the penalty factors for frosts, high air temperature in the beginning of fruit formation, and water deficiency along the production cycle, as will be described subsequently.

The yield loss caused by adverse low air temperatures (frost) is represented by Ltmin, which was calculated as:

$$\mathrm{Ltmin} = 140.34455 \times \exp^{\left(\frac{-(\mathrm{Tmin}-2.9580)^2}{6.266508}\right)} \qquad (2)$$

where Tmin is the absolute minimum air temperature at 2 m height, endured from April of year “n” to March of year “n+1”, which penalizes the yield if it falls below 2°C, as defined by Camargo et al. (2005).

The yield loss caused by adverse high temperatures during the beginning of fruit formation was calculated on the basis of the mean air temperature:

$$\mathrm{Ltmean} = 141.771 \times \exp^{-\exp^{(17.9486-0.6782\ \mathrm{Tmean})}} \qquad (3)$$

where Tmean is the mean air temperature at 2 m height, during the 30 days after flowering, when coffee is most vulnerable to high temperatures. Tmean was calculated as the average of the minimum and maximum air temperatures. The flowering was set to start in the first 10-day period from July onwards for which the accumulated potential evapotranspiration since April is greater than 335 mm, which corresponds to 1579°C day, and rainfall is greater than 7 mm (Zacharias et al. 2008). The model penalizes the yield if the mean temperature in this critical period after flowering exceeds 23°C following a Gompertz function, which according to (Santos 2005) represents penalization of absolute maximum air temperatures exceeding 34°C.

The yield loss due to the water deficit was calculated with the following equation:

$$\mathrm{Lwdef} = \mathrm{Ky}\left(1 - \frac{\mathrm{ETa}}{\mathrm{ETp}}\right) \qquad (4)$$

where ETa is the actual evapotranspiration, calculated through the Thornthwaite & Mather (1955) water balance model with an assumed soil water holding capacity of 100 mm. ETp is the potential evapotranspiration and was calculated with the method of Thornthwaite (1948). Ky is the yield response factor which penalizes the yield as a function of the water deficit in accordance to the vulnerability of the coffee plant along its phenological phases. The yield response factors were calibrated by Santos (2005) with historic yield data and expressed in two series (Table 2). The first of these series starts in April and runs until flowering. The second starts at flowering and runs for seventeen 10-day periods. After this, the coffee is assumed to be harvested.

To improve the performance of the model, making it applicable for regions with irrigated Arabica and for future atmospheres with higher CO_2 levels, it was altered in four ways. Firstly, the potential yield was replaced by a so-called reference yield (Yref), which represents the yield of a municipality under optimal climate conditions, but with actual sub-optimal management practices. Secondly, the bienniality coefficient was eliminated, because biennial bearing affects the coffee yield of individual years, but not the average yield over a prolonged period, which is relevant in this study. Furthermore, as the magnitude of the biennial bearing effect depends on the management practices, this loss is already considered in the determination of the Yref. Thirdly, use of irrigation was set to reduce the impact of the water deficit as well as of high air temperatures, as irrigation can cool the canopy temperature. Lastly, augmented CO_2 concentrations in future climates were incorporated by increasing the Yref proportionally. The adapted model can be represented as:

$$\mathrm{Yest} = \mathrm{Yref}\left(1 - \frac{\mathrm{Ltmin}}{100}\right)\left(1 - \frac{\mathrm{Ltmean}}{100}\right)\left(1 - \frac{\mathrm{Lwdef}(1-\mathrm{Ir})}{100}\right) \quad (5)$$

where Ir is the fraction of coffee area with irrigation in a given municipality. This Yref was determined as follows:

$$\mathrm{Yref} = \mathrm{Ymean} * \mathrm{Kyref} * \mathrm{Cfert} \quad (6)$$

where Ymean is the mean yield of Arabica in a municipality observed along the 23 years before; Kyref is the reference yield coefficient; and Cfert the percentage of Arabica yield increase due to CO_2 fertilization. The adapted model estimates yields on the basis of the reference yield instead of the potential yield as in the original model for two reasons; primarily, because the potential yield was a function of the maximum observed yield, which makes it very sensitive to erroneous outliers; and secondly, the gap between the reference yield and the potential yield, once it is determined, give an estimation of the successfulness of the non-climatic management practices, such as pest, disease and weed control, pruning and fertilizer application. The Kyref was determined through calibration of the model with historic data. To adjust the Yref to scenarios with elevated CO_2 concentrations, the Ymean was also multiplied by Cfert, the CO_2 fertilization effect. This value was determined by the increased yield of Arabica under elevated CO_2 concentrations, due to improved photosynthetic performance. As Arabica does not demonstrate symptoms of photosynthetic downregulation under higher CO_2 concentrations (DaMatta et al. 2016), the augmentation of yield under elevated CO_2 concentrations can be attributed to the increased potential yield of the plant, which also increase the reference yield as used in this study. The widely used Brazilian coffee cultivars Catuaí and Obatã grown with free-air CO_2 enrichment to 550 ppm, yielded 14.6% and 12% more (Ghini et al. 2015). The average CO_2 concentration between 2040 and 2070 is projected to be 493 ppm under RCP 4.5 (van Vuuren et al. 2011). So, if the positive effect of CO_2 fertilization effect on coffee yield persists as expected and its effect on Catuaí and Obatã is representative for other cultivars in Brazil, then Yref of Arabica in Brazil between 2040 and 2070 will increase by 8.56%. Cfert is therefore equal to 1.0856.

Table 2. Series 1 and 2 with the yield response factors (Ky) along the coffee crop cycle per 10-day periods. The values were determined by Santos (2005), with exception of the values from Nov 1 until Jan 3, which are a continuation of the value of Oct 3 to enable the sensitivity analysis.

Series 1				**Series 2**	
10-day period	Ky	10-day period	Ky	10-day period	Ky
Apr 1	0.04	Sep 1	0.02	Anthesis	0.04
Apr 2	0.04	Sep 2	0.02	+1	0.05
Apr 3	0.04	Sep 3	0.05	+2	0.05
May 1	0.03	Oct 1	0.05	+3	0.10
May 2	0.03	Oct 2	0.10	+4	0.10
May 3	0.03	Oct 3	0.10	+5	0.15
Jun 1	0.02	Nov 1	0.10	+6	0.15
Jun 2	0.02	Nov 2	0.10	+7	0.20
Jun 3	0.02	Nov 3	0.10	+8	0.20
Jul 1	0.01	Dec 1	0.10	+9	0.20
Jul 2	0.01	Dec 2	0.10	+10	0.20
Jul 3	0.01	Dec 3	0.10	+11	0.15
Aug 1	0.00	Jan 1	0.10	+12	0.15
Aug 2	0.00	Jan 2	0.10	+13	0.10
Aug 3	0.00	Jan 3	0.10	+14	0.10
				+15	0.10
				+16	0.05

In the original model the use of irrigation was not taken into account (Camargo et al. 2005). However, irrigation has a significant effect on crop water deficit and plants' maximum air temperatures in coffee plantations (Steiner et al. 1983). Therefore, an irrigation factor was included in the model to calculate the losses due to water deficit and high air temperatures more accurately.

To account for the effect of irrigation on the water deficit, the loss of water deficit was reduced in proportion to the percentage of irrigated coffee area in a given municipality (Ir). As irrigation in Brazilian coffee plantations is predominantly realized with sprinklers (Paulino et al. 2011; ANA - Agência Nacional de Águas & Embrapa Milho e Sorgo 2016), the irrigation also has an effect on the canopy temperature (Lobell et al. 2008). Sprinkler irrigation is found to reduce the maximum, minimum, and mean canopy air temperatures during irrigation by respectively 3.0, 1.5, and 1.5°C in a corn field (Steiner et al. 1983). This reduction in temperature is most pronounced in hot days and takes 3 hours or longer to be gradually undone after irrigation (Urrego-Pereira et al. 2013). To include this effect of irrigation on the canopy temperature, the mean air temperature was reduced by 2°C proportionally to the coffee area irrigated in the municipality. This effect is represented as:

$$\mathrm{Tmean_{Ir}} = \mathrm{Tmean} - 2 * \mathrm{Ir} \quad (7)$$

whereby $\mathrm{Tmean_{Ir}}$ replaces Tmean in Equation 3. It must be noted that for Brazil there was only data available on irrigation use among coffee farms for the year of 2006, so this figure was used as representative of Ir for the years 1980-2013.

