Using the yield-SAFE model to assess the impacts of climate change on yield of coffee (*Coffea arabica* L.) under agroforestry and monoculture systems

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Received: 30 July 2018 / Accepted: 9 February 2019
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Abstract Ethiopia economy depends strongly on *Coffea arabica* production. Coffee, like many other crops, is sensitive to climate change and recent studies have suggested that future changes in climate will have a negative impact on its yield and quality. An urgent development and application of strategies against negative impacts of climate change on coffee production is important. Agroforestry-based system is one of the strategies that may ensure sustainable coffee production amidst likelihood future impacts of climate change. This system involves the combination of trees in buffer extremes thereby modifying microclimate conditions. This paper assessed coffee production under: (1) coffee monoculture and (2) coffee grown using agroforestry system, under: (a) current climate and (b) two different future climate change scenarios. The study focused on two representative coffee growing regions of Ethiopia under different soil,

climate and elevation conditions. A process-based growth model (yield-SAFE) was used to simulate coffee production for a time horizon of 40 years. Climate change scenarios considered were: representative concentration pathways (RCP) 4.5 and 8.5. The results revealed that in monoculture systems, the current coffee yields are between 1200 and 1250 kg ha⁻¹ year⁻¹, with expected decrease between 4–38 and 20–60% in scenarios RCP 4.5 and 8.5, respectively. However, in agroforestry systems, the current yields are between 1600 and 2200 kg ha⁻¹ year⁻¹, the decrease was lower, ranging between 4–13 and 16–25% in RCP 4.5 and 8.5 scenarios, respectively. From the results, it can be concluded that coffee production under agroforestry systems has a higher level of resilience when facing future climate change and reinforce the idea of using this type of management in the near future for adapting climate change negative impacts on coffee production.

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Keywords *Albizia gummifera* · CORDEX · Ethiopia · HADCM3 model · Process-based model · System resilience

Introduction

Coffee, which is grown in about 70 countries, is one of the most important tree crops in the world and covers an area of about 11 million ha. In 2015, coffee

generated over US\$ 39.3 billion export revenues for many developing countries (ICO 2016). In the same year, Ethiopia was the fifth exporter of coffee in the world, contributing to about 4.5% for the world's total coffee production (Gole 2015; ICO 2016). Coffee is an important export commodity for Ethiopian economy, being responsible in 2015 for about 25–30% of total exports (Hirons et al. 2018) and 10% of the country's GDP (Gole 2015). There is even a popular saying: “coffee is the backbone of our life”, meaning how the crop is so closely interlinked with livelihoods of many smallholder farmers (Bossolasco 2009). Indeed, coffee supports, directly or indirectly, the livelihoods of 15 million Ethiopians (representing about 16% of the total population) (Moat et al. 2017).

In Ethiopia, *Coffea arabica* L. grows in a wide range of agro-ecological conditions, mainly confined within altitudes of 1200–3000 m, with optimum temperatures between 18 and 22 °C and annual total rainfall between 800 and 2100 mm (Muleta et al. 2011; Moat et al. 2017). It is grown following four management alternatives in Ethiopia: forest, monoculture plantations, semi-forest and garden, which cover, respectively, 5, 10, 35 and 50% of the total coffee areas. In forest and semi-forest systems, coffee is naturally grown under the shade of native trees with minimal human interventions (Labouisse et al. 2008). However, in the garden system, coffee is mostly grown under the shade of low-density trees, corresponding to a typical example of agroforestry systems with intensive traditional human interventions (Muleta et al. 2011; Negash and Kanninen 2015). On the other hand, in recent years, large areas of coffee monoculture plantations have been installed with the main objective of maximizing yields by using agronomic practices such as improved seedlings, pruning and chemical weeding (Labouisse et al. 2008; Bote and Struik 2011; Gole 2015).

