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Using Yield-SAFE model to assess climate change impact on yield of coffee (*Coffea arabica*) under agroforestry and monoculture systems

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Dissertation to obtain the degree of Master in

Mediterranean Forestry and Natural Resources Management

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2016

LISBOA | UNIVERSIDADE DE LISBOA

AKNOWLEDGMENTS

My heartfelt gratitude goes to my supervisor Doutor João Palma for his continuous and friendly support from title identification, model calibration, scientific writing process and excellent guidance. My thesis would not have been accomplished without his immense support. Again, I thank you very much!

I would also graceful to my co-supervisor Doutora Tânia Sofia Oliveira for her huge support in model calibration, constructive comments and suggestions on my thesis write-up.

I would also thank to Josep Crous-Duran for his friendly and hearty support in model calibration and sharing of valuable scientific papers.

I would also to extend my sincere thanks to Professora Margarida Tomé for her lecture of Forest Models course that was the beginning to do my dissertation in modeling.

My special thanks also goes to my friend and colleague Samuray Bagaram for his help to mapping of the study districts in GIS, and the good friendship which we are already established.

I also deeply acknowledge to the European Union for funding my study in Erasmus Mundus MEDFOR program for the last two years. I would also like to thank very much all MEDFOR committee members who selected me to be member of this amazing program.

I would also thank to professors and fellows in MEDFOR program for their love, unforgettable moments, and a lot of new experiences.

Finally, I will be always grateful to all my friends, family and my fiancée who have kindly supported and shared not only happy moments but also difficult times.

ABSTRACT

Ethiopia economy strongly depends on coffee (*Coffea arabica L.*) production. Coffee, like many other agricultural crops, is sensitive to climate change. Future changes in climate will have a negative impact on coffee yield and quality. Studies have called for an urgent development of coffee's adaptation strategies against climate change and agroforestry systems have received attention as an adaptation and mitigation strategy for coffee production under future climate. This study contributes to the assessment of coffee production in 1) monoculture and in 2) agroforestry systems, under different climate scenarios, in four different regions, providing insights for preliminary recommendations for coffee growers and policy makers. The Yield-SAFE process-based model was used to predict yield of coffee in monoculture and under agroforestry systems for forty years of current and future climate (Representative Concentration Pathways (RCP) 4.5 and 8.5 - HadCM2 model). In monoculture system, coffee yield was estimated to decrease between 4-38 % and 16-58 % in RCP 4.5 and 8.5, respectively from its current yield of 1000-1600 kg ha^{-1} yr^{-1}. However, in agroforestry system the decrease was between 4-13 % and 13-25 % in RCP 4.5 and 8.5, respectively from its current yield of 1200-2200 kg ha^{-1} yr^{-1}, showing that agroforestry systems have a higher resilience when facing future climate change.

Key words: Climate change adaptation, Ethiopia, process based model, system resilience , shade trees

RESUMO

Usando o modelo Yield -SAFE para avaliar o impacto das alterações climáticas sobre a produção de café (*Coffea arabica*) em sistemas agroflorestais e monocultura

A economia da Etiópia está muito dependente da produção de café (*Coffea arabica L.*). O café, como muitas outras culturas agrícolas, é sensível a alterações climáticas. Alterações climáticas futuras vão ter um impacto na produtividade e qualidade do café, ao alterarem a dinâmica das populações de pragas e doenças dos cafezeiros. Estudos recentes têm alertado para o desenvolvimento urgente de estratégias de adaptação do café às mudanças climáticas e os sistemas agroflorestais têm recebido atenção como estratégias de adaptação e mitigação para a produção de café num futuro de clima incerto.

Este trabalho contribui para a avaliação da produção de café em 1) monocultura e em 2) sistemas agroflorestais, em quatro regiões diferentes e sob diferentes cenários climáticos, proporcionando recomendações preliminares para produtores de café e decisores políticos. O modelo de base processual Yield-SAFE foi utilizado para prever o rendimento do café em monocultura e em sistemas agroflorestais ao longo de quarenta anos de clima atual e futuro (cenários RCP 4.5 e RCP 8.5 - modelo HadCM2). Em monocultura, prevê-se que a produção de café diminua entre 4-38 % e 16-58 % segundo os senários RCP 4.5 e 8.5, respectivamente, do seu rendimento atual de 1000-1600 kg ha^{-1} ano^{-1}. No entanto, em sistema agroflorestal, a redução prevista é de apenas 4-13 % e 13-25 % segundo os senários RCP 4.5 e 8.5, respectivamente, do seu rendimento atual de 1200-2200 kg ha^{-1} ano^{-1}, mostrando que os sistemas agroflorestais têm uma resiliência maior quando enfrentam as mudanças climáticas futuras.

Palavras-chave: árvores de sombra, adaptação a alterações climáticas, Etiópia, modelo de base processual, resiliência do sistema

RESUMO ALARGADO

A economia da Etiópia é muito dependente da produção de café. No entanto, a produção de café está a ser e continuará a ser impactada no futuro por alterações climáticas. Estudos recentes têm chamado a atenção para a necessidade de um desenvolvimento urgente de estratégias de adaptação do café às alterações climáticas e os sistemas agroflorestais têm recebido atenção como estratégia de adaptação para a produção sustentável de café. Este estudo contribui para a avaliação da produção de café em 1) monocultura e em 2) sistemas agroflorestais, em quatro regiões distintas e considerando diferentes cenários climáticos por forma a fornecer recomendações preliminares para produtores de café e decisores políticos.

A fim de avaliar o rendimento do café em monocultura e sob o coberto da *Albizia gummifera* (Agrofloresta), foi utilizado um modelo de base processual e pouco exigente em parâmetros denominado Yield-SAFE. Além dos parâmetros de crescimento do café e das árvores de *Albizia gummifera*, o modelo necessita também de dados de clima e de solo como input. Os parâmetros de crescimento do café e das árvores foram obtidos a partir de materiais publicados. Os cenários climáticos atual e os dois futuros (RCP 4.5 e RCP 8.5 - HadCM2) foram recolhidos dos datasets ESG. Foi desenvolvido um programa em linguagem de programação Python para extrair os dados climáticos para cada uma das áreas de estudo. Os dados climáticos foram então processados para o formato necessário para servirem de input climático para o Yield-SAFE.

O rendimento e crescimento das árvores de *Albizia gummifera* e do café foram simulados com o modelo Yield-SAFE usando os respectivos parâmetros de crescimento, clima histórico diário de 20 anos e inputs do solo. A biomassa das árvores de *Albizia gummifera*, área foliar e diâmetro à altura do peito em sistema de monocultura foram então calibrados usando os seus valores de referência (reais). Além disso, o rendimento de café em monocultura e em sistemas agroflorestais foi também calibrado usando os valores de referência em cada um dos distritos estudados. Os parâmetros como o índice de colheita e a eficiência de uso da água foram ajustados dentro dos limites fisiológicos aceitáveis referidos na bibliografia a fim de calibrar o rendimento simulado de café. O modelo calibrado foi então usado para predizer a produção de café em monocultura e agroflorestas em cada uma das áreas de estudo ao longo de quarenta anos usando os cenários atual e futuros de alterações climáticas.

No distrito de Wonago (sul da Etiópia), a temperatura média mensal atual (20°C) vai aumentar 0,6 e 0,8°C segundo os cenários RCP 4.5 e 8.5, respectivamente, e a precipitação anual total (1.136 milímetros) aumenta também 90 e 124 mm segundo os cenários RCP 4.5 e 8.5, respectivamente. Usando o clima atual, o modelo Yield-SAFE estimou o rendimento médio de café em monocultura ao longo dos 40 anos em 1.200 kg ha^{-1} ano^{-1} e este valor diminui 38 e 58% segundo os cenários RCP 4.5 e 8.5, respectivamente. Por outro lado, o rendimento do café em agroflorestas no clima atual, estimado em 1.600 kg ha^{-1} ano^{-1}, diminui em 13 e 25% segundo os cenários RCP 4.5 e 8.5, respectivamente.

Da mesma forma, no distrito Limu Kosa (Sudoeste da Etiópia), a temperatura média mensal atual é de 19,5°C e vai aumentar 0,5 e 1°C segundo os cenários RCP 4.5 e 8.5, respectivamente. A precipitação total anual também aumenta a partir do seu valor atual (1.265 milímetros) em 70 e 120 mm segundo os cenários RCP 4.5 e 8.5, respectivamente. No sistema de monocultura sob o clima atual, o rendimento médio do café foi modelado em 1.250 kg ha^{-1} ano^{-1} e diminui 4 e 20% segundo os cenários RCP 4.5 e 8.5, respectivamente. Também foi previsto pelo modelo que o rendimento médio de café em sistemas agroflorestais seja de 2.200 kg ha^{-1} ano^{-1} e que diminua 4 e 16% segundo os cenários RCP 4.5 e 8.5, respectivamente.

No distrito de Manasibu (Oeste da Etiópia) a temperatura média mensal atual é de 19,7°C e prevê-se um aumento de 0,6 e 0,8°C segundo os cenários RCP 4.5 e 8.5, respectivamente. A precipitação anual total actual (1,261 milímetros) também irá aumentar 40 e 96 mm segundo os cenários RCP 4.5 e 8.5, respectivamente. Usando clima atual, o modelo Yield-SAFE estima o rendimento médio de café em monocultura como sendo de 1.600 kg ha^{-1} ano^{-1}, havendo uma diminuição de 10 e 16% segundo os cenários RCP 4.5 e 8.5, respectivamente. O rendimento médio do café em agroflorestas no clima atual foi estimado em 1.800 kg ha^{-1} ano^{-1} e diminui 6 e 13% segundo os cenários RCP 4.5 e 8.5, respectivamente.