2.4 Calibration and validation

The value for the reference yield coefficient (Kyref) was determined collectively for all sites by calibration. The model as described before was calibrated with the yield and climate data of 28 municipalities from 1989 to 2013 (Fig. 1, Table 1). The calibration was carried out by reaching the highest index of confidence (C) in an iterative way and with help of the Solver function of Microsoft Excel (2016). The model was validated by applying the model with the calibrated Kyref on the remaining 14 municipalities (Fig. 1, Table 1).

The results from the calibration and validation phases were analyzed with the following statistical indexes: Willmott agreement index (d) (Willmott et al. 1985); mean absolute error (MAE); the percentage of the mean absolute error (MAPE); mean error (ME); coefficient of determination (R^2); the root mean square error (RMSE); and the confidence index (C) (Camargo & Sentelhas 1997). The indexes are represented as followed:

$$\mathrm{d} = 1 - \frac{\sum_{i=1}^{n}(\mathrm{Est_i} - \mathrm{Obs_i})^2}{\sum_{i=1}^{n}(|\mathrm{Est_i} - \mathrm{Obs_m}| + |\mathrm{Obs_m}|)^2} \quad (8)$$

$$\mathrm{MAE} = \frac{1}{n} * \sum_{i=1}^{n}(|\mathrm{Est_i} - \mathrm{Obs_i}|) \quad (9)$$

$$\mathrm{MAPE} = \left[\frac{1}{n} * \sum_{i=1}^{n}\left(\frac{|\mathrm{Est_i} - \mathrm{Obs_i}|}{\mathrm{Obs_i}}\right)\right] * 100 \quad (10)$$

$$\mathrm{ME} = \frac{1}{n} * \sum_{i=1}^{n}(\mathrm{Est_i} - \mathrm{Obs_i}) \quad (11)$$

$$\mathrm{R}^2 = \frac{\frac{1}{n} * \sum_{i=1}^{n}\left[(\mathrm{Est_i} - \mathrm{Obs_m}) * (\mathrm{Obs_i} - \mathrm{Obs_m})\right]^2}{\left[\frac{1}{n} * \sum_{i=1}^{n}(\mathrm{Est_i} - \mathrm{Est_m})^2\right] * \left[\frac{1}{n} * \sum_{i=1}^{n}(\mathrm{Obs_i} - \mathrm{Obs_m})^2\right]} \quad (12)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} * \sum_{i=1}^{n}(\mathrm{Est_i} - \mathrm{Obs_i})^2} \quad (13)$$

$$\mathrm{C} = \sqrt{\mathrm{R}^2} * \mathrm{d} \quad (14)$$

whereby Est_i and Obs_i are the estimated and observed coffee yields (t ha^{-1}), respectively, of each specific year (i); Est_m and Obs_m are the mean estimated and observed coffee yields (t ha^{-1}), respectively, and; n is the number of observations.

2.5 Sensitivity analysis

To gain insight on how the model reacts to changes of mean and minimum air temperatures and rainfall, a sensitivity analysis was carried out for the municipalities of Apucarana (Paraná state), with Cfa climate, Franca (São Paulo state), with Cwb, and Cocos (Bahia state), with an Aw climate, with baseline climate from the years 1980-2010. These three locations were chosen to represent different climates where Arabica is produced in Brazil. The model's sensitivity was measured as percentage change of yield (t ha^{-1}) with a temperature change of 1, 2 or 3°C decrease or increase, and a rainfall change of 15, 30 and 45% decrease or increase.

2.6 Climate change impact analysis

The Arabica yield results were analyzed to conclude how climate change would impact Arabica cultivation in Brazil, comparing the average yields and losses from 1980-2010 to those from 2040-2070, under three different irrigation scenarios: actual irrigated area in each municipality (referred to as "constant" irrigation), 0 and 100% irrigated coffee area. To extrapolate the results, the yields and losses of each municipality were averaged per climate zone to which they adhered. These climate zones were: humid subtropical zone with dry winter and temperate summer (Cwb), humid subtropical zone with dry winter and hot summer (Cwa), oceanic climate without dry season with hot summer (Cfa), tropical zone with dry winter (Aw), and oceanic climate without dry season with temperate summer (Cfb). Lastly, the yields and losses of each climate zone were weighted according to their share of total Arabica production in Brazil from 2012 to 2015 (Table 3). This was done to determine an average representative of the five most important Arabica coffee regions in Brazil, which together are responsible for 97.7% of Arabica production (Table 3).

Table 3: Annual Arabica production, share and average yield of each climate zone in Brazil from 2012 to 2015 (IBGE 2016).

Climatic classification (Köppen)	**Annual production (tons)**	**Share Brazilian production (%)**	**Average yield (t ha^{-1})**
Humid subtropical with dry winter and temperate summer (Cwb)	1153080	53.6	1.25
Humid subtropical with dry winter and hot summer (Cwa)	419448	19.5	1.15
Oceanic climate without dry season with hot summer (Cfa)	241220	11.2	1.07
Tropical zone with dry winter (Aw)	176612	8.2	1.12
Oceanic climate without dry season with temperate summer (Cfb)	111896	5.2	1.24
Tropical with dry summer (As)	24572	1.1	0.57
Dry with low latitude and altitude (BSh)	21603	1.0	0.53
Tropical monsoon (Am)	1292	0.1	0.50
Tropical without dry season (Af)	124	0.0	0.35
Brazil	2149847	100	1.07

3 Results

3.1 Model Calibration and Validation

The calibration and validation of the coffee yield simulation model confirmed that it is able to represent the average yield from 1989-2013 satisfactorily (C = 0.92). In the calibration phase, the model estimated the mean yield of 28 municipalities with high precision (R^2 = 0.91) and accuracy (d = 0.96, RMSE = 0.15 t ha^{-1}), and reduced errors (MAPE = 8.58%) (Table 4). These results were obtained with the reference yield coefficient (Kyref) calibrated as 1.24. The validation phase confirmed the suitability of the model, as it represented historic average yield with even a higher precision (R^2 = 0.96), high accuracy (d = 0.95, RMSE = 0.20 t ha^{-1}) and acceptable errors (MAPE = 11.16%) (Table 4). However, particularly in the validation phase, the model underestimated low yields and overestimated high yields (y = 1.4886x - 0.6507), to which part of the mean errors can be attributed (MAE = 0.15 t ha^{-1}, ME = 0.66 t ha^{-1}) (Fig. 2b, Table 4).

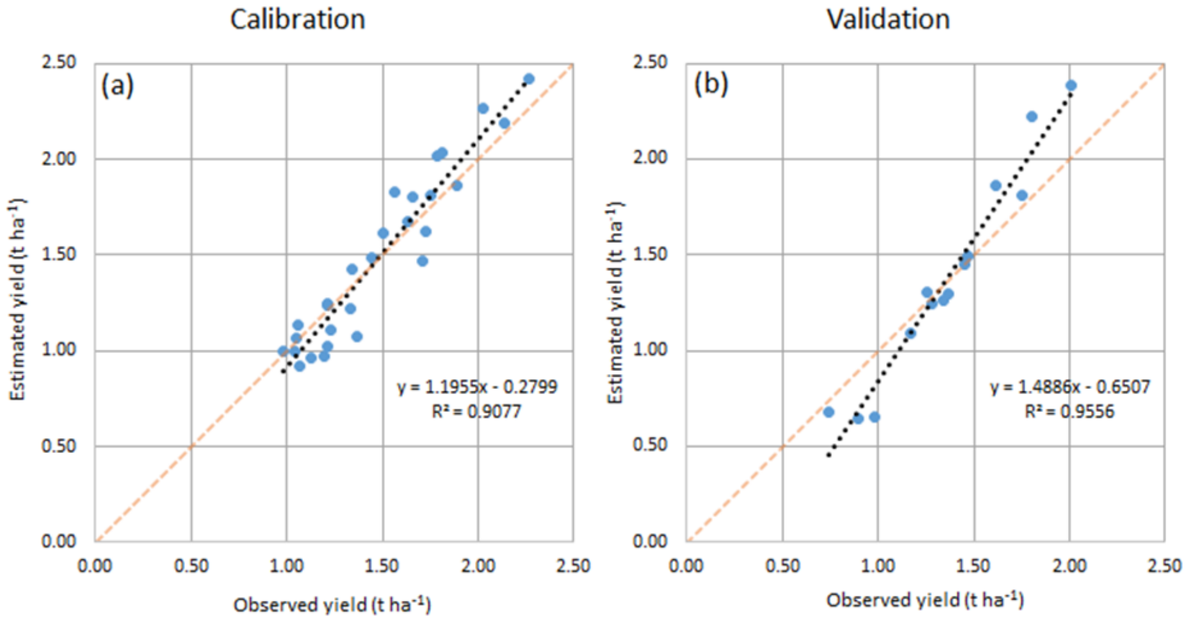

Fig. 2. Relationship between observed and estimated coffee yields during calibration (a) and validation (b) phases of the Camargo et al. (2005) model. The dashed line represents the line of complete correlation, while the dotted line shows the trendline of the data correlation.