The Intergovernmental Panel on Climate Change (IPCC) set different climate change scenarios depending on world future population growth and economic development (Wayne 2013). On its fifth assessment report, the latest Representative Concentration Pathways (RCPs) scenarios were developed for its use as input data for climate models. These new scenarios projected by 2050 to increase mean temperature between 1.1 and 3.1 °C whereas to decrease precipitation between 5 and 10% during the rainy season (June–August) in Ethiopia (Carabine et al. 2014).

Some studies have assessed how these new conditions would affect coffee production in Ethiopia: Davis et al (2012) suggest that the land suitability is expected to decrease by 65–100% in 2080 while the prolonged drought and higher temperatures would have an effect on coffee flowering and fruiting resulting in a decline of productivity and quality (Bote and Struik 2011; Belachew and Teferi 2015; Moat et al. 2017; Hirons et al. 2018). In addition, it is expected that the climate change effects would also enhance the severity and occurrence of pests affecting coffee plants (Jaramillo et al. 2011; Alemu 2015; Belachew and Teferi 2015).

The presence of trees with coffee in agroforestry systems allows to buffer extreme temperatures, reduce soil evaporation and coffee transpiration (Lin 2010; Bote and Struik 2011; Nonato et al. 2012; Kufa and Burkhardt 2015; Jayakumar et al. 2016). In addition, other environmental benefits have been associated to agroforestry-based coffee production, such as the reduction on severity and occurrence of coffee pests (Ngo et al. 2011; Alemu 2015; Belachew and Teferi 2015) and the improvement of soil nutrient and moisture retention (Lin 2010; Bote and Struik 2011; Muleta et al. 2011; Nonato et al. 2012; Kufa and Burkhardt 2015). Due to these positive effects, agroforestry-based coffee production has been considered as a potential practice for tackling climate change negative impacts (Lin 2010; Bote and Struik 2011; Muleta et al. 2011; Jassogne et al. 2013; Belachew and Teferi 2015; Moat et al. 2017) and has been strongly suggested as an adaptation strategy for ensuring sustainable coffee production in the future (Lin 2010; Bote and Struik 2011; Kufa and Burkhardt 2011, 2015; Ebisa 2014; Belachew and Teferi 2015; Hirons et al. 2018).

Ecological models are developed for a wide range of purposes, including projecting impacts of climate change on crop yields or tree growth (van der Werf et al. 2007; Luedeling et al. 2016). Modelling results can help decision makers on the selection of adaptation strategies against impacts of climate change (Oijen et al. 2010; Luedeling et al. 2016). Up to date, just a few process-based models have been developed to project impacts of climate change on agroforestry systems (van der Werf et al. 2007; Oijen et al. 2010; Luedeling et al. 2016). The yield-SAFE model (van der Werf et al. 2007) is one of these few models and is able to predict impacts of climate, soil and management on yields of crop monoculture, agroforestry

systems or forestry plantations (Palma et al. 2017). The model is a process-based and daily time-step, requiring daily climate data, species growth parameters, soil physical characteristics and management regimes as inputs (Palma et al. 2017). It is able to simulate yields of crops and/or trees in monoculture and agroforestry systems, based on water and light competitions. A full description of the model, including its differential equations and parameters inputs are provided by van der Werf et al. (2007) with extended algorithms in Palma et al. (2017). The model is characterized by having few parameters that are easily parameterized, and thus it can be easily adjusted to different crops and environmental conditions (Graves et al. 2010). It has been already used to predict impacts of climate change on temperate (Palma et al. 2014, 2018) and tropical (Holst et al. 2012) agroforestry systems. It has also been widely used to study environmental benefits of agroforestry systems (Palma et al. 2007, 2018; Crous-Duran et al. 2018) and productivity of crops and trees under agroforestry systems (Graves et al. 2010; Artru et al. 2017; Crous-Duran et al. 2018).