No distrito de Darolebu (Este da Etiópia), a temperatura média mensal atual (20,4°C) aumenta 0,6 e 0,8°C segundo os cenários RCP 4.5 e 8.5, respectivamente. A precipitação total anual aumenta também a partir da sua quantidade atual de 1.160 mm em 36 mm e 50 mm segundo os cenários RCP 4.5 e 8.5, respectivamente. Usando o clima atual, o rendimento médio do café em monocultura foi estimado em 1.000 kg ha^{-1} ano^{-1} e vai diminuir 30 e 40% segundo os cenários RCP 4.5 e 8.5, respectivamente. O modelo também simulou o rendimento médio do café em agroflorestas em 1.200 kg ha^{-1} ano^{-1}, diminuindo 8% e 17% segundo os cenários RCP 4.5 e 8.5, respectivamente.

Os resultados deste trabalho estão de acordo com trabalhos de outros autores, nos quais se nota um padrão de redução da produção de café em monocultura e em sistemas agroflorestais quando se considera o clima futuro. No entanto, os resultados aqui apresentados sugerem que a produção de café em sistemas agroflorestais será menos impactada pelas alterações climáticas, em comparação com a monocultura. Isso pode ser justificado no modelo através de

árvores que fazem sombra, cuja presença já foi provada que é eficaz na redução da evaporação do solo, evapotranspiração, transpiração e na manutenção da humidade volumétrica do solo.

O impacto dos cenários climáticos de futuro no rendimento simulado de café na Etiópia foi diferente em cada um dos distritos estudados. A produtividade do café nos distritos de Wonago e Darolebu será altamente impactada por mudanças futuras no clima, enquanto nos distritos de Limu Kosa e Manasibu os impactos serão relativamente menores. Em todos os distritos, o café produzido em sistemas agroflorestais será menos impactado por alterações climáticas futuras quando comparado com os sistemas em monocultura. Portanto, a promoção da produção de café sob a sombra das árvores (sistema agroflorestal) poderá ser um mecanismo chave de adaptação para a produção sustentável de café em situações de alterações climáticas.

Palavras-chave: árvores de sombra, adaptação a alterações climáticas, Etiópia, modelo de base processual, resiliência do sistema.

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1. INTRODUCTION

Coffee *(Coffea arabica, L.)* is the most important tropical beverage crop, cultivated in more than fifty tropical and sub-tropical countries. It is the most important tradable crop commodity in the world next to petroleum (Amsalu and Ludi, 2010). Teketay and Tegineh (1991) suggested that the origin of coffee is Ethiopia. Currently, Ethiopia is the leading coffee producer in Africa and is ranked 5th in the world following Brazil, Vietnam, Colombia and Indonesia. Area coverage of coffee in Ethiopia is estimated to be about 800,000 ha with a yearly production of 397500 tons of coffee beans (Gole, 2015). Ethiopian economy is strongly dependent on coffee, for example, this commodity is responsible for about 35 % of total exports (Muleta et al., 2011), more than 25 % of the country's foreign exchange earnings, and over 10 % of the Gross Domestic Product (Gole and Senbeta, 2008). Coffee supports, directly and indirectly, the livelihoods of 15 million Ethiopians, about 17 % of the total population (Muleta et al., 2011), where there is a popular saying that "coffee is the backbone of our life" (Bossolasco, 2009).

In Ethiopia, coffee grows in areas with an altitudinal range of 1000-2200 meter above sea level (masl); rainfall between 1500-2000 mm year^1, annual average temperature between 18° to 24°C; relative humidity between 30 to 85 %; and soils with rich organic matter (Muleta et al., 2011; Gole, 2015). Being coffee a shade-tolerant plant, it is widely cultivated under the shade of trees and shrubs. However, it is also currently grown as a monoculture system. Depending on the climatic and soil conditions, coffee takes 3 years to produce edible coffee beans (Kufa and Burkhardt, 2011).

According to Woldemariam et al. (2003) and Gole (2015), coffee production systems in Ethiopia can be grouped into four categories, namely: coffee plantations, forest coffee, semi-forest coffee and garden coffee. They account for 5, 10, 35 and 50 % of the total national coffee production, respectively. Coffee production under modern plantations is mainly run by the state or investors. It follows an appropriate way of site preparation, planting method, fertilizers, irrigation, insecticides and harvesting methods, where the primary management goals are production maximization (Bossolasco, 2009). On the contrary, forest coffee production systems can be defined as naturally growing coffee as an understory of trees and/or shrubs without intensive human management. This type of production system is mainly concentrated on the Southwest part of Ethiopia, its average yield has been estimated to be 200-250 kg ha^{-1}, far below the national average yield between 450-472 kg ha^{-1} (Gole, 2015).

Semi-forest coffee production systems are defined as forest coffee growing near to main roads, towns or villages and managed with cultural practices such as weeding and shade regulation. The average yield of this coffee production system is estimated to be around 300-400 kg ha^{-1} (Woldemariam et al., 2003).

Garden coffee production systems are widely practiced in the vicinity of farmers' residences. Its praxis usually mixes crops or shade trees and some improved management can occur by planting in orthogonal patterns where shading trees are adjacent to coffee plants. This type of production system is widely used in South, South-western and Eastern parts of Ethiopia (Woldemariam et al., 2003; Bossolasco, 2009). In Garden coffee, the most representative production system, coffee is intercropped with fruits, herb, cash crop or forage in the same unit of land (Teketay and Tegineh, 1991; Negash and Kanninen, 2015), but it is also grown under the shade of trees and shrub species, corresponding to a typical example of agroforestry systems. In Ethiopia, coffee is commonly grown as understory of different tree species depending on the region (Table 1), where 69 % of the trees in south-eastern region are leguminous (Teketay and Tegineh, 1991).

The Intergovernmental Panel on Climate Change (IPCC) set different climate change scenarios dependent on world future economy and population growth. Representative Concentration Pathways (RCP) 4.5 scenario of the IPCC assumes a lower population growth (10.4 billion) and CO_2 eq concentration (500-720 part per million) in the atmosphere by 2100. Another scenario, RCP 8.5, assumes higher world population (15 billion) and CO_2 eq concentration (more than 1000 ppm) in the atmosphere by 2100 (Wayne 2013). In both scenarios, temperature will be expected to increase in Ethiopia. Mean annual temperature across Ethiopia will be expected to increase by 2.2 and 2.6^{o}C in RCP 4.5 and 8.5, respectively by 2050. Moreover, according to RCP 4.5 scenario, rainfall from December to February will be expected to increase 5-20 % and rainfall from June to August will decrease 5-10 % in East Africa by 2050 (IPCC 2015).

Table 1. Common tree species used as shading trees for garden coffee production in Ethiopia

Region of Ethiopia	Species	Reference
South	*Millettia ferruginea* *Cordia Africana* *Erythrina abyssinica* *Albezia* spp.	Nigussie et al., 2014
Southwest	*Croton machrostachiyus* *Albizia gummifera* *Cordia Africana* *Ficus vasta*	Mahmood, 2008 Bossolasco, 2009
Southeast	*Milletia ferruginea* *Erythrinaburana* *Sesbania sesban* *Ficus* sp. *Acacia albida* *Cordia Africana*	Teketay and Tegineh, 1991
West	*Cordia Africana* *Croton microstachyus* *Albizea gummifera* *Acacia abyssinic*	Ebisa, 2014

There is evidence that coffee production is currently influenced by climate change. For example, Davis et al. (2012) suggests that the coffee ecological range is currently being narrowed by climate change in Ethiopia and it will be likely more narrowed in the future. Similarly, changes in temperature and rainfall patterns will decrease coffee growing areas in Haiti (Eitzinger et al., 2013). In Tanzania, coffee yield is predicted to decrease 137 kg ha^{-1} by 2060, if the minimum temperature increases by 1°C (Craparo et al., 2015). There are also predictions of increased coffee disease and pests as temperature increases in Ethiopia (Jaramillo et al., 2011; Belachew and Teferi, 2015).

In this study, in order to assess the yield of coffee under monoculture and in association with shading trees, we used a parameter-sparse, process-based model called Yield-SAFE, a Yield Estimator for Long term Design of Silvoarable AgroForestry in Europe (van der Werf et al. 2007). Process-based models are essentially used for understanding light, water and nutrient use by trees or crops in agriculture, forestry or agroforestry systems (Graves et al., 2007; Oijen et al., 2010). Models are also useful tools for simulating yield of crops or trees under different soil types, climate conditions and management regimes (Luedeling et al., 2016; Oijen et al., 2010) which, experimentally, would be timely and expensive.

The Yield-SAFE model is one of the few agroforestry models with a daily time step and it was conceptualized for simulating yield of crops and trees in forestry, agriculture and agroforestry based on resource acquisition and use efficiency. Moreover, it is a useful tool for predicting influences of climate, tree and crop species, soil type and management choices on tree and crop production, economy and environment (van der Werf et al. 2007). The Yield-SAFE model has been used to predict long term yield of trees under different climate change scenarios (Palma et al., 2007; Crous et al., 2014; Palma et al., 2014). It has been also used extensively for modelling the yield of crops in Europe (Mayus et al., 2007; Palma et al., 2007; Van der Werf et al., 2007; Graves et al., 2010) and for predicting walnut-maize systems in China (Holst et al., 2012 cited in Luedeling et al., 2016).