3.2 Sensitivity analysis

The sensitivity analysis of the municipalities of Apucarana (Paraná state), Franca (São Paulo state) and Cocos (Bahia state), presented in Fig. 3, confirms that a change in air temperature or rainfall affects coffee yield differently depending on their baseline climate. Apucarana has an oceanic climate without dry season and with a hot summer (Table 1), but also with occurrences of frosts (Table 5). This makes it sensitive to a decrease in the minimum air temperature, as well as to an increase in the mean air temperature and decrease of rainfall (Fig. 3a, d, g). Franca has a humid subtropical climate with a dry

Table 4. Statistical indexes to evaluate the performance of the Arabica coffee yield simulation model, during the calibration and validation phases.

Statistical index	Calibration phase	Validation phase
R^2	0.91	0.96
d	0.96	0.95
C	0.92	0.92
ME	0.82	0.66
MAE	0.13	0.15
RMSE	0.15	0.20
MAPE	8.58%	11.16%

winter, temperate summer and very low occurrence of frosts. As a result, Franca is not very sensitive to a decrease in minimum air temperatures or rainfall, and only slightly sensitive to an increase of mean air temperature (Fig. 3b, e, h). Cocos has a more pronounced sensitivity profile, with a tropical climate with dry winter. As a tropical climate, it is not affected by a decrease of the minimum air temperature by 3°C, but severely affected by an increase of the mean air temperature. While it has a dry winter, Cocos is not affected by a decrease in rainfall, because 93% of its coffee area is irrigated (Table 1, Fig. 3c, f, i).

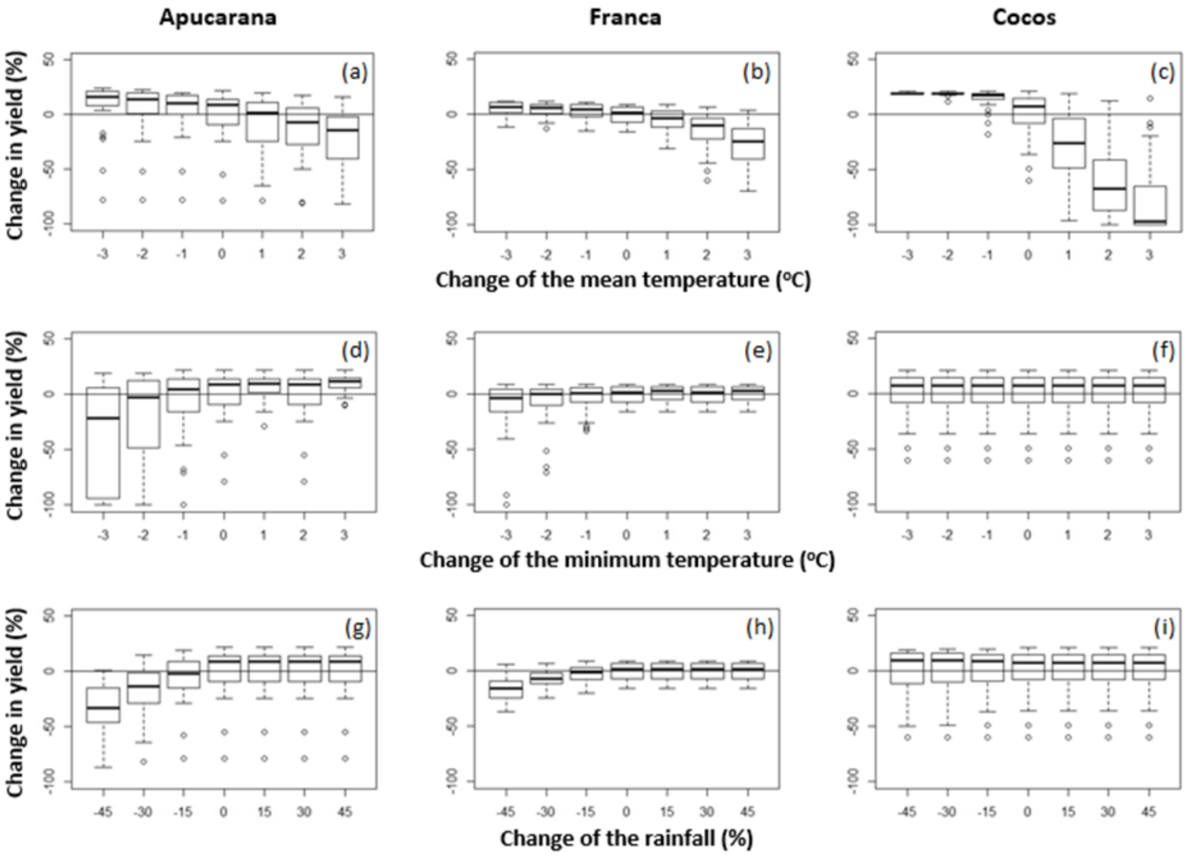

Fig. 3. Effect of changed mean and minimum air temperatures (without effecting mean temperature) and rainfall on the coffee yield from 1980 until 2010 in Apucarana, Paraná state (a, d, g), Franca, São Paulo state (b, e, h), and Cocos, Bahia state (c, f, i). The bold line represents the median yield, the edges of the boxes represent the upper and lower quartile, the wiskers represent the maximum and minimum values (excluding the outliers) and the points represent the outliers (values 3/2 times greater than the upper quartile, or 3/2 times smaller than the lower quartile).

3.3 Climate change impact on Arabica yield

Minimum and mean air temperatures and the water deficit will increase significantly from 1980-2010 to 2040-2070 in the Arabica production regions of Brazil under a RCP 4.5 climate change scenario (Table 5). Nevertheless, the model projects that the Arabica cultivation in Brazil will benefit from climate change, with the average yield increasing by 0.8% from 1.47 t ha^{-1} in 1980-2010 to 1.48 t ha^{-1} in 2040-2070, assuming growing locations and irrigation remain the same (Fig. 4a, c). This slight yield increase can be attributed to the CO_2 fertilization effect, as net losses due to unfavorable climate conditions are also projected to increase. The total loss due to unfavorable climate conditions is projected to increase by 9.5%, but the reference yield is projected to increase by 10.3% (in relation to the estimated yield), resulting in the net yield increase of 0.8% (Fig. 4a, c). Without the CO_2 fertilization effect, the average yield would decline by 7.5%, from 1.47 t ha^{-1} in 1980-2010 to 1.36 t ha^{-1} in 2040-

2070 (Fig. 4a, b). However, the CO_2 fertilization effect will not offset the negative impacts of increased temperatures and water deficit in all Arabica growing regions. In our study, the yield of municipalities in the regions with Aw and Cfb climates, together responsible for 13.4% of national production, declined by respectively 27.6 and 1.5% (Fig. 4g, h, Table 3), while the yield increased by 5.1, 1.7 and 4.5% in municipalities with respectively Cwb, Cwa and Cfa climates, which together are responsible for 83.4% of the national production (Fig. 4d to f, Table 3).