In Ethiopia, there is a limited study on long-term impacts of climate change on coffee productivity at a hectare basis using a process-based model (Moat et al. 2017; Hirons et al. 2018). The objective of this study was then to fill this gap of knowledge by assessing long-term impacts of climate change on coffee productivity under monoculture and agroforestry systems using a process-based model (yield-SAFE), under different climate change scenarios, in two coffee growing regions of Ethiopia (south-eastern and south-western) that can be representative coffee production systems of Ethiopia under different soil, climate and elevation conditions (Bossolasco 2009; Bote and Struik 2011; Kufa and Burkhardt 2015).

Materials and methods

Study sites

South-eastern and south-western regions of Ethiopia are major contributors for Ethiopian total coffee production and exportation, with estimation of 92 and 88%, respectively in 2015 (<https://www.ecx.com.et/commodities.aspx#Coffee>; Minten et al. 2015). The regions also represent all types of coffee production

systems in Ethiopia including agroforestry and monoculture systems under different soil, climate and elevation conditions (Bossolasco 2009; Kufa and Burkhardt 2011; Hirons et al. 2018). One representative site, from each of these regions, was then considered for this study to be a nation assessment on impacts of future climate change on coffee production.

The Wonago site is found in the Wonago district at the Gedeo zone, located in the south-eastern part of Ethiopia, distanced 390 km from Addis Ababa, capital city of Ethiopia (6°3'N and 38°3'E—Fig. 1). Its elevation ranges between 1200 and 2100 m with long-term average monthly temperature and total annual rainfall of 20 °C and 1150 mm, respectively. The dominant soil type of the site is Nitisol classified as “fine” texture following FAO soil classification with a depth of 1 m and lower fertility status (Talemos and Sebsebe 2014). The total area of the district is around 25,000 ha, comprising mainly coffee-based agroforestry (95%), grassland (1.4%), wetland (0.8%), natural forest (1%), pure coffee plantations (1%) and others (0.8%) (Negash and Kanninen 2015). The Limu Kosa site is located in Limu Kosa district at the Jimma zone, south-western part of Ethiopia, located 420 km from Addis Ababa (7°50'N and 36°44'E—Fig. 1). The elevation of the area is between 1200 to 3020 m, with an average monthly temperature and total annual rainfall of 21 °C and 1500 mm, respectively. Its dominant soil type is Nitisol with fine textural class, a depth of 1.5 m and good fertility status (Bossolasco 2009; Bote and Struik 2011). The total area of the district is 280,000 ha, of which coffee grown in agroforestry and monocultures covers about 22% of this area, preceded by agriculture (45%), and followed by grazing (14%) and other land use types (19%) (Bossolasco 2009).

In both study sites, coffee is mostly grown under a moderate shade of native trees in the agroforestry systems. Native trees include: *Albizia gummifera*, *Acacia abyssinica*, *Cordia africana*, *Erythrina brucei*, *Milletia ferruginea*, *Mangifera indica* and *Ficus vasta* (Bossolasco 2009; Bote and Struik 2011; Negash and Kanninen 2015). However, in recent times, coffee started to be also produced without shade trees, a typical example of monoculture systems (Gole 2015; Moat et al. 2017). In agroforestry systems, coffee is produced following conventional farming, without application of chemicals to support its growth. However, in monoculture systems, coffee production has

Fig. 1 Geographical locations of the study sites

followed the recommended practices, including the use of chemicals (Labouisse et al. 2008; Gole 2015).

Different data sources were used for validation the yield-SAFE model. In each study site, 20 plots (each 20 m × 20 m) were established inside of the coffee farms (agroforestry-based and monoculture) with an interval of 500 m along elevation gradient following the procedures developed by Negash and Kanninen (2015) for the sites. For agroforestry-based coffee production, the peacock flower tree (*Albizia gummifera*), a native multipurpose leguminous tree was selected as being the most common shade tree for coffee in the sites (Bossolasco 2009; Talemoss and Sebsebe 2014; Gole 2015). From each plot, density of coffee and the tree was counted and the tree's diameter at breast height (DBH) at 1.30 m and height (m) were measured using tape meter and clinometer,