Recent scientific evidence suggests that the severity of climate extremes is increasing and developing adaptation is an absolute necessity for sustainable coffee production (Belachew and Teferi, 2015). Adaptations such as growing coffee under the shade of trees (agroforestry system) may reduce coffee vulnerability to climate change (Amsalu and Ludi, 2010; Jaramillo et al., 2011; Davis et al., 2012). Shade trees growing with coffee are able to reduce temperature by up to 4^{o}C, and by up to 34 % of the Coffee Berry disease (Jaramillo et al., 2011; Alemu, 2015). Coffee productivity has been declining for three consecutive years in Western Ethiopia and this is typically associated with climate. To overcome this problem, research is urgently recommending to examine the roles of shading trees along with coffee for climate change adaptation strategies (Alemu, 2015; Belachew and Teferi, 2015; Gole, 2015). However, in Ethiopia, the roles of shade trees on coffee productivity under long term climatic change have not been studied so far. This study tries to assess coffee productivity in agroforestry and monoculture systems under different climate scenarios, hoping to yield recommendations for coffee growers and policy makers.

2. MATERIAL AND METHODS

2.1 Description of the study Areas

Southern, Southwest, Western and Eastern parts of Ethiopia are suitable areas for coffee production (Teketay and Tegineh, 1991; Woldemariam et al., 2003). Among the districts in Southern part of Ethiopia, the Wonago district is one of the potential area for coffee production (Negash and Kanninen, 2015). The Limu kosa (Southwest Ethiopia), the Manasibu district (West Ethiopia) and Darolebu (East Ethiopia) are also the potential areas for coffee production (Teketay and Tegineh, 1991; Gole, 2015). In the Wonago and Manasibu districts, coffee is mostly grown under the shade of trees and shrubs Ebisa, 2014; Nigussie et al., 2014) while in the Limu kosa it is grown in monoculture and agroforestry systems (Bossolasco, 2009). In the Darolebu district it is mostly intercropped with fruits and cereals, but it is also grown under the shade of trees and shrubs (Teketay and Tegineh, 1991; Gebermedin & Tolera, 2015). Climate features and geographical locations of the study districts are showed in Table 2 and Figure 1.

Table 2. Geographical description, climate features and common coffee production system in the study districts

District Name	Latitude and Longitude	Temperature (°C)	Rainfall (mm)	Altitude (masl)	Coffee system practiced	References
Wonago	6° 36'N 38° 26'E	11-27	1269-1342	1800-1890	Garden systems	Nigussie et al., 2014
Limu Kosa	7°50'N 36°44'E	12-30	1385-1850	1200 - 1320	Garden systems	Bossolasco, 2009
Manasibu	9° 54' N 35°06'E	22	950	1249-1933	Garden systems	Ebisa, 2014
Darolebu	8°12'N 40°30'E	14 -26	963	1350-1838	Garden systems	Gebermedin & Tolera, 2015

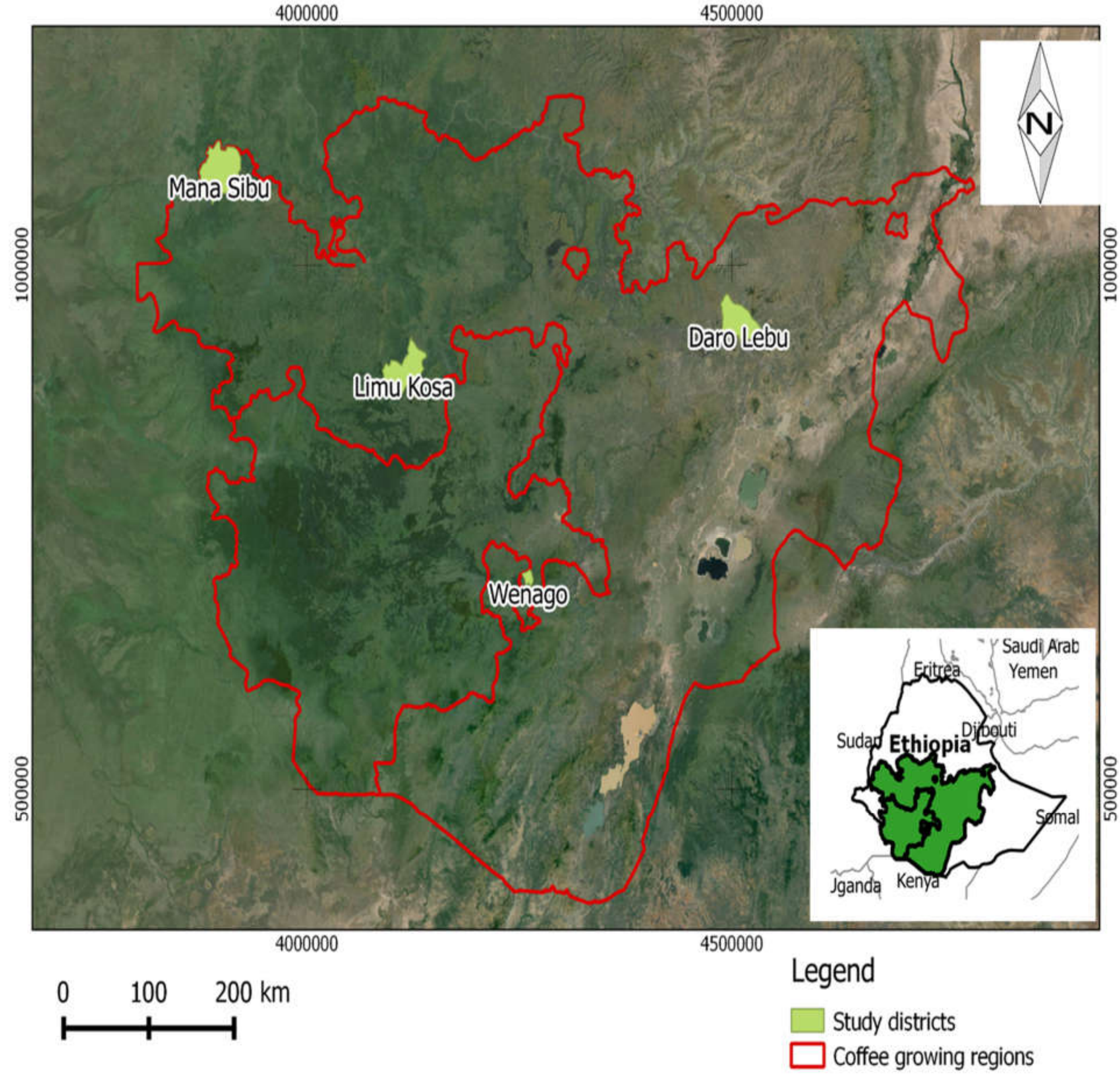

Figure 1. Geographical location of the study areas

2. 2. Tree species selection

In the study areas coffee is grown both as monoculture and agroforestry systems. In agroforestry system, it is grown under the shade of different trees and shrubs, for example: *Erythrina* Spp*., Milletia Ferruginea, Albizia* spp*., Croton spp., Cordia africana, Croton macrostachyus, Sesbania sesban* and *Acacia* spp (Bossolasco, 2009; Gebermedin & Tolera, 2015). The majority of these shade trees and shrubs are leguminous (Teketay and Tegineh, 1991; Muleta et al., 2011). *Albizia gummifera* is a leguminous multipurpose indigenous tree to Ethiopia and the most appropriate shade tree for coffee production (Yisehak and Belay, 2011). It improves coffee yield and quality through modifying microclimate of the system (Muleta et al., 2011). It is also used for soil improvement and conservation, medicine, firewood and forage (Mahmood, 2008; Nigussie et al., 2014). Densities of coffee growing under the shade of *Albizia gummifera* trees in the study districts have not been previously identified. Therefore, in this study, for the purpose of modelling, a general average recommendation by regions (Workafes and Kassu 2000; cited in Gole, 2015) was used (Table 3).

Table 3. Density of coffee tree growing under shade of *Albizia gummifera* tree in the study districts

District Name	Region of Ethiopia	Tree species	*Albizia gummifera* density (tree ha^{-1})	Coffee density under *Albizia gummifera* (tree ha^{-1})
Wonago	South	*Albizia gummifera*	60	2000-2500
Limu Kosa	Southwest	*Albizia gummifera*	60	2000-2500
Manasibu	West	*Albizia gummifera*	30-60	1000-2000
Darolebu	East	*Albizia gummifera*	30-60	1000-2000

2.3. Yield-SAFE model

The Yield Estimator for Long Term Design of Silvoarable AgroForestry in Europe (Yield-SAFE) model was developed to predict long-term yield of crops and trees based on physiological and ecological interactions in monoculture and agroforestry systems (van der Werf et al. 2007). The model has few, simple, well conceptualized mathematical equations that allow the simulation of yield and growth dynamics of crops and trees under uncertain conditions (Graves et al. 2010). Moreover, it has few parameters that are easily parameterized (van der Werf et al. 2007), and its code is compact enough to be included in agro-environmental modelling environments (Donatelli et al., 2002). Due to these reasons, the model is flexible and easily adapted to different crops and environmental conditions by adjusting parameter values and input functions (Graves et al. 2007).