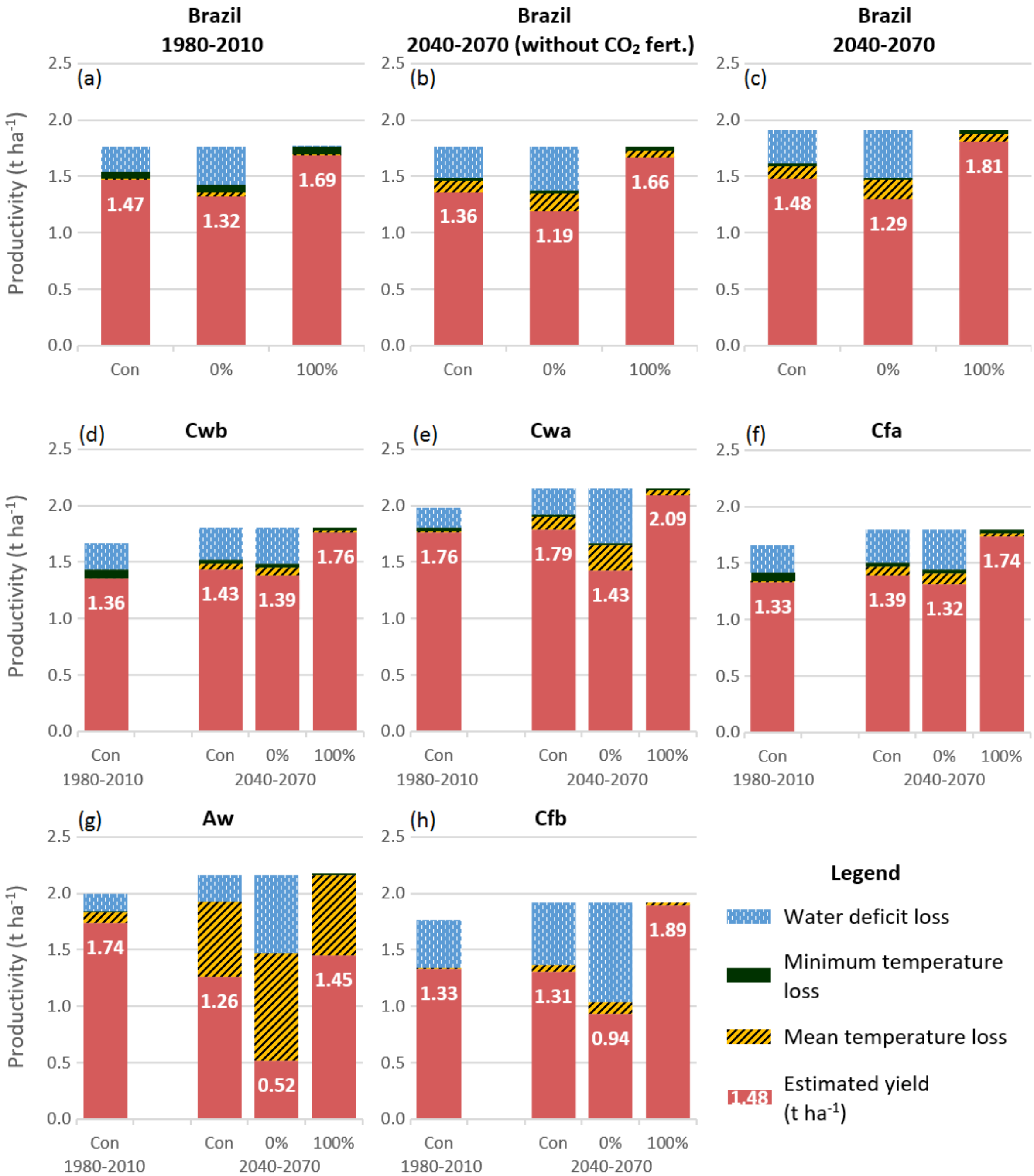

Fig. 4. Estimated Arabica yield and losses in Brazil (a, b, c) and for the five climate zones important for Arabica production (d to h), simulated for the periods 1980-2010 and 2040-2070 under different irrigation scenarios (Con = constant irrigation at the level of 2006; 0% = no irrigation; 100% = full irrigation). For Brazil, the results are also presented without incorporation of the CO_2 fertilization effect (b). The results of Brazil are the mean values of the 42 municipalities weighted by the share of their climate zone in Brazilian production. The results of the climate zones are the mean values of their municipalities: 11 for the humid subtropical zone with dry winter and temperate summer, Cwb (d); 8 for the humid subtropical zone with dry winter and hot summer, Cwa (e); 13 for the oceanic climate without dry season with hot summer, Cfa (f); 7 for the tropical zone with dry winter, Aw (g); and 3 for the oceanic climate without dry season with temperate summer, Cfb (h). The upper limit of the boxes indicates the reference yield.

Table 5. Average total water deficit (Wat. def.) from April to March, minimum temperature (Tmin) from April to March, mean temperature (Tmean) 30 days after flowering, and estimated yield (Yield) for the periods 1980-2010 and 2040-2070 and their respective percentage of change for the 42 municipalities, their climate zones and of Brazil, for which the averages where weighted by the production share of each climate zone.

Municipality name / Climate classification	Wat. def. 1980-2010 (mm)	Changed Wat. def. 2040-2070 (mm)	Tmin 1980-2010 (°C)	Changed Tmin 2040-2070 (°C)	Tmean 1980-2010 (°C)	Changed Tmean 2040-2070 (°C)	Yield 1980-2010 (t ha^{-1})	Yield 2040-2070 (t ha^{-1})	Changed yield 2040-2070 (%)
Andradas	65	+14	1.5	+1.4	20.6	+1.2	1.41	1.67	+18
Araxá	193	+76	6.6	+1.9	22.6	+1.7	1.69	1.51	-11
Boa Esperança	135	+36	3.5	+1.5	21.6	+1.2	1.28	1.40	+9
Bom Jardim	94	+30	6.9	+1.2	21.1	+0.7	1.87	1.99	+6
Capelinha	314	+100	7.2	+1.3	22.5	+1.4	1.05	0.97	-8
Carmo de Minas	85	+22	1.9	+1.3	21.6	+1.0	1.43	1.68	+17
Ervália	169	+61	6.2	+1.5	21.4	+1.1	1.00	1.01	+1
Franca	154	+10	5.6	+1.9	21.9	+1.6	1.45	1.50	+3
Machado	104	+31	2.6	+1.5	21.4	+1.2	1.43	1.60	+12
Manhuaçu	237	+72	6.4	+1.3	22.0	+0.8	1.11	1.09	-2
Varginha	121	+35	2.9	+1.4	21.5	+1.2	1.20	1.35	+13
Cwb	152	+44	4.7	+1.5	21.6	+1.2	1.36	1.43	+5
Altinópolis	139	+46	4.5	+1.8	22.4	+1.4	1.84	1.83	-1
Caratinga	289	+85	7.3	+1.3	22.3	+1.1	0.99	0.95	-4
Cravinhos	105	+35	4.6	+1.5	22.1	+1.3	2.15	2.29	+7
Mococa	108	+38	4.0	+1.5	21.9	+1.3	1.13	1.20	+6
Nuporanga	107	+41	5.4	+1.9	21.6	+1.6	2.43	2.60	+7
Patos de Minas	217	+77	7.5	+1.7	22.6	+1.9	2.38	2.18	-8
Pedregulho	151	+56	5.6	+1.9	22.2	+1.6	1.65	1.61	-2
Rio Pardo de Minas	199	+71	8.1	+1.2	20.9	+1.9	1.54	1.63	+6
Cwa	164	+56	5.9	+1.6	22.0	+1.5	1.76	1.79	+1
Apucarana	93	+38	3.0	+1.4	22.2	+0.8	1.25	1.33	+6
Barra do Choça	303	+162	9.9	+1.4	22.0	+1.0	0.67	0.60	-10
Carlópolis	81	-24	2.6	+1.4	21.0	+0.9	1.71	2.10	+23
Dois Córregos	129	+50	4.9	+1.7	21.8	+1.1	1.84	1.88	+2
Gália	129	+55	4.9	+1.6	22.1	+1.2	1.32	1.32	0
Japurá	112	+52	2.5	+1.3	22.2	+0.8	0.93	1.01	+9
Londrina	122	+49	2.9	+1.5	22.1	+0.8	1.27	1.33	+5
Marília	132	+61	5.0	+1.5	22.3	+1.2	1.14	1.13	-1
Maringá	109	+40	3.3	+1.3	22.3	+0.8	1.01	1.04	+3
Pederneiras	77	-17	4.9	+1.9	21.3	+1.1	1.92	2.08	+8
Pitangueiras	110	+42	3.3	+1.3	22.2	+0.8	1.86	1.91	+3
Tamboara	127	+51	3.0	+1.3	22.2	+0.9	1.12	1.16	+4
Varre-Sai	230	+79	8.5	+1.2	22.4	+0.7	1.26	1.20	-5
Cfa	135	+49	4.5	+1.4	22.0	+0.9	1.33	1.39	+5
Araguari	210	+88	7.6	+2.0	23.2	+1.9	2.09	1.72	-18
Barreiras	385	+146	11.7	+1.3	24.6	+2.0	2.40	1.06	-56
Cocos	497	+146	11.6	+1.3	24.9	+1.9	2.03	1.04	-49
Cristalina	216	+30	8.8	+1.7	22.5	+1.9	2.22	2.13	-4
Estrela d'Oeste	333	+110	6.2	+1.5	24.2	+1.5	0.70	0.45	-36
Junqueirópolis	229	+73	4.9	+1.4	23.1	+1.1	0.69	0.63	-9
São João d'Aliança	233	+53	11.6	+1.6	22.9	+2.1	2.03	1.81	-11
Aw	300	+92	8.9	+1.5	23.6	+1.8	1.74	1.26	-27
Brejetuba	325	+94	9.8	+1.2	22.7	+0.9	1.11	1.01	-9
Mucugê	170	+102	10.7	+1.3	21.9	+1.5	1.94	2.03	+5
Sta.Maria de Jetibá	339	+103	12.2	+1.3	22.5	+0.7	0.93	0.89	-4
Cfb	278	+100	10.9	+1.3	22.4	+1.0	1.33	1.31	-2
Brazil	172	+54	5.6	+1.5	21.9	+1.3	1.47	1.48	+1