respectively. The observed DBH of the tree was found in the ranges of 20–40 cm at age of 20 years with average height of 13 and 15 m in Wonago and Limu Kosa, respectively. Age of the tree plantations was considered to be 20 years in the sites (Ebisa 2014; Wondrade et al. 2015). Tree biomass was then estimated using allometric equation developed by Binkley and Ryan (1998) using the observed DBH and height, valuing between 95–215 kg tree⁻¹ for Wonago and 105–225 kg tree⁻¹ for Limu Kosa. Furthermore, the tree's leaf area was considered in between 75 and 105 m² tree⁻¹ at age of 20 years (Ebisa 2014; Wondrade et al. 2015). The emphasis was given for these three variables of the tree as they are the main variables that affect coffee growth located underneath (Bote and Struik 2011; Kufa and Burkhardt 2011; Ebisa 2014).

In addition, for validating coffee yield, its seven years' average yield was taken from previous studies instead of taking from the sample plots as it is fluctuated due to seasonal weather (Bote and Struik 2011; Netsere and Kufa 2015) and for practical reasons. Yields in monoculture and agroforestry systems were then considered to be 1000–1200 and 1400–1520 kg ha⁻¹ year⁻¹, respectively for Wonago (Netsere and Kufa 2015) and 1100–2100 and 1400–2100 kg ha⁻¹ year⁻¹, respectively for Limu Kosa (Bote and Struik 2011).

Model inputs

For simulating coffee yield under monoculture and agroforestry systems, yield-SAFE model needs different inputs from each study site, including soil (texture and depth), tree and/or crop managements and parameters, daily climate. The model requires tree and/or crop management inputs, including planting density, pruning and thinning to simulate yields under monoculture and agroforestry systems (Graves et al. 2010). For the simulation of agroforestry-based coffee production, 60 trees of *Albizia gummifera* and 2500 coffee plants ha⁻¹ were considered from our field count. However, for coffee monoculture plantations the planting density was higher (3000 plants ha⁻¹). Coffee plants were also considered to be harvested each year whereas thinning management was not considered for both the tree and coffee plants throughout productive life span of coffee (40 years) (Gole 2015). The tree and coffee crop parameter inputs for the model were also collected from intensive literature review (Table 1).

To predict the impacts of 40 years climate variability on coffee yield under monoculture and agroforestry systems, historical daily climate data (current) and two future climate scenarios of the sites were also needed as inputs for the model. RCP scenarios are developed by the IPCC and consider the effects of increasing anthropogenic atmosphere emissions. For this study, the scenarios RCP 4.5 and 8.5 were selected. These scenarios represent an increase of the radiative force values of 4.5 and 8.5 W m⁻², respectively, that would represent an increase of 2.4 °C or 4.9 °C by 2100 in the world (Wayne 2013).

As no historical climate data is available for the study sites (Moat et al. 2017), simulated historical

climate data was retrieved from the CORDEX data base (Coordinated Regional climate Downscaling Experiment <https://www.cordex.org>—for Africa). The CORDEX platform provides historical and future climate data for Africa at 0.44° resolution from daily to monthly temporal scales simulated by different global climate models. For this study, the datasets developed by the Hadley Centre for Climate Prediction and Research's General Circulation Model (HadCM3) were used as they have offered decent results in previous studies in Ethiopia (Jaramillo et al. 2011; Davis et al. 2012; Moat et al. 2017). Forty years of daily temperature, precipitation, radiation and relative humidity of historical (1966–2005) and for the two future climate scenarios (2006–2045) were downloaded from the platform. A program in Python programming language (www.python.org) was developed to retrieve data time series for the latitude and longitude of the study sites, and the data then formatted to be used as yield-SAFE model inputs.