The Yield-SAFE model operates on a daily time-step providing yield of crops or trees in monoculture systems. Then, yield in agroforestry systems can be simulated by setting non-zero planting density of the crop and the trees (van der Werf et al. 2007). To run the improved Yield-SAFE model, it requires a daily climate with minimum and maximum temperature, solar radiation, precipitation, relative humidity and wind speed are required as inputs (Palma et al. 2016) Soil depth and texture are also required as inputs. In addition, parameters either from experiment or published materials that describe tree and crop growth are also needed as inputs for the model (Graves et al., 2010). The main outputs of the model are daily growth dynamics and yields of crop and trees (van der Werf et al. 2007).

2.4. Yield-SAFE model inputs and parameters for the study areas

2.4.1 Climate data inputs

There is scarcity of long term historical (current) daily climate data in the study areas, therefore simulated climate data (historical and future scenarios) was retrieved from the Earth System Grid (ESG) data portal. Recent research is providing support to the use of simulated historical climate as input for Yield-SAFE with minor loss of quality in comparison to real data (Palma et al., 2014). ESG has several Global Climate Models and, among them, the datasets developed by the Centre for Climate Prediction and Research General Circulation Model (HadCM2) were used for this study because it provides good daily simulated climate data for Africa compared to other models in ESG (Jaramillo et al., 2011) and seems to be a reference for climate change assessments in Ethiopia (Jaramillo et al., 2011; Davis et al., 2012).

Daily minimum and maximum temperature, precipitation, radiation, relative humidity and wind speed of historical (1966-2005) and two climate change scenarios (2006-2045) were downloaded to be used as Yield-SAFE model inputs for each of the study area. Two climate change scenarios, the Representative Concentration Pathways (RCP) 4.5 and 8.5 were used. RCP 4.5 scenario assumes a lower population growth (10.4 billion) and CO_2 eq concentration (500-720 ppm) in the atmosphere by 2100 whereas RCP 8.5 scenario assumes higher world population (15 billion) and CO_2 eq concentration (more than 1000 ppm) in the atmosphere by 2100 (Wayne 2013).

A program in Python programming language (www.python.org) was developed to retrieve the climate of the study areas for current and two scenarios from the downloaded datasets (see Annex I). The data was then processed to be formatted as needed to serve as Yield-SAFE climate input.

Averages of 20 years of historical and two future climate scenarios for monthly temperature and total annual precipitation in the study areas were simulated using HadCM2 global climate model (Table 4). Current (1986-2005) and two scenarios (2006-2025) climate trends of the study districts are also showed in Figure 2 and Figure 3. The temperature rises across the scenarios. The precipitation will increase in months where there is already abundant rain, whereas dry months will become drier in the future scenarios (Figure 3).

Table 4. Average of 20 years' monthly temperature (ºC) and total annual precipitation (mm) of the study districts in current (1986-2005) and RCP 4.5 and 8.5 (2005-2025) scenarios

District name	Temperature (ºC)			Precipitation (mm)		
	Current	RCP 4.5	RCP 8.5	Current	RCP 4.5	RCP 4.5
Wonago	20	20.6	20.8	1136	1226	1260
Limu kosa	19.5	20	20.4	1265	1334	1384
Manasibu	19.7	20.3	20.5	1261	1301	1357
Darolebu	20.4	21	21.3	1160	1196	1210

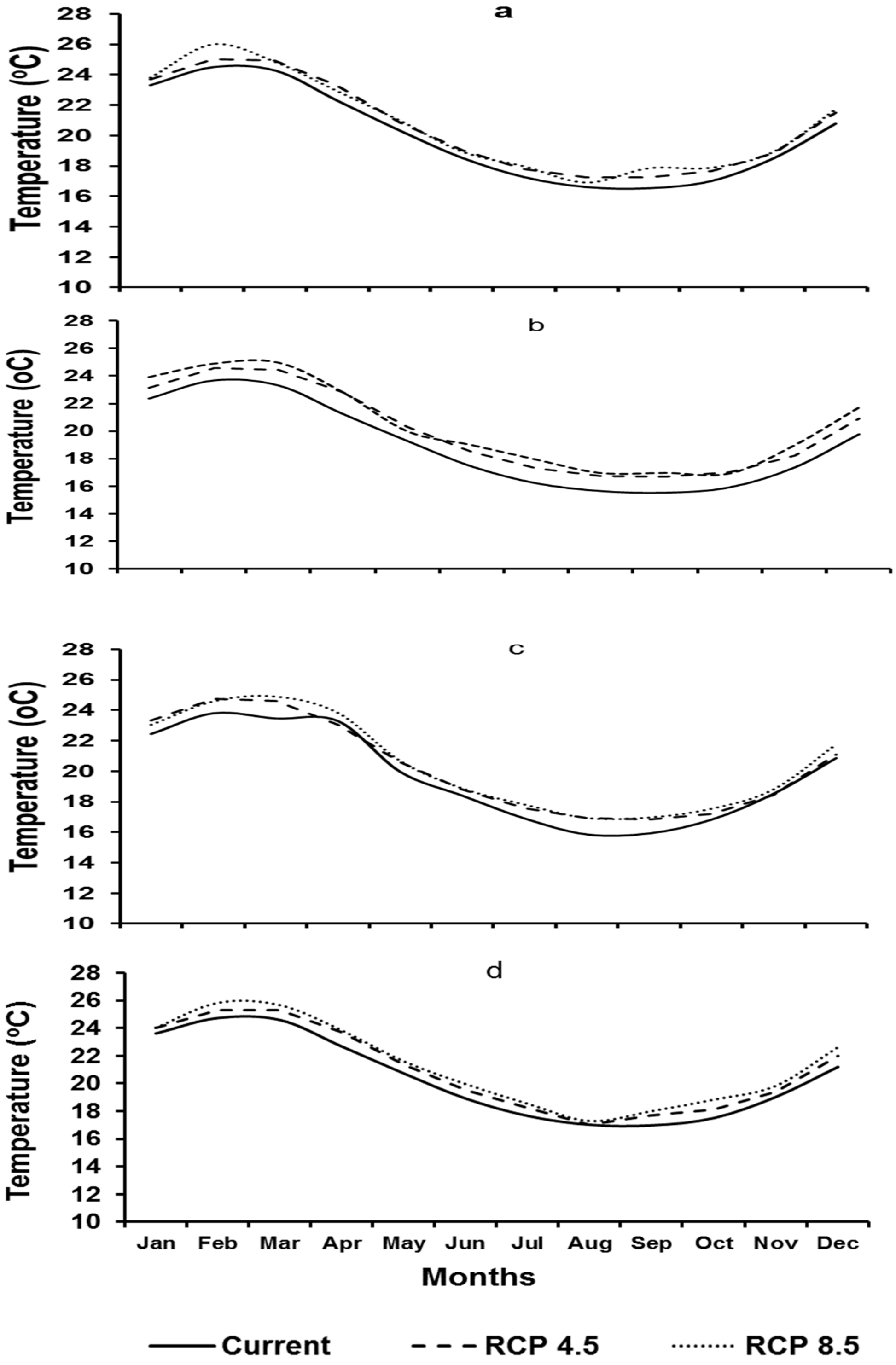

Figure 2. Average of 20 years' monthly temperature in current (1986-2005) and two future scenarios (2006-2025) in the study areas a) Wonago b) Limu kosa c) Manasibu d) Darolebu