The water deficit, the difference between the potential and actual evapotranspiration, will remain the climate variable that most penalizes Arabica yields in Brazil by 2040-2070. From 1980 to 2010 the water deficit was responsible for a loss of 12.6% in relation to the reference yield and this loss is projected to increase to 15.5% (Fig. 4a, c). The water deficit will increase particularly in the municipalities of the climate zones Aw and Cfb, where it will reach a level of respectively 300 and 278 mm (Table 5). In the Aw municipalities, where on average 69% of the coffee is irrigated, yield losses can be alleviated by water supply, but in the Cfb municipalities, where only 28% of the coffee area is irrigated, losses due to the water deficit are projected to increase from 0.43 t ha^{-1} in 1980-2010 to 0.55 t ha^{-1} in 2040-2070 (Table 1, Fig. 4h).

Due to the global warming, high air temperatures will damage Arabica yields more than low air temperatures by 2040-2070, which used to be the opposite (Fig. 4a, c). From 1980 to 2010 frosts reduced the Brazilian yields by 0.06 t ha^{-1}, in particular due to losses in Cwb and Cfa municipalities (Fig. 4a). In these climate zones, the minimum temperatures will increase by respectively 1.5 and 1.4°C, leading to a minimum loss in Brazil due to frosts of only 0.02 t ha^{-1} in 2040-2070 (Table 5, Fig. 4c). To the contrary, yield losses caused by high mean temperatures will increase significantly. In the Arabica regions of Brazil, the mean temperature of the 30 days after flowering (generally occurring between September and December) will increase from 21.9 to 23.2°C, while temperatures above 23°C are considered detrimental (Table 5; Santos 2005). As a consequence, the losses due to high mean temperatures in Brazil will increase from a mere 0.01 to 0.11 t ha^{-1} (Fig. 4a, c). Just as with the losses due to the water deficit, municipalities in the climate zone Aw will be hit particularly hard. In this climate zone, the mean air temperature after flowering was already the highest (23.6°C), and on top it will endure the highest temperature increase (1.8°C) (Table 5). Consequently, yield losses due to high air temperatures in Aw municipalities will increase from 0.10 to 0.66 t ha^{-1} (Fig. 4g).

Losses of both water deficit and high air temperatures can be controlled by irrigation, so use of this technique will become even more important in the future of Brazilian Arabica production. Already under the current climate, yields would decrease by 0.15 t ha^{-1} if no irrigation would be used (Fig. 4a). In the future climate, this loss would be 0.19 t ha^{-1} (Fig. 4c). To the contrary, if by 2040, 100% of the Arabica area would be irrigated, yields would increase in all climate zones, except the Aw zones, attaining an average Brazilian yield of 1.81 t ha^{-1} (Fig. 4c to h).

4 Discussion

4.1 Context and implications

The results of this climate change impact assessment that included the effects of CO_2 fertilization, contradict those of earlier assessments that did not include this effect and found that Arabica yields in Brazil will decline by 2050. The CO_2 fertilization effect in this study was incorporated in a coffee yield simulation model by augmenting the reference yield by 8.56%, in accordance with the results of Arabica grown under free-air carbon dioxide enrichment (Eq. 6). In the Arabica coffee producing regions of Brazil, the annual minimum and mean air temperatures after flowering is projected to increase 1.5 and 1.3°C respectively, while the annual water deficit is projected to increase 54 mm (Table 5). As a result, yield losses due to high air temperatures and water deficit are projected to increase, while losses due to frost are projected to decrease. In conclusion, the model simulations project that the increased reference yield of Arabica coffee under elevated CO_2 concentrations will offset the extra losses due to higher temperatures and water deficit in Brazil. The average yield in

Brazil will increase 0.8% under climate change from 1.47 t ha^{-1} in 1980-2010 to 1.48 t ha^{-1} in 2040-2070, assuming growing locations and irrigation use remain the same (Fig. 4a, c). On average, yields in Arabica regions with Cwb, Cwa and Cfa climates, which are responsible for 84.3% of the Brazilian production, are projected to benefit from climate change (Table 3, 5, Fig. 4d, e, f). At the other hand however, yields in Arabica regions with Aw and Cfb climate, responsible for 13.4% of the Brazilian production, are projected to decrease (Table 3, 5, Fig. 4g, h). In the Arabica producing regions of all climates, except the Aw climate, simulations predict that yields could be increased by expanding the use of irrigation (Fig. 4d to h). If all Arabica plantations would be fully irrigated, yields could reach up to 1.81 t ha^{-1} by 2040-2070 (Fig. 4c).

The results of this study are in line with other researches, which found that models project yields under climate change higher if the CO_2 fertilization effect is incorporated (Easterling et al. 2007). However, the projected Arabica yield increase in Brazil is only 0.8%, and the response varies considerably between municipalities of the same and different climate zones (Table 5). This implies that the accuracy of projected yields and losses of a municipality improves if it is carried out for specific municipalities of interest. For future assessments it is important to take into account the following sources of uncertainty and areas of improvement.

4.2 Room for improvement

The modelling of climate change impacts come with the inherent uncertainties of choosing a climate change scenario, the projections of global circulation models, the development of new cultivars and model inaccuracies. However, there are five aspects that could improve the model's accuracy in future applications.

The first opportunity for improvement is the redefinition of the model's air temperature tolerance with the results of prolonged Arabica CO_2 fertilization studies. This study based itself on a two-year study on the effects of CO_2 fertilization on Arabica, but research notes that effects can change over years (Porter et al. 2014). The results of prolonged studies should therefore be used, once available. The published results indicate that the air temperature and water deficit tolerance of Arabica increase under augmented CO_2 concentrations. The accuracy of the estimated losses would therefore improve if the results of the CO_2 fertilization studies were incorporated on the air temperature and water deficit tolerances of the model, instead of on the reference yield. The accuracy of the model could further improve if the penalization of high air temperatures would be based on the maximum air temperature, instead of the mean air temperature. The reason for this is that a rise of the mean air temperatures in a region can be caused by an increase of the minimum temperatures, while the maximum temperature remains unchanged (Craparo et al. 2015).

A second aspect that could improve the model's accuracy is the use of more precise data on the type and use of irrigation in each municipality. To incorporate the effects of irrigation despite the absence of precise data, two assumptions were made in this model. The first assumption was that irrigation levels of the municipalities were at the level of 2006 (the only year with data) from 1980 until 2013. However, general irrigation use in Brazil has increased unevenly since 1980, so this might have led to an under- or overestimation of the irrigation effect, affecting the calibration of the reference yield and cause errors (ANA - Agência Nacional de Águas & Embrapa Milho e Sorgo 2016). The second assumption was that all irrigation systems use sprinklers instead of drip systems. Drip irrigation, however, is also commonly used by coffee farmers in Brazil and has a lower cooling effect on canopy and leaf temperature. This can explain why the model tends to overestimate the yields of municipalities with high productivity, as these often have high irrigation use (Fig. 2), and a part of the errors (Table 4).

A third advancement of the model would be to run it on grid cells where Arabica coffee is grown. For this study, the model was run for one location per municipality, but this approach neglects the nuance of topo- and microclimates, which are of particular importance to the production of coffee (DaMatta 2004). The accuracy of the model could therefore be improved considerably, if the model was run with specific climate data for the intra-municipal grid cells where coffee is grown. This would be possible since recent remote sensing techniques with satellite images enable the identification of the specific locations where coffee is planted in a municipality (Moreira et al. 2010).