At the study sites, in future climate scenarios, the monthly average temperature will increase, whereas precipitation is expected to decrease. These values differ for both sites: in the Wonago, the 40 years average monthly temperature (20 °C) is expected to increase by 0.6 in the RCP 4.5 and 0.8 °C in the RCP 8.5. However, the average monthly precipitation is expected to decrease from its current average of 94 mm by 3 and 6 mm for both scenarios (Fig. 2a). Similarly, for the Limu Kosa, it is projected that the average monthly temperature under current scenario (19.5 °C) is to increase by 0.5 and 0.7 °C while the average monthly precipitation (96 mm) is to decrease by 2 and 3 mm in RCP 4.5 and 8.5 scenarios, respectively (Fig. 2b). In both sites, dry months (February–May) will be wetter whereas wet months (June–August) will be drier under future climate scenarios (Fig. 2).

Model calibration and validation

For each study site, DBH, tree biomass and leaf area of *Albizia gummifera* grown in monoculture were first simulated by the yield-SAFE model using the parameters presented in Table 1 and historical climate data. The parameters related to DBH were then adjusted in order to match within the range of “reference” (observed) DBH values of 20–40 cm at age of

Table 1 Parameter set for *Albizia gummifera* and *Coffea arabica* used in yield-SAFE model

Parameters	Unit	Value ranges	Value used	References
Light use efficiency	g MJ ⁻¹	0.76	0.76	Binkley et al. (1992)
Water use efficiency	m ³ g ⁻¹	0.00023–0.004	0.001	Andrew et al. (2013)
Maximum leaf area	m ² tree ⁻¹	80–110	105	Andrew et al. (2013)
Specific leaf area	m ² kg ⁻¹	2.96–3.65	3.08	Andrew et al. (2013)
Leaf area index		1.3–4.0	2.5	Missanjo and Maya (2015)
Initial leaf area	m ² tree ⁻¹	0.0136–0.04	0.02	Missanjo and Maya (2015)
Initial biomass	g tree ⁻¹	11.3–27.2	18.6	Andrew et al. (2013) and Missanjo and Maya (2015)
<i>Coffea arabica</i>				
Light use efficiency	g MJ ⁻¹	0.06–2.76	1.88	Netsere and Kufa (2015)
Water use efficiency	m ³ g ⁻¹	0.0037–0.011	0.001	Kufa and Burkhardt (2015)
Specific leaf area	m ² kg ⁻¹	9.8–14.21	12.8	Kufa and Burkhardt (2015)
Maximum leaf area	m ² tree ⁻¹	9–18	17	Montoya et al. (2013)
Initial leaf area	m ² tree ⁻¹	0.189–0.22	0.19	Camargo (2010)
Leaf area index		0.8–5	4.5	Montoya et al. (2013) and Kufa and Burkhardt (2015)
Harvest index	g g ⁻¹	0.1–0.7	0.5	Rodrigues et al. (2015)
Initial biomass	g tree ⁻¹	26–36	32	Netsere and Kufa (2015)
Maintenance respiration coefficient	g g ⁻¹	0.0031	0.0031	Rodrigues et al. (2015)

20 years. The parameters related to tree biomass was also adjusted to fit the reference values in between 95 and 215 kg tree⁻¹ for Wonago and 105–225 kg tree⁻¹ for Limu Kosa. Furthermore, leaf area was also adjusted to match with the reference values of the sites between 75 and 105 m² tree⁻¹ (Fig. 3).

Similarly, coffee yield in monoculture system was simulated in the model using the crop parameters (Table 1), soil inputs and daily historical climate data. The average simulated yield was then calibrated to fit the reference values between 1000 and 1200 kg ha⁻¹ year⁻¹ in the Wonago and between 1100 and 2100 kg ha⁻¹ year⁻¹ in the Limu Kosa.