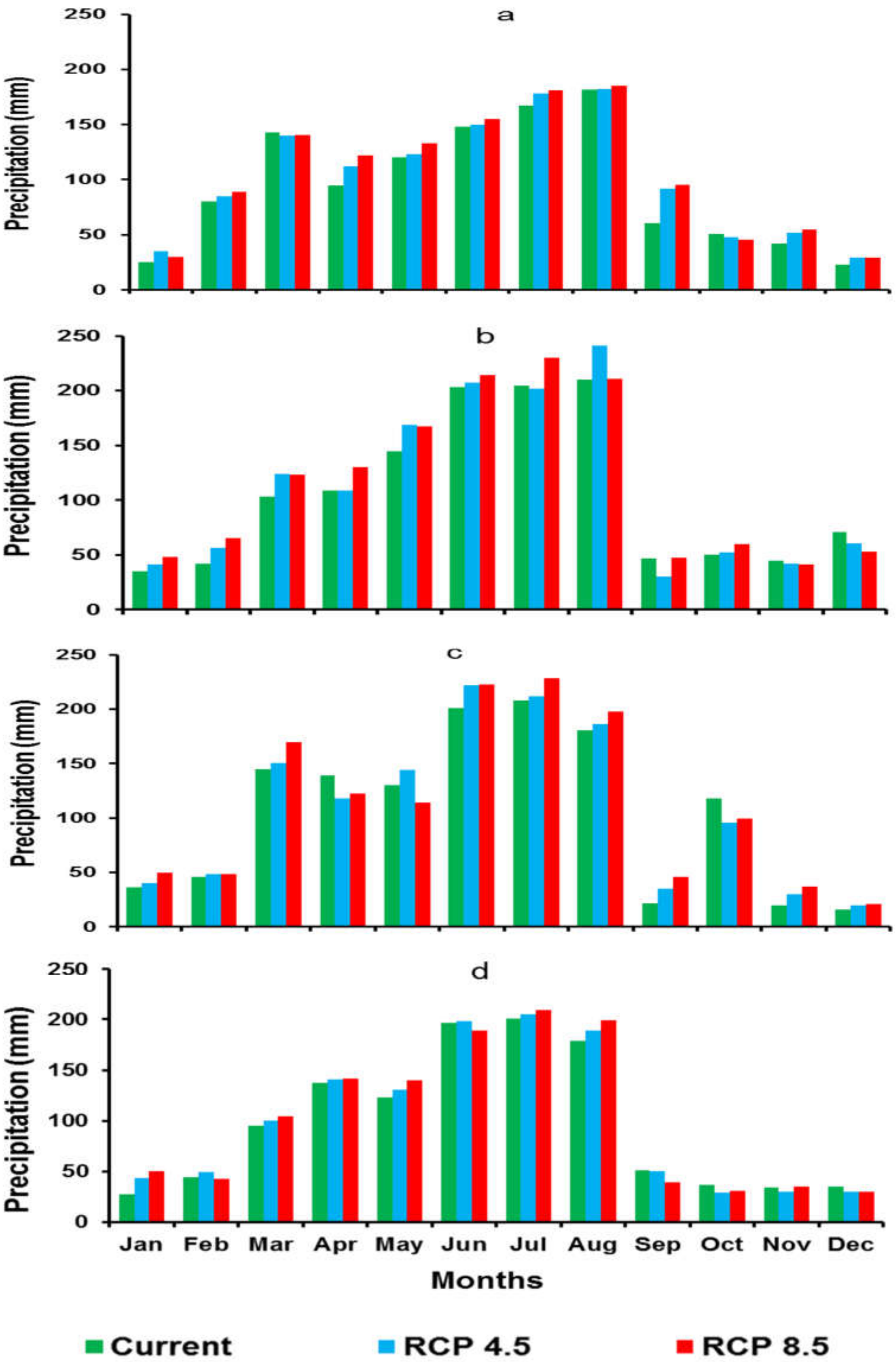

Figure 3. Average of 20 years' monthly precipitation in current (1986-2005) and two future scenarios (2006-2025) in the study areas a) Wonago b) Limu kosa c) Manasibu d) Darolebu

2.4.2. Tree and coffee parameters

The parameters used to describe the growth of coffee and *Albizia gummifera* in the Yield-SAFE model were obtained from published materials (Table 5 and Table 6).

Table 5. Parameter values for coffee obtained from literature

Parameter	Unit	Values	Reference
Radiation use efficiency (RUE)	g MJ^{-1}	0.06-2.76	Charbonnier, 2013
Water use efficiency (WUE)	m^3 g^{-1}	0.0037-0.0073	Beining, 2007
WUE	m^3 g^{-1}	0.0073-0.011	Hiwot, 2011
Specific Leaf Area (SLA)	m^2 kg $^{-1}$	14.21	Kufa & Burkhardt, 2015
SLA	m^2 kg $^{-1}$	9.8-11.6	Bote & Struik, 2011
Maximum leaf area	m^2 $tree^{-1}$	9-18	Montoya et al., 2013
Initial leaf area (4-month-old seedling)	m^2 $tree^{-1}$	0.189-0.22	Dias et al., 2007
Leaf area index		2.8-5	Kufa & Burkhardt, 2015
Leaf area index		0.8-2	Montoya et al., 2013
Harvest index	g g^{-1}	0.1-0.7	Rodrigues et al., 2015
Initial biomass (1 year old seedling)	g $tree^{-1}$	26-36	Kufa, 2012
Maintenance respiration coefficient	g g^{-1}	0.0031	Brand et al., 2002
Density	trees ha^{-1}	2000-2500	Netsere & Kufa, 2015
Base temperature	°C	10.2	Pezzopane et al., 2012

Table 6. Parameter values for *Albizia gummifera* tree obtained from literature

Parameter	Unit	Values	Reference
Radiation use efficiency (RUE)	g MJ^{-1}	0.76	Binkley et al., 1992
Water use efficiency (WUE)	m^3 g^{-1}	0.00004	Zahid et al., 2010
WUE	m^3 g^{-1}	0.00023	Andrew et al., 2013
Maximum leaf area	m^2 $tree^{-1}$	80-110	Andrew et al., 2013
Specific leaf area	m^2 kg^{-1}	2.96-3.65	Andrew et al., 2013
Leaf area index		1.3-4	Omer et al., 2016
Initial leaf area (6 months-old seedling)	cm^2 $tree^{-1}$	136-405	Missanjo and Maya, 2015
Initial biomass (6 months old seedling)	g $tree^{-1}$	11.3	Missanjo and Maya, 2015
Initial biomass (6-months old seedling)	g $tree^{-1}$	27.2	Andrew et al., 2013
Wood density	g m^{-3}	430000-800000	Reyes et al., 1992
Density	trees ha^{-1}	30-60	Workafes and Kassu 2000; cited in Gole, 2015)

2.4.3. Soil data inputs

Soil texture and depth are also needed as inputs in Yield-SAFE model. Soil texture should be classified based on either FAO's soil classification or van Genuchten soil parameterizations for the model (Palma et al., 2014). FAO classified soil texture into five classes based on different soil properties: course, medium, medium-fine, fine and very fine (Barham et al. 2006). Based on FAO's classification, soil textural classes of the study districts are showed in Table 7

Table 7 Soil texture and depth (cm) in the study districts

Nama of the district	Soil type	Soil common name	FAO's soil texture	Soil depth (cm)	Reference
Wonago	Nitisol	Clay	Very fine	15-40	Worku, 2014
Limu Kosa	Nitisol	Clay	Very fine	35	Nigussie et al., 2013
Manasibu	Fluvisols	Clay	Very fine	15-30	Ebisa, 2014 Geremew et al., 2015
Darolebu	Luvisols	Clay loam	Fine	22-40	Derege, 2013

2.5. Model calibration

The yield and growth of *Albizia gummifera* tree and coffee shrub species were simulated with the Yield-SAFE model (van der Werf et al. 2007) using their respective monoculture growth parameters (Figure 5 and Table 6), historical climate (1986-2005) and soil inputs in each study district. *Albizia gummifera* tree biomass in monoculture system was then calibrated in the model using its reference biomass of 16 kg tree^{-1} at age 8 (Binkley et al., 1992) and 85-138 kg tree^{-1} at age 14 (Binkley and Ryan, 1998). Furthermore, its leaf area and diameter at breast height were also calibrated using its reference value of 75-105 m^{2} tree^{-1} at age 18 (Andrew et al., 2013) and 20-60 cm at age 11 (Temesgen et al. 2015), respectively. Biomass, leaf area and diameter of *Albizia gummifera* trees have a significant effect on the coffee shrub understory (Hunde et al., 2014).

The Yield-SAFE model output is biomass, so coffee yield was predicted using biomass multiplied by an harvest index (Rodrigues et al., 2015). Coffee yield in monoculture and under *Albizia gummifera* (agroforestry) systems was then calibrated using its reference (actual) yield in each study area. Coffee reference yield in monoculture and under *Albizia gummifera* in each study district was collected from published papers (Table 8). Parameters like harvest index, water use efficiency and management regimes were adjusted within acceptable physiological boundaries (Van Ittersum and Rabbinge, 1997) in order to fit modelled and reference yield of coffee. The calibrated model was then used to predict coffee yield in monoculture and under the shade of *Albizia gummifera* trees in each study district for forty years in current (1966-2005) and future climate change scenarios (2006-2045).

Table 8. Coffee reference (actual) yield in monoculture and under shade of *Albizia gummifera* (agroforestry) in the study districts

Name of districts	Coffee yield in monoculture (kg ha^{-1} yr^{-1})	Coffee yield in agroforestry (kg ha^{-1} yr^{-1})	Reference
Wonago	1000-1200	1400-1520	Netsere et al., 2015
Limu kosa	1000-1200	2000-2100	Bote and Struik, 2011
Manasibu	1300- 1600	1400- 2000	Ebisa, 2014 Tadsesse et al.,2015
Darolebu	600-1000	1000-1100	Bekeko, 2013

3. RESULTS AND DISCUSSION

3.1. Yield-SAFE model parametrization

The calibration process produced the parameter sets for coffee and *Albizia gummifera* presented in Table 9 and Table 10, respectively. When the model was calibrated at each study area, the parameters are the same except the harvest index of coffee, the change here is introduced with the climate and soil. The harvest index of coffee was parametrized as 0.2 in Wonago (South Ethiopia) and Limu kosa (Southwest Ethiopia) districts, 0.25 in Manasibu (West Ethiopia) district and 0.13 in Darolebu (East Ethiopia) district. Though the value of harvest index was different across districts, it is still in the range of reference values of coffee harvest index, which is 0.1-0.7 (Rodrigues et al., 2015).

Table 9. Set of parameter values found for coffee in monoculture and under *Albizia gummifera* (agroforestry) systems in Yield-SAFE model

Parameter	**Unit**	**Values monoculture**	**Values agroforestry**	**Reference from literature** (Table 5, **page 12)**
Radiation use efficiency (RUE)	g MJ^{-1}	2.7	2.7	0.06-2.76
Water use efficiency (WUE)	m^3 g^{-1}	0.0001	0.0001	0.0001-0.011
Radiation extinction coefficient		0.7	0.7	
Specific Leaf Area (SLA)	m^2 kg^{-1}	14	14	9.8-14.21
Initial leaf area	m^2 $tree^{-1}$	0.14	0.14	0.189-0.22
Harvest index	g g^{-1}	0.2	0.13-0.25	0.1-0.7
Initial biomass	g $plant^{-1}$	27	27	26-36
Maintenance respiration coefficient	g g^{-1}	0.0031	0.0031	0.0031
Critical pF value for crop	log (cm)	3.2	3.2	
Density	plants ha^{-1}	2000	2000	2000-2500
Base temperature	°C	10.2	10.2	10.2
Day of yield collection	days	180	180	

Table 10. Set of parameter values found for *Albizia gummifera* trees in Yield-SAFE model

Parameter	Unit	Values	Reference from literature (Table 6, page 13)
Radiation use efficiency (RUE)	g MJ^{-1}	0.76	0.76
Radiation Extinction coefficient		0.8	
Water use efficiency (WUE)	m^3 g^{-1}	0.0002	0.00004-0.00023
Maximum leaf area	m^2 $tree^{-1}$	110	80-110
Maximum leaf area for a single bud	m^2	0.25	
Specific leaf area	m^2 kg^{-1}	3	2.96-3.65
Initial leaf area (6 months-old seedling)	cm^2 $tree^{-1}$	112	106-405
Initial biomass (6 months old seedling)	g $tree^{-1}$	25	11.3-27.2
Wood density	g m^{-3}	615,000	430,000-800,000
Density	trees ha^{-1}	60	30-60

3.2. Model calibration outputs

3.2.1 Albizia gummifera tree growth

Tree biomass, diameter at breast height (DBH) and leaf area in monoculture system were calibrated against reference values for 20 years in each study district. The calibration results of these tree variables were different across the study districts. In the following section we present the calibration results in each study district in detail.