Fourthly, the model should be made applicable in countries with a longer harvesting period. The yield response factor (Ky) as used in this study, has been calibrated for Brazilian conditions, where the harvest period is concentrated between May and August (Cardenas 2015). Many other countries however, have a prolonged harvesting period, such as in Colombia, where harvests occur all year long (Sachs et al. 2015). Therefore, to apply this model outside of Brazil, the model should be calibrated for a prolonged harvesting period for which the determination of the anthesis and the Ky values would have to be altered.

A fifth and last advancement necessary to make the model more widely applicable is the determination of the reference yield on the basis of climate, soil, crop cultivar and management data, instead of historic yield data. For many countries, there is no accurate yield data available on a municipal scale, as mentioned by Sachs et al. (2015). It would therefore be better if this variable could be determined on the basis of external factors, such as solar radiation, photoperiod, air temperature, cultivar characteristics and crop management variables.

5. Conclusions

This study projects that climate change following a RCP 4.5 scenario will benefit the average Brazilian Arabica production with a yield increase of 0.8% from 1980-2010 to 2040-2070, by which it contradicts earlier impact assessments. This net yield increase is caused by the CO_2 fertilization effect, which more than offsets the extra losses of higher air temperatures and water deficits. According to this study's projections, farmers in the majority of Arabica regions of Brazil will be able to uphold their production without having to rely on adaptation measures. This increases the realization of long-term investments and public policies, which can aid the improvement of yields and farmers' livelihoods. And while this study was carried out in particular for Arabica coffee in Brazil, the CO_2 fertilization mechanism applies worldwide and to a degree on Robusta coffee, which means that coffee farmers worldwide will probably not be as hard hit by climate change as previously projected.

However, as the implications of this finding are so great, it is important to repeat the study resolving the aforementioned limitations and uncertainties. First of all, the results can gain validity by running the model for more climate change scenarios, to assess whether the CO_2 fertilization effect remains offsetting the negative impacts if global warming is less or more severe than the RCP 4.5 scenario used in this study. Secondly, the results can gain accuracy and precision by running it on a grid cell basis, with accurate irrigation data, and the results of longer-term CO_2 fertilization experiments acting directly on the temperature and water deficit tolerance of coffee. The model can gain wider applicability by calibrating the yield response factor for other regions and countries and determining the reference or potential yield with local climatic, cultivar and crop management variables. Such enhancements would not only improve the climate change impact assessment of current production locations, but also allow for the identification of new potential Arabica cultivation locations, for example in regions where frost will disappear in the coming decades.

While the model can be further enhanced, the results of this study make it clear that the CO_2 fertilization effect has the potential to offset the negative impacts of climate change on Arabica coffee in Brazil. This confirms the importance of including this factor in climate change impact assessments on coffee. Furthermore, the study demonstrates that losses due to water deficit and high mean air temperatures will increase, while losses to low air temperatures will almost disappear in current Arabica locations. Researchers and public policies should therefore focus on these factors in the development of cultivars and adaptation strategies. In addition, laws to regulate the just and sustainable extraction of water resources will become critical, as yields become more dependent on irrigation and climate change threatens the stability of water supplies.

6. Acknowledgements

Numerous people helped me to accomplish my thesis, but some of them I would like to thank in particular. My parents and sister gave me the confidence to pursue my dream of going to Brazil. While they were geographically far away, I always felt their emotional support nearby. Professor Paulo Sentelhas supervised my stay and work here in all senses. I carry him with me as an example of a person who gives full and cheerful attention to both his work and the people around him. My fellow students of our workspace, the *Cupula,* have helped me through the long workdays with their knowledge, but most importantly, with their laughs in the breaks. My housemates of the *República Matadouro* and their families have shaped my view of Brazil. É-Vc, Mtvil, Disga, Camilo, Miller, Pino, Teiu, Léo, Tornera, Xak-U, Treçeme, Ta E(R)²Ado, Ioco-Onu, Pik Do Saci, Fernandão and Rolando, have taught me how it is to be in a band of brothers, with few secrets, a lot of 'zoeira' and most of all, respect. Furthermore, I want to thank Koala for her invariable willingness to help and optimism, and the lovely people from *Refazenda* for giving me a feeling of belongingness in Brazil (on an eco-farm). Natalia has made me even more excited to explore the world, and dedicate myself to that, because interesting jobs "don't fall from the sky". The *gringaiada* has enriched my life here with their cultures, dances and endless conversations in the student restaurant. Last but not least, I want to thank the people of Brazil, for receiving me with their open hands, and showing me how beautiful it is to laugh.

7. Supplementary material

To facilitate the full assessment of this master thesis project and encourage further verification, development and application of the Arabica coffee yield simulation model, I made the main climate, irrigation and yield files, scripts and simulations publically accessible through the DOI: https://doi.org/10.6084/m9.figshare.c.3692239.v1 The names of the files and their interrelation can be observed in Fig. 5. The published collection of files also includes a description and exemplary calculation of the Agro-ecological Zoning (AEZ) as developed by Doorenbos & Kassam (1979) applied on Arabica coffee. The description and the simulations of this model were not used in the final study, but are relevant for the assessment of this thesis and might be of interest to other researchers, so they were included in the file collection. The description of the Agro-ecological Zoning model applied on Arabica coffee has been included in the supplementary material section hereafter as well.

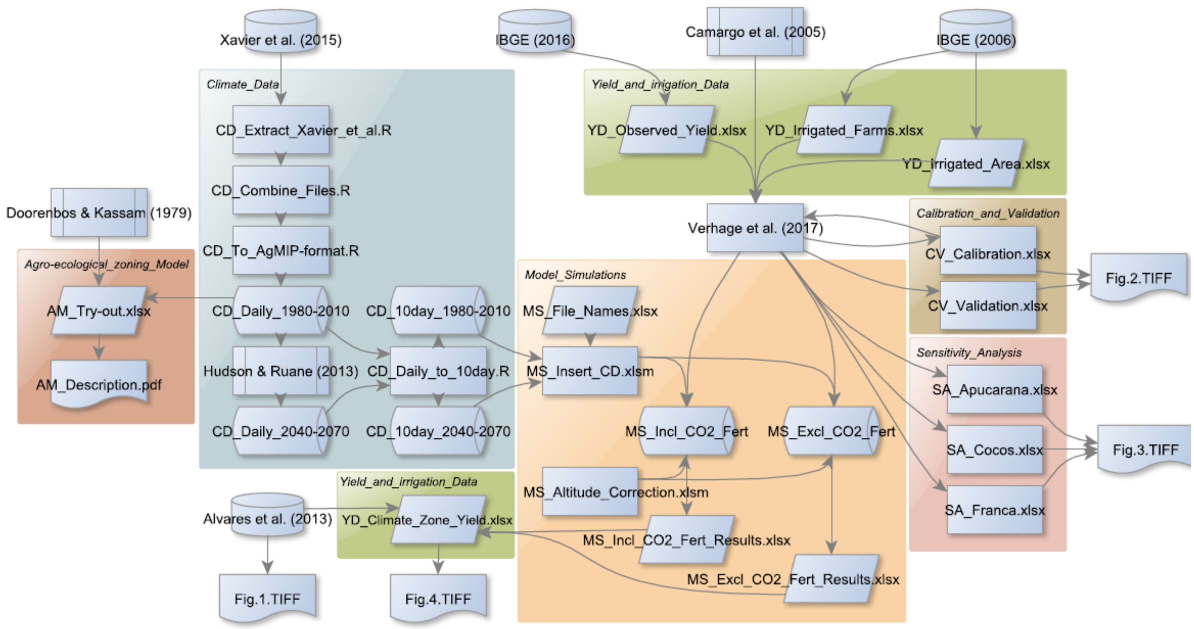

Fig. 5. Flowchart with the interrelation of the main climate, irrigation and yield files, scripts and simulations used in this study and made publically accessible through the aforementioned DOI.

7.1 Description of Agro-ecological Zoning (AEZ) model for Arabica coffee

This text gives a brief description of the Agro-ecological Zoning (AEZ) model developed to calculate the Yield Potential (Yp) of Arabica coffee. The model is described here, because it was not used in the final study, but might be of interest to other researchers. The AEZ-model was evaluated in combination with a coffee yield simulation model, similar (but not equal) to the one described by Camargo et al. (2005). To not generate confusion about the model of Camargo et al. (2005), this text only describes the AEZ-model and the results of the evaluation are not published.