After the model calibration for the tree and coffee plantations grown as monoculture systems, we used the same parameter set to simulate coffee yield under agroforestry systems, where both species are combined and competing for light and water. The reference coffee yields used were between 1400 and 1520 kg ha⁻¹ year⁻¹ for Wonago and between 1400

and 2100 kg ha⁻¹ year⁻¹, for Limu Kosa (Fig. 4). Selected parameters in the model (the water use efficiency, harvest index, and light use efficiency) were adjusted within the ranges found in the literature in order to match the modeled values with the reference values (Graves et al. 2010). Full detail descriptions about the yield-SAFE model calibration and validation process can see in Graves et al. (2007).

The parameter set defined during the validation process was then used for simulating coffee yield under monoculture and agroforestry systems for a simulation period of 40 years comparing historical climate data and two future climate change scenarios (RCP 4.5 and RCP 8.5).

Fig. 2 Average monthly temperature and precipitation in current (1966–2005) and two future scenarios (2006–2045) in the **a** Wonago, **b** Limu Kosa districts

Results

Model validation outputs

In both study sites there were a good fit between modeled and reference growth pattern of DBH, biomass and leaf area (Fig. 3). There were also a good match between modeled and reference coffee yield under monoculture and agroforestry systems. For instance, the modeled 40 years average yield (1200 and $1250 \text{ kg ha}^{-1} \text{ year}^{-1}$, respectively for Wonago and Limu Kosa) in monoculture systems was found to be between the reference values of the sites. Similarly, under agroforestry systems, the modeled yields were 1600 and $2200 \text{ kg ha}^{-1} \text{ year}^{-1}$, respectively for Wonago and the Limu Kosa. These values are found between the ranges of the reference values of the sites (Fig. 4), confirming that the model can be used to predict the impacts of climate change on coffee yields under different climate scenarios.

Impacts of climate change on coffee productivity

For the Wonago site, under current climate scenario, yield-SAFE model simulated an average coffee yield in monoculture system around $1200 \text{ kg ha}^{-1} \text{ year}^{-1}$. Simulated yields with climate change scenarios show this average yield to decrease by 38 and 60% in RCP 4.5 and 8.5 scenarios, respectively (Fig. 5a). However, the average yield under agroforestry system in current climate was $1600 \text{ kg ha}^{-1} \text{ year}^{-1}$ and the expected decrease was lower (13% in RCP 4.5 and 25% in 8.5 scenarios) (Fig. 5a).

There were also consistent predictions for the Limu Kosa site: the average yield in monoculture system under current scenario was simulated to be $1250 \text{ kg ha}^{-1} \text{ year}^{-1}$. With climate change scenarios this average yield was expected to decrease by 4 and 20% in RCP 4.5 and 8.5 scenarios, respectively (Fig. 5b). But, the average yield under agroforestry systems in current climate was $2200 \text{ kg ha}^{-1} \text{ year}^{-1}$ and the expected decrease due to climate change is 4

Fig. 3 Yield-SAFE model estimation (line) and average reference (points) values for *Albizia gummifera* tree variables at: **a** Wonago, **b** Limu Kosa (the error bars show maximum and minimum reference values of the tree variables)

and 16% in RCP 4.5 and 8.5 scenarios, respectively (Fig. 5b). In this site, effects of climate change on coffee yield will be lower compared to Wonago site due to a lower increase of temperature and a smaller decrease in precipitation across the climate scenarios (Fig. 2), in addition to being an area with higher rainfall and good soil fertility.

It was projected that the average coffee yields reduction under monoculture systems in the study sites to be between 4–38% in RCP 4.5 and 20–60% in RCP 8.5. However, the yield reduction under agroforestry system was lower (4–13% in RCP 4.5 and 16–25% in RCP 8.5 scenarios) (Fig. 5). For a lower yield reduction under agroforestry systems, the yield-SAFE model suggests that the tree presence with coffee