In the Wanago district, the model estimated biomass of 16 kg $tree^{-1}$ at age 6 and 125 kg $tree^{-1}$ at age 14, respectively (Figure 4a) and these values are close to the reference biomass of 16 kg $tree^{-1}$ at age 6 (Binkley et al., 1992) and 112 kg $tree^{-1}$ at age 14 (Binkley and Ryan, 1998) (Figure 4a). However, the model predicted slightly lower leaf area (74 m^2 $tree^{-1}$) at age 18 compared to the reference values of 75-105 m^2 $tree^{-1}$ (Andrew et al., 2013) (Figure 4a).

Similarly, in the Limu kosa district, the model estimated tree biomass as 112 kg tree^{-1} at age 14 and this exactly matched with its reference value of 112 kg tree^{-1} (Binkley and Ryan, 1998) (Figure 4b).The model also predicted a 48 cm DBH at age 10 and this value is found in the reference range of 20-60 cm (Temesgen et al., 2015) (Figure 4b). On the contrary, Figure 4b shows lower leaf area (73 m^2 tree^{-1} at age 18) when compared to its the reference values of 75-105 m^2 tree^{-1} (Andrew et al., 2013)

The model also estimated biomass of 112 kg tree^{-1} at age 14 in Manasibu district, and this value matches with the average reference value of 112 kg tree^{-1} (Binkley and Ryan, 1998) (Figure 5a). DBH was also predicted to be 49 cm at age 10 and it is within the range of reference values of 20-60 cm (Temesgen et al., 2015) (Figure 5a). However, Figure 5a shows lower leaf area (68 m^2 tree^{-1} at age 18) when compared to the reference ranges of 75-105 m^2 tree^{-1} (Andrew et al., 2013).

In the Darolebu district, tree biomass was also predicted in the model to be 112 kg tree^{-1} at age 14 and this value exactly fit with the average reference value of 112 kg tree^{-1} (Binkley and Ryan, 1998) (Figure 5b). In addition, the model estimated DBH of 47 cm at age 10 and this is found in the range of reference values of 20-60 cm (Temesgen et al., 2015), (Figure 5b). However, the model predicted leaf area of 64 m^2 tree^{-1} at age 18 and this is a lower value compared to the reference values of 75-105 m^2 tree^{-1} (Andrew et al., 2013) (Figure 5b).

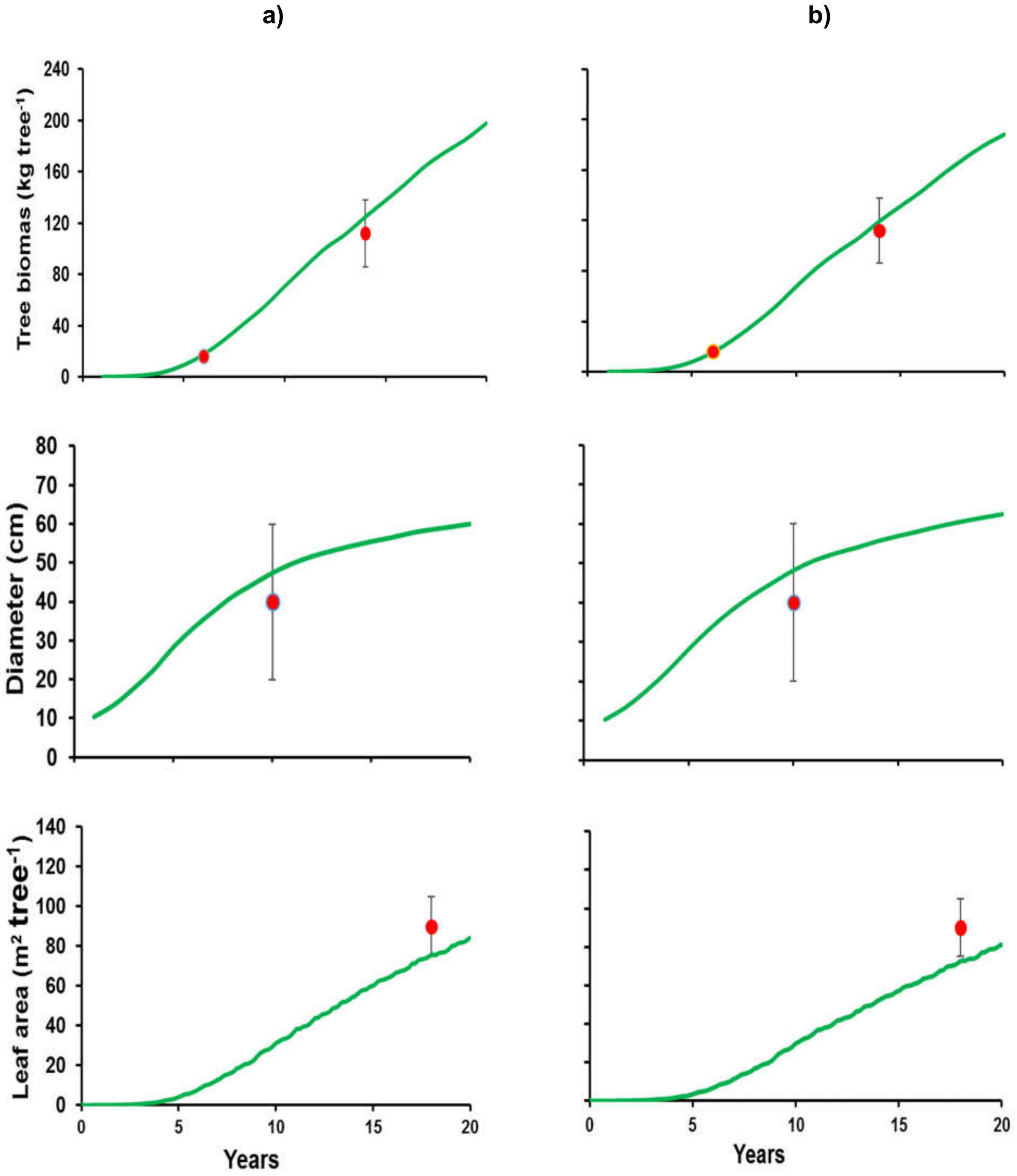

Figure 4. Reference values (points) and Yield-SAFE model estimation (green line) for *Albizia gummifera* tree in the study districts a) Wonago b) Limu kosa (error bars show the maximum and minimum values of the tree variables)