The initial objective of this research project was to assess the impact of climate change on Arabica coffee yields around the world. The Arabica coffee yield simulation model used in this study requires a reference yield on municipal scale. However, for most Arabica coffee production countries, there is no historic yield data available on a municipal or even regional scale. Therefore, we tried to run the Arabica coffee yield simulation model on the basis of the yield potential (Yp) instead of on the basis of the yield reference (Yref), as Yp can be calculated with bioclimatic factors. However, we found that the Arabica coffee yield simulation model was not capable to estimate actual yields satisfactorily. We assume that the main reason for this is that this coupled model did not account for management factors, which are responsible for a great share of the yield losses.

The *Yp* of Arabica coffee was calculated using the Agro-ecological Zoning (AEZ) model developed by Doorenbos & Kassam (1979). The inputs of this model are the daily mean air temperature and insolation of a location and several crop coefficients. The model assumes the crop is grown under optimal water, nutritional and phytosanitary conditions. The agro-ecological zoning model can be represented as:

$$Yp = \sum_{i=1}^{m} GP_i * C_{LAI} * C_{RESP} * C_H * (1 - C_W)^{-1}$$

where Yp represents the yield potential of a harvest (kg/ha); m represents the growing cycle, so the period for which the model is run; i is the time step for which the model is run; GP_i is the gross photosynthesis per time interval (kg DM/ha/i); C_{LAI} corrects for Leaf Area Index; C_{RESP} corrects for the maintenance respiration; C_H corrects for the harvest index; C_W corrects for the water content of the harvested part.

The model was run with a time interval (i) of one day. The gross photosynthesis per day (GP_i) was estimated as the sum of the photosynthesis with a clear sky (GP_C) and overcasted sky (GP_O) as:

$$GP_i = GP_C + GP_O$$

where GP_C and GP_O were calculated as:

$$GP_C = (107.2 + 0.36 * Q_O) * cTc * \left(\frac{n}{N}\right)$$

$$GP_O = (31.7 + 0.219 * Q_O) * cTo * \left(1 - \frac{n}{N}\right)$$

where Q_O is the extra-terrestrial solar irradiation (cal/cm2/d); n is the insolation; N the photoperiod; and cTc and cTo two dimensionless coefficients representing the photosynthetic efficiency according to the crop type and the temperature, as defined by Doorenbos & Kassam (1979). The C_{LAI} coefficient was estimated by the equation of Doorenbos & Kassam (1979):

$$C_{LAI} = 0.0093 + 0.185 * LAI_{Max} - 0.0175 * {LAI_{Max}}^2$$

where LAI_{Max} is the maximum Leaf Area Index of Arabica coffee, which was set to 3, as reported by Fischer et al. (2003). The coefficient C_{RESP} was set to 0.6 on days with a mean temperature ≤ 20 ºC and 0.5 for days with a mean temperature > 20 ºC according to Doorenbos & Kassam (1979). The coefficient C_W was set to 0.12, as coffee yields are reported with a moisture content of 12% (Coffee Research Institute 2006).

The literature was indecisive on the harvest index (C_H) and the length of the growing cycle (m) of Arabic coffee, so the model was calibrated for these coefficients. The reported harvest indexes for Arabica coffee varied from 0.04 (Fischer et al. 2003) and 0.10-0.23 (Almeida 2013) to 0.72 (Pereira 1999). While the length of the growing cycle for Arabic coffee was reported as 2900 degree days (DD) for the cultivar Mundo Novo and 2990 DD for the cultivar Catuaí (Bardin-Camparotto et al. 2012). Hence, the model was run for 15 municipalities with a harvest index (C_H) of 14, 15, 16 and 17%, and a growing cycle (m) of 2900 and 2990 DD. Comparing the modelled results with observed values, the r^2-coefficient was highest for the model with a harvest index of 15% and a growing cycle of 2900 DD, so these values were used.

8. References

Almeida, T.S., 2013. *Modelagem agrometeorológica-espectral para estimativa da produtividade de cafeeiros para areas irrigadas do noroeste de Minas Gerais*. Universidade Federal de Viçosa.

Alvares, C.A. et al., 2013. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift*, 22(6), pp.711–728.

ANA - Agência Nacional de Águas & Embrapa Milho e Sorgo, 2016. *Levantamento da agricultura irrigada por pivôs centrais no Brasil - 2014*, Brasília (FD). Available at: http://arquivos.ana.gov.br/imprensa/arquivos/ProjetoPivos.pdf.

Assad, E.D. et al., 2004. Climatic changes impact in agroclimatic zonning of coffee in Brazil. *Pesquisa Agropecuaria Brasileira*, 39(11), pp.1057–1064.

Bardin-Camparotto, L., Camargo, M.B.P. de & Moraes, J.F.L. de, 2012. Época provável de maturação para diferentes cultivares de café arábica para o Estado de São Paulo. *Ciência Rural*, 4242(44), pp.594–599.

Bote, A.D., 2016. *Examining growth, yield and bean quality of Ethiopian coffee trees: towards optimizing resources and tree management*. Wageningen University.

Bote, A.D. & Vos, J., 2016. Branch growth dynamics, photosynthesis, yield and bean size distribution in response to fruit load manipulation in coffee trees. *Trees - Structure and Function*, 30(5), p.1911.

Bunn, C. et al., 2015. A bitter cup: climate change profile of global production of Arabica and Robusta coffee. *Climatic Change*, 129(1–2), pp.89–101.

Butt, M.S. & Sultan, M.T., 2011. Coffee and its consumption: benefits and risks. *Crit Rev Sci Nutr*, 51(4), pp.363–73. Available at: http://www.ncbi.nlm.nih.gov/pubmed/21432699.

Camargo, A.P. & Camargo, M.B.P., 2001. Definition and outline for the phenological phases of arabic coffee under Brazilian tropical conditions. *Bragantia*, 60(1), pp.65–68.

Camargo, A.P. de & Sentelhas, P.C., 1997. Performance evaluation of different potential evapotranspiration estimating methods in the State of São Paulo, Brazil. *Revista Brasileira de Agrometeorologia*, 5(1), pp.89–97.

Camargo, M.B.P. De et al., 2005. Test of an agrometeorological model for monitoring and predicting coffee yield in São Paulo state, Brazil.

Camargo, M.B.P. De, 2010. The impact of climatic variability and climate change on Arabic coffee crop in Brazil. *Bragantia*, 69, pp.239–247.

Cardenas, R.R., 2015. *Climate change assessment for Minas Gerais - Brazil with emphasis on coffee areas*, Hamburg. Available at: http://www.coffeeandclimate.org/reports_studies.html?file=tl_files/CoffeeAndClimate/downloads/Climate change assessment for MG Brazil_climate projections_Part 2.pdf.

Chemura, A. et al., 2016. Bioclimatic modelling of current and projected climatic suitability of coffee (Coffea arabica) production in Zimbabwe. *Regional Environmental Change*, 16(2), pp.473–485. Available at: http://dx.doi.org/10.1007/s10113-015-0762-9.

CIAT - International Center for Tropical Agriculture, 2010. *Climate change adaptation and mitigation in the Kenyan coffee sector*, Cali. Available at: http://dapa.ciat.cgiar.org/wp. (accessed on 14.05.2015).

Climate Action Tracker, 2016. *Paris Agreement in force, but no increase in climate action*, Available at: http://climateactiontracker.org/assets/publications/briefing_papers/CAT_temperature_update_November_2016.pdf.

Coffee Research Institute, 2006. Coffee Drying. Available at: http://www.coffeeresearch.org/agriculture/drying.htm [Accessed April 16, 2016].

Craparo, A.C.W. et al., 2015. Coffea arabica yields decline in Tanzania due to climate change: Global implications. *Agricultural and Forest Meteorology*, 207, pp.1–10.

DaMatta, F.M., 2004. Ecophysiological constraints on the production of shaded and unshaded coffee: A review. *Field Crops Research*, 86(2–3), pp.99–114.

DaMatta, F.M. et al., 2016. Sustained enhancement of photosynthesis in coffee trees grown under free-air CO2 enrichment conditions: Disentangling the contributions of stomatal, mesophyll, and biochemical limitations. *Journal of Experimental Botany*, 67(1), pp.341–352.

Davis, A.P. et al., 2012. The impact of climate change on indigenous Arabica coffee (Coffea arabica): predicting future trends and identifying priorities. *PLoS ONE*, 7(11), pp.10–14.