Fig. 4 Minimum and Maximum reference yields and yield-SAFE modeled coffee yields under monoculture and agroforestry systems at **a** Wonago, **b** Limu Kosa sites

plants is effective in reducing soil evaporation and total evapotranspiration, both from the soil and the coffee (Fig. 6), especially under future climate scenarios. In the Wonago site, the effects of climate change on coffee yield were expected to be higher (Fig. 5a) due to the positive effects of the tree presence with coffee on microclimate, loss of water from soil in the form of evaporation was found to be lower by 61 and 74% in RCP 4.5 and 8.5 climate scenarios, respectively, as compared to monoculture coffee (Fig. 6a). Total evapotranspiration from the soil and the coffee crop was also predicted to be lower under agroforestry-based coffee production compared to monoculture coffee by 16 and 26% in RCP 4.5 and 8.5 scenarios, respectively (Fig. 6b).

Discussion

Impacts of climate change on coffee productivity

In both study sites, in future climate scenarios, average monthly temperature will be expected to increase by 0.5–0.8 °C. It is also expected a precipitation increases by 5–15 mm in February–May, when coffee demands a lower moisture for its fruit setting and filling (Kufa and Burkhardt 2015; Jayakumar et al. 2016) and a decrease in precipitation by 20–30 mm in the rainy months of June–August, when coffee requires a good moisture for its vegetative growth (Camargo 2010; Bote and Struik 2011) (Fig. 2). These weather changes were the main reasons in our study for a reduction of coffee yields under future climate scenarios (Fig. 5). Exposing coffee plants continuously to high temperature coupled with precipitation stress (water deficit in wet season and excess during dry season) declines its

Fig. 5 Coffee yields under monoculture and agroforestry systems in current and future climate change scenarios at: **a** Wonago, **b** Limu Kosa sites

productivity (Damatta and Ramalho 2006; Dias et al. 2007; Belachew and Teferi 2015; Craparo et al. 2015; Moat et al. 2017). For example, if expected higher temperatures occur during sensitive stages of the crop such as flowering or fruit setting, yield will be adversely affected (Bote and Struik 2011; Jassogne et al. 2013). In extreme cases, high temperatures occur at blossoming stage with a prolonged dry season and this may cause the abortion of crop flowers (Damatta and Ramalho 2006; Dias et al. 2007; Camargo 2010). Also, low temperatures coupled with water deficit affect the crop's photosynthesis by reducing stomata conductance and carbon metabolism (Bote and Struik 2011; Kufa and Burkhardt 2015). Moreover, an increase in rain levels during the flowering stage will disturb the crop's fruit setting and filling, thereby

declining its productivity and quality (Damatta and Ramalho 2006; Dias et al. 2007; Bote and Struik 2011; Jassogne et al. 2013; Jayakumar et al. 2016; Moat et al. 2017).

The results found in this study follow previous evidence (Lin 2010; Bote and Struik 2011; Nonato et al. 2012; Belachew and Teferi 2015; Kufa and Burkhardt 2015; Jayakumar et al. 2016) that coffee productivity will decrease in future climate scenarios due to increasing temperature and precipitation stress. Also in east Africa, particularly in Tanzania, coffee productivity is expected to decrease by 137 kg ha⁻¹ - year⁻¹ as the average minimum temperature (18 °C) increases by 1 °C, suggesting that a rise of temperature is the key factor for declining future coffee productivity in the country (Craparo et al. 2015). Similarly,

Fig. 6 Comparison of water dynamics between agroforestry-based and monoculture coffee production systems under current and two future climate scenarios at Wonago site

India coffee yield was projected to decrease by 10% when maximum average temperature rose beyond 28 °C in dry months (January and February) under future climate scenarios (Jayakumar et al. 2016). In addition of direct impacts of climate change on coffee productivity, there are also indirect impacts. For example, the population of the coffee berry borer (*Hypothenemus hampei*), which is considered to be the most damaging coffee pest, was predicted to increase its growth rate by 8.5% for every 1 °C increase (Jaramillo et al. 2011). Infestation of Coffee berry disease (*Colletotrichum kahawa*) on coffee under future scenarios was also predicted to increase due to the expected prolonged drought conditions (Jassogne et al. 2013; Belachew and Teferi 2015; Alemu 2015). In addition, the population of bees, one of the key pollinators of coffee, has been projected to decrease by

8–18% in future climate scenarios (Ngo et al. 2011; Imbach et al. 2017).