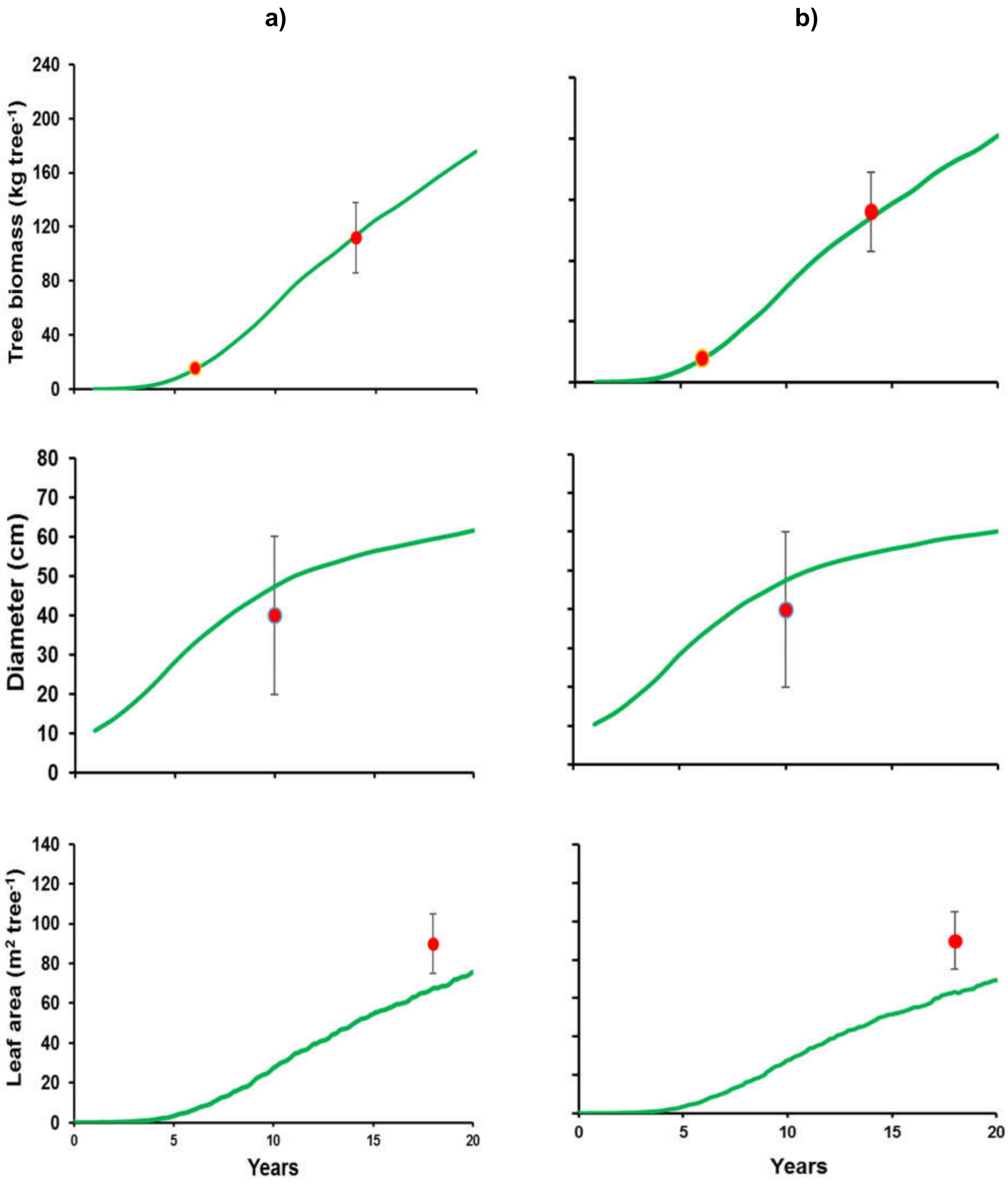

Figure 5. Reference values (points) and Yield-SAFE model estimation (green line) for *Albizia gummifera* tree in the study districts a) Manasibu b) Darolebu (error bars show the maximum and minimum reference values of the tree variable)

3.2.2. Coffee yield

Yield of coffee in monoculture and agroforestry systems simulated using Yield-SAFE model showed yearly variation in the study areas. This may be due to annual variation in temperature (Figure 2), precipitation (Figure 3), solar radiation, relative humidity and wind speed. Temperature and precipitation are the most important climatic factors affecting yield of coffee (Eitzinger et al., 2013). Coffee yield in monoculture and agroforestry systems was calibrated for 20 years using its reference yield in each study area and the results are presented in detail in the following section.

In the Wonago district, the model predicted coffee yield in monoculture system to be 1063-1274 kg ha^{-1} yr^{-1} and with its 20 years' average of 1185 kg ha^{-1} yr^{-1}. This average yield is found in the range of the district reference yield, which is 1000-1200 kg ha^{-1} yr^{-1} (Netsere & Kufa, 2015) (Figure 6a). Yield of coffee under the agroforestry system was also well calibrated, the model estimated the yield to be 1300-1600 kg ha^{-1} yr^{-1} with an average of 1530 kg ha^{-1} yr^{-1}. This average yield is closely fit to the maximum reference yield of the district, which is 1520 kg ha^{-1} yr^{-1} (Netsere & Kufa, 2015) (Figure 6b).

Similarly, yield of coffee in monoculture and agroforestry systems was also well calibrated in the model for the Limu kosa district. Figure 6c shows coffee yield in the monoculture system that was predicted to be 1000-1300 kg ha^{-1} yr^{-1} with an average of 1050 kg ha^{-1} yr^{-1}. This average yield is found in the reference ranges of the district, which is 1100-1200 kg ha^{-1} yr^{-1} (Bote and Struik, 2011). Figure 6d also shows yield of coffee under the agroforestry system to be 1800-2400 kg ha^{-1} yr^{-1} with an average of 2060 kg ha^{-1} yr$^{-1.}$ This average yield is closely fit with it's the average reference yield of the district, which is 2050 kg ha^{-1} yr^{-1} (Bote and Struik, 2011).

The Yield-SAFE model also produced a good fit between simulated and reference yield of coffee in Manasibu district. In the monoculture system, yield of coffee was modelled to be 1300-1600 kg ha^{-1} yr^{-1} with average of 1470 kg ha^{-1} yr^{-1}. This average simulated yield is closely matched with its average reference yield of 1450 kg ha^{-1} yr^{-1} (Ebisa, 2014) (Figure 6e). Yield of coffee under the agroforestry system was estimated to be 1450-2000 kg ha^{-1} yr^{-1} with an average of 1650 kg ha^{-1} yr^{-1}. This simulated average is closely fitted with its average reference yield of the district, which is 1600 kg ha^{-1} yr^{-1} (Tadsesse et al., 2015) Figure 6f).

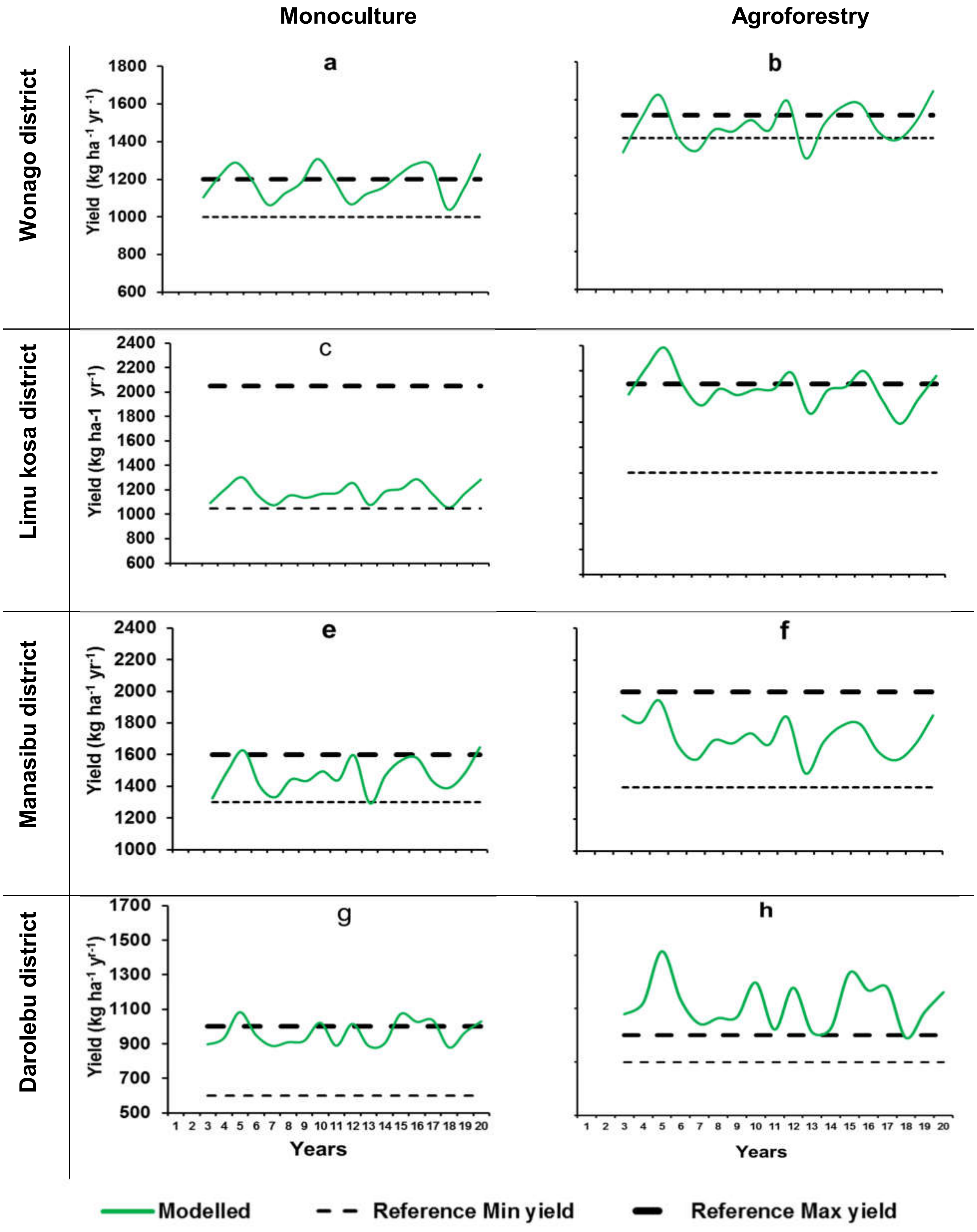

Figure 6. Reference and Yield-SAFE estimated yield of coffee in monoculture and agroforestry systems in the study districts

However, in the Darolebu district, the model overestimated the yield of coffee. Yield of coffee in the monoculture was estimated to be 900-1100 kg ha^{-1} yr^{-1} with an average of 960 kg ha^{-1} yr^{-1}. This simulated average yield is higher than the average reference yield of the district, which is 800 kg ha^{-1} yr^{-1} (Bekeko, 2013) Figure 6g). The model also predicted yield of coffee under the agroforestry system to be 1100 -1400 kg ha^{-1} yr^{-1} with average of 1250 kg ha^{-1} yr^{-1}. The simulated average is overestimated compared to an average reference yield of the district, which is 1050 kg ha^{-1} yr^{-1} (Bekeko, 2013) (Figure 6h).