Doorenbos, J. & Kassam, K.H., 1979. *Yield response to water, Irrigation and drainage paper 33*,

Easterling, W.E. et al., 2007. Food, fibre and forest products. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. pp. 273–313. Available at: http://gala.gre.ac.uk/2359/.

Eitzinger, A. et al., 2013. *Prediction of the impact of climate change on coffee and mango growing areas in Haiti*,

Estrada, F., Gay, C. & Conde, C., 2012. A methodology for the risk assessment of climate variability and change under uncertainty. A case study: Coffee production in Veracruz, Mexico. *Climatic Change*, 113(2), pp.455–479.

Fischer, G., Velthuizen, H. Van & Nachtergaele, F., 2003. *Interim Report Global Agro-Ecological Zones Assessment for Citrus , Cocoa , Coffee , Tea , Tobacco , Yam and selected Vegetables . Methodology and Results*,

Ghini, R. et al., 2015. Coffee growth, pest and yield responses to free-air CO2 enrichment. *Climatic Change*, 132(2), pp.307–320.

Ghini, R. et al., 2011. Incubation period of Hemileia vastatrix in coffee plants in Brazil simulated under climate change. *Summa Phytopathol*, 37(2), pp.85–93.

Gulizia, C. & Camilloni, I., 2015. Comparative analysis of the ability of a set of CMIP3 and CMIP5 global climate models to represent precipitation in South America. *International Journal of Climatology*, 35(4), pp.583–595.

Hudson, N. & Ruane, A., 2013. AgMIP Climate Scenario Generation Tools with R. Available at: http://tools.agmip.org/acsgtr.php.

IBGE, 2006. Censo Agropecuário: Tabela 1819 - Número de estabelecimentos agropecuários com uso de irrigação e Área dos estabelecimentos por método utilizado para irrigação e grupos e classes de atividade. Available at: https://sidra.ibge.gov.br/tabela/1819.

IBGE, 2016. Produção Agrícola Municipal: Tabela 1613 - Área destinada à colheita, área colhida, quantidade produzida, rendimento médio e valor da produção das lavouras permanentes. Available at: https://sidra.ibge.gov.br/tabela/1613#notas-tabela.

Jaramillo, J. et al., 2011. Some like it hot: The influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa. *PLoS ONE*, 6(9).

Jassogne, L., Läderach, P. & Van Asten, P., 2013. *The impact of climate change on coffee in Uganda. Lessons from a case study in the Rwenzori Mountains*, Available at: https://www.oxfam.de/system/files/rr-impact-climate-change-coffee-uganda-030413-en.pdf.

Kanemasu, E.T., 1983. Yield and Water-Use Relationships: Some Problems of Relating Grain Yield to Transpiration. In T. R. TAYLOR, H.M.; JORDAN, W.R.; SINCLAIR, ed. *Limitations to Efficient Water Use in Crop Production*. Madison: American Society of Agronomy, pp. 413–17.

Lobell, D.B. et al., 2008. Irrigation cooling effect on temperature and heat index extremes. *Geophysical Research Letters*, 35(9), pp.1–5.

Maro, G.P. et al., 2014. Developing a coffee yield prediction and integrated soil fertility management recommendation model for Northern Tanzania. *International Journal of Plant & Soil Science*, 3(4), pp.380–396.

Martins, M.Q.. b et al., 2016. Protective response mechanisms to heat stress in interaction with high [CO2] conditions in coffea spp. *Frontiers in Plant Science*, 7(JUNE2016), pp.1–18. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84976486833&partnerID=40&md5=4ad1414a979cca28794202173e74dbec.

Microsoft Excel, 2016. Microsoft Excel.

Moreira, M. a. et al., 2010. Geotechnologies to map coffee fields in the states of Minas Gerais and São Paulo. *Engenharia Agrícola*, 30, pp.1123–1135.

Ovalle-Rivera, O. et al., 2015. Projected shifts in Coffea arabica suitability among major global producing regions due to climate change. *PLoS ONE*, 10(4), pp.1–13.

Paulino, J. et al., 2011. Brazil agriculture irrigated status according to the agricultural census of 2006. *Irriga*, 16(2), pp.163–176.

Pereira, J., 1999. *Eficiência Nutricional de Nitrogênio e de Potássio em Plantas de Café (Coffea arábica L.)*. Universidade Federal de Viçosa.

Picini, A.G. et al., 1999. Test and analysis of agrometeorological models for predicting coffee yield. *Bragantia*, 58(1), pp.157–170.

Porter, J.R. et al., 2014. Food security and food production systems. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. pp. 485–533.

Rodrigues, W.P. et al., 2016. Long-term elevated air [CO2] strengthens photosynthetic functioning and mitigates the impact of supra-optimal temperatures in tropical Coffea arabica and C. canephora species. *Global Change Biology*, 22(1), pp.415–431.

Rodríguez, D. et al., 2011. A coffee agroecosystem model: I. Growth and development of the coffee plant. *Ecological Modelling*, 222(19), pp.3626–3639.

Rodríguez, D. et al., 2013. A coffee agroecosystem model: II. Dynamics of coffee berry borer. *Ecological Modelling*, 248, pp.203–214.

RStudio Team, 2015. RStudio: Integrated Development for R. Available at: http://www.rstudio.com/.

Sachs, J. et al., 2015. *The impacts of climate change on coffee: trouble brewing*, New York. Available at: http://eicoffee.net/files/report/main.pdf.

Sanford, T. et al., 2014. The climate policy narrative for a dangerously warming world. *Nature Climate Change*, 4(3), pp.164–166. Available at: http://www.nature.com/doifinder/10.1038/nclimate2148.

Santos, M.A. dos, 2005. *Calibration of sensitivity coefficients and test of a agrometeorological model for predicting coffee (Coffea arabica L.)*. Available at: http://www.iac.sp.gov.br/areadoinstituto/posgraduacao/dissertacoes/pb1805803.pdf.

Schroth, G. et al., 2014. Winner or loser of climate change? A modeling study of current and future climatic suitability of Arabica coffee in Indonesia. *Regional Environmental Change*, 15(7), pp.1473–1482.

Silveira, C. da S. et al., 2013. Performance assessment of CMIP5 models concerning the representation of precipitation variation patterns in the twentieth century on the Northeast of Brazil, Amazon and Prata Basin and analysis of projections for the scenery RCP8.5. *Revista Brasileira de Meteorologia*, 28(3), pp.317–330.

van der Sleen, P. et al., 2015. No growth stimulation of tropical trees by 150 years of CO2 fertilization but water-use efficiency increased. *Nature Geoscience*, 8(January), pp.24–28.

Steiner, J.L., Kanemasu, E.T. & Hasza, D., 1983. Microclimatic and Crop Responses to Center Pivot Sprinkler and to Surface Irrigation. *Irrigation Science*, 4, pp.201–214.

Sterck, F. et al., 2016. Trait Acclimation Mitigates Mortality Risks of Tropical Canopy Trees under Global Warming. *Frontiers in Plant Science*, 7(May), pp.1–10. Available at: http://journal.frontiersin.org/Article/10.3389/fpls.2016.00607/abstract.

Stocker, T.F. et al., 2015. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. *CEUR Workshop Proceedings*, 1542, pp.33–36.

Thornthwaite, C.W., 1948. An approach toward a rational classification of climate. *Geographic review*, 38, pp.55–916.

Thornthwaite, C.W. & Mather, J.R., 1955. The water balance. *Climatology*, 4(1).

Urrego-Pereira, Y. et al., 2013. Microclimatic and physiological changes under a center pivot system irrigating maize. *Agricultural Water Management*, 119(September 2016), pp.19–31.

van Vuuren, D.P. et al., 2011. The representative concentration pathways: An overview. *Climatic Change*, 109(1), pp.5–31.

Willmott, C.J. et al., 1985. Statistics for the evaluation and comparison of models. *Journal of Geophysical Research*, 90(C5), pp.8995–9005.

Xavier, A.C., King, C.W. & Scanlon, B.R., 2015. Daily gridded meteorological variables in Brazil (1980-2013). *International Journal of Climatology*, 2659(October 2015), pp.2644–2659.

Yin, L. et al., 2013. How well can CMIP5 simulate precipitation and its controlling processes over tropical South America? *Climate Dynamics*, 41(11–12), pp.3127–3143.

Zacharias, O. et al., 2008. Agrometeorological model for estimating the beginning of the flowering period for coffee crop (Coffea arabica L.). *Bragantia*, 67(1), pp.249–256. Available at: http://www.redalyc.org/articulo.oa?id=90867130.