Agroforestry for adaptation to climate change

Our simulations suggest that coffee yield will decrease under monoculture and agroforestry systems in future climate scenarios. However, in all scenarios, coffee yield under agroforestry systems will be less vulnerable compared to monoculture systems (Fig. 5). For this, the present study suggests that the presence of the tree with coffee can reduce soil evaporation (Fig. 6a) and total evapotranspiration both from the soil surface and the coffee plant (Fig. 6b), especially under future climate scenarios. These results are consistent with other studies mentioning that shade trees could reduce wind movement (Lin 2010; Alemu 2015), sunlight

radiation (Bote and Struik 2011; Alemu 2015; Kufa and Burkhardt 2015) and air and soil temperatures (Lin 2010; Bote and Struik 2011; Nonato et al. 2012), all creating a microclimate effect that reduces evapotranspiration. The presence of shade trees was also found to reduce coffee transpiration and daily soil evaporation by up to 32 and 41%, respectively, compared to monoculture coffee, suggesting that trees act as a key factor in the strategy to be adopted against the impacts of future climate change on coffee productivity (Lin 2010). Other studies supporting the role of trees in future coffee production show that shade trees present with coffee are able to buffer high temperature episodes (up to 5 °C) (Bote and Struik 2011; Jassogne et al. 2013; Alemu 2015; Kufa and Burkhardt 2015). This effect is essential in many coffee growing tropical areas where water loss through evapotranspiration is the main factor for reducing coffee productivity (Lin 2010; Muleta et al. 2011; Nonato et al. 2012). In addition, coffee plants under agroforestry systems, when compared to coffee monoculture, showed smaller transpiration rates and leaf temperature (Bote and Struik 2011; Kufa and Burkhardt 2015), bigger coffee berries (Bote and Struik 2011; Ebisa 2014; Alemu 2015; Kufa and Burkhardt 2015) and higher leaf nitrogen content (Bote and Struik 2011; Nonato et al. 2012). Shade trees used for coffee also improved soil organic carbon and microbial activities (Nonato et al. 2012; Ebisa 2014) and soil water retention (Lin 2010; Muleta et al. 2011; Kufa and Burkhardt 2015), ensuring better soil conditions for a better coffee productivity (Nonato et al. 2012).

Conclusion

This was the first time that the process-based yield-SAFE model was calibrated and validated for *coffee arabica*, showing an interesting performance when used for predicting impacts of future climate scenarios on coffee productivity under monoculture and agroforestry systems in Ethiopia. Findings of the present study evidence that future climate change is expected to decrease coffee productivity between 4 and 25% in agroforestry systems and up to 20–60% in monoculture systems, depending on the climate scenarios. The lower yield reduction of coffee produced in agroforestry system seems to be due to the presence of shade trees that help to reduce soil evaporation and

coffee respiration through a decrease in radiation exposure, wind speed and vapor pressure. Therefore, this study offers evidence of the agroforestry systems as a practice to be included in the adaptation strategy for mitigating the negative impacts of future climate change on coffee production.

However, to strengthen the findings of the present study, more research should be done in different regions of Ethiopia and the world in order to understand the full potential of agroforestry systems against the impacts of future climate change on coffee production. In addition, at present, the yield-SAFE model does not consider competition with herbaceous plants (e.g. weeds) with coffee for resources. In future versions of the model, it would be good to include these effects for a better coffee yield prediction under climate change.

Acknowledgements We gratefully acknowledged for the program of education, training, youth and sport of the European Commission for its financial support for the study of the first author in the Erasmus Mundus MEDOFR program. We also thank European Union FP7 Project AGFORWARD (Agroforestry that will advance rural development—contract nr 613520).

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