The calibration yield of coffee in monoculture and agroforestry systems in Yield-SAFE model was within the reference ranges in all study areas except a slightly overestimation in the Darolebu district. Previous studies have confirmed that different crops and trees have been successfully calibrated in the Yield-SAFE model. For example, annual acorn yield was well calibrated with its measured yield (Crous-Duran et al. 2015). Graves et al. (2010) also found a good fit between Yield-SAFE estimated and measured yield of wheat, barley, grain maize and oil seed in Europe. Moreover, grain and biomass of maize were also well calibrated in the model using its measured yield (Holst et al., 2012 cited in Luedeling et al., 2016; Mayus et al., 2007).

3.3. Impact of climate change on coffee yield

After the model was well calibrated for the yield of coffee in monoculture and under the *Albizia gummifera* (agroforestry) systems, a simulation was made to predict the yield of coffee under current climate and two climate scenarios: RCP 4.5 and 8.5 for 40 years in each study area.

In the Wonago district, the current average monthly temperature (20°C) will increase by 0.6 and 0.8°C in RCP 4.5 and 8.5, respectively, and the total annual precipitation (1136 mm) will also increase by 90 and 124 mm in RCP 4.5 and 8.5, respectively (Table 4) However, the precipitation will increase in months where there is already abundant rain, whereas dry months will become drier (Figure 3). Using current climate, Yield-SAFE model estimated yield of coffee in monoculture system to be 1000-1400 kg ha^{-1} yr^{-1} and this will decrease by 38-40 % and 57-60 % in RCP 4.5 and 8.5, respectively (Figure 7a). The overall 40 years average yield was also estimated to be 1200 kg ha^{-1} yr^{-1} and this will decrease by 38 and 58 % in RCP 4.5 and 8.5, respectively (Table 11). Moreover, yield of coffee under agroforestry system in current climate was predicted to be

1300-1800 kg ha^{-1} yr^{-1} and this will decrease by 11-22 % and 44-46 % in RCP 4.5 and 85, respectively (Figure 7b). The 40 years overall average yield was simulated to be 1600 kg ha^{-1} yr^{-1} and it decreases by 13 and 25 % in RCP 4.5 and 8.5, respectively (Table 11)

In the Limu kosa district, current monthly average temperature is 19.5°C and it will increase by 0.5 and 1°C in RCP 4.5 and 8.5, respectively. Total annual precipitation also increases from its current amount (1265 mm) by 70 and 120 mm in RCP 4.5 and 8.5, respectively (Table 4). However the precipitation will increase in months where there is already abundant rain, whereas dry months will become drier (Figure 3). In the monoculture system under current climate, yield of coffee was modelled to be 1100-1400 kg ha^{-1} yr^{-1} and this will be expected to decrease by 7-9 % and 14-27 % in RCP 4.5 and 8.5, respectively (Figure 7c). The overall average yield of coffee in the monoculture was also estimated to be 1250 kg ha^{-1} yr^{-1} and it decreases by 4 and 20 % in RCP 4.5 and 8.5, respectively (Table 11). It was also predicted yield of coffee under the agroforestry in current climate to be 1800-2500 kg ha^{-1} yr^{-1} and this will decrease by 4-6 % and 12-17 % in RCP 4.5 and 8.5, respectively (Figure 7d). Overall average the yield of coffee (2200 kg ha^{-1} yr^{-1}) under the agroforestry estimated to decrease by 4 and 16 % in RCP 4.5 and 8.5, respectively (Table 11).

It was predicted that the current average monthly temperature (19.7°C) of Manasibu district will increase by 0.6 and 0.8°C in RCP 4.5 and 8.5, respectively. Its current total annual precipitation (1261 mm) also increases by 40 and 96 mm in RCP 4.5 and 8.5, respectively (Table 4). However the precipitation will increase in months where there is already abundant rain, whereas dry months will become drier (Figure 3). Using current climate, Yield-SAFE model estimated yield of coffee in monoculture to be 1300-1700 kg ha^{-1} yr^{-1} and this will decrease by 4-5 % and 6-9 % in RCP 4.5 and 8.5, respectively (Figure 7e). The overall average current yield of coffee in monoculture was also estimated to be 1600 kg ha^{-1} yr^{-1} and this decreases by 10 and 16 % in RCP 4.5 and 8.5, respectively (Table 11). Yield of coffee under agroforestry system in current climate was also estimated to be 1500-1900 kg ha^{-1} yr^{-1} and it will decrease by 3-4 % and 5-8 % in RCP 4.5 and 8.5, respectively (Figure 7f). The overall average yield of coffee under agroforestry was also estimated to be 1800 kg ha^{-1} yr^{-1} and this decreases by 6 and 13 % in RCP 4.5 and 8.5, respectively (Table 11).

Finally, in the Darolebu district, the current average monthly temperature (20.4 ^{o}C) increases by 0.6 and 0.8^{o}C in RCP 4.5 and 8.5, respectively. Total annual precipitation also increases from its current amount of 1160 mm by 36 and 50 mm in RCP 4.5 and 8.5, respectively (Table 4). Again, the precipitation will increase in months where there is already abundant rain, whereas dry months will become drier (Figure 3). Using current climate, the Yield-SAFE predicted yield of coffee in monoculture to be 850-1100 kg ha^{-1} yr^{-1} and this will reduce by 27-35 % and 36-41 % in RCP 4.5 and 8.5, respectively (Figure 7g). The overall average yield of coffee in monoculture was also predicted to be 1000 kg ha^{-1} yr^{-1} and it will decrease by 30 and 40 % in RCP 4.5 and 8.5, respectively (Table 11). It also modelled the yield of coffee under the agroforestry in current climate to be 1100-1400 kg ha^{-1} yr^{-1} and it decreases by 14-23 % and 21-25 % in RCP 4.5 and 8.5, respectively (Figure 7h). The overall average yield of coffee under agroforestry was also estimated to be 1200 kg ha^{-1} yr^{-1} and it will be expected to decrease by 8 % and 17 % in RCP 4.5 and 8.5, respectively (Table 11).

Results of this study seem to evidence that coffee yield in monoculture system will decrease 4-38 % in RCP 4.5 and 16-58 % in RCP 8.5 compared to current yield of 1000-1600 kg ha^{-1} yr^{-1} in the study districts. It is also estimated that coffee yield under agroforestry system will decrease 4-13 % in RCP 4.5 and 13-25 % in RCP 8.5 compared to current yield of 1200-2200 kg ha^{-1} yr^{-1} (Table 11). These yield reductions are associated with temperature increase and higher precipitation in months of January-March (when the coffee plant demands lower water) and lower precipitation in months August-October (when the coffee plant demands higher water for flowering development) in the future climate scenarios (Figure 2 and Figure 3).

Results of this study have similarities with other studies. Craparo et al. (2015) found that increasing temperature in future scenarios is the most significant climatic variable responsible for coffee yield reduction in Tanzania. The same authors reported that for every 1^{o}C rise in the minimum temperature, the coffee yield will decrease by 137 kg ha^{-1} yr^{-1}. Davis et.al. (2012) studied the effects of climate change on *Coffee arabica* in Ethiopia, which is the main African coffee exporter. Their research shows that the coffee growing success is linked directly to accelerated climate change. They predicted that under RCP 4.5 there will be a 65 % decrease in coffee yield by the year 2080. On contrary, in scenario RCP 8.5, they say that there will be a 100 % coffee yield reduction by 2080. Globiom model has estimated the average yield of coffee at national level in Ethiopia to decrease by 3-13 % in scenario RCP 6 in 2050, from its current yield of 440-670 kg ha^{-1} yr^{-1} (Bunn 2015). Oijen et al., (2010) also used a dynamic process based model called Caf2007 to assess yield of coffee under climate change and they found increases in temperature that significantly decrease the yield of coffee trees in Costa Rica. Ecocrop model was also used by Lane and Jarvis (2007) to simulate the impact of climate change on the most important crops, and coffee ranked among the most affected crops. Moreover, the Maxent model has been extensively used to study the impact of climate change on coffee. This model projected a decrease of the suitable areas with optimum temperature for coffee as temperature rises due to climate change in Nicaragua (Läderach et al. 2013). Changes in seasonal temperature and precipitation due to climate change were also found as the main reasons for coffee yield reductions in Kenya (Ciat 2010).

Ethiopia, the genetic origin of *Coffee arabica* has experienced increases in temperature between 1ºC (Asela district) and 1.4ºC (Nefgele district) per decade. These changes in temperature are now the main factors for spreading coffee and crop pests and diseases in those districts (Mekasha et al., 2014). It was also reported that *Hypothenemous hampei*, one of the main insects that feeds on coffee berries, increases its population growth exponentially as temperature increases in thiopia (Jaramillo et al., 2011; Belachew and Teferi, 2015).

Table 11. Predicted 40 years' average yield of coffee (kg ha^{-1} yr^{-1}) in monoculture and agroforestry in current, RCP 4.5 and 8.5 scenarios in the study districts. Percentage in brackets shows yield reduction in scenarios compared to yield under current climate

Name of the district	**Monoculture**			**Agroforestry**		
	Current	**RCP 4.5**	**RCP 8.5**	**Current**	**RCP 4.5**	**RCP 8.5**
Wonago	1200	750 (-38%)	500 (-58%)	1600	1400 (-13%)	1000 (-25%)
Limu kosa	1250	1200 (-4%)	1000 (-20%)	2200	2100 (-4%)	1900 (-14%)
Manasibu	1600	1450 (-10%)	1350 (-16%)	1800	1700 (-6%)	1600 (-13%)
Darolebu	1000	700 (-30%)	600 (-40%)	1200	1100 (-8%)	1000 (-17%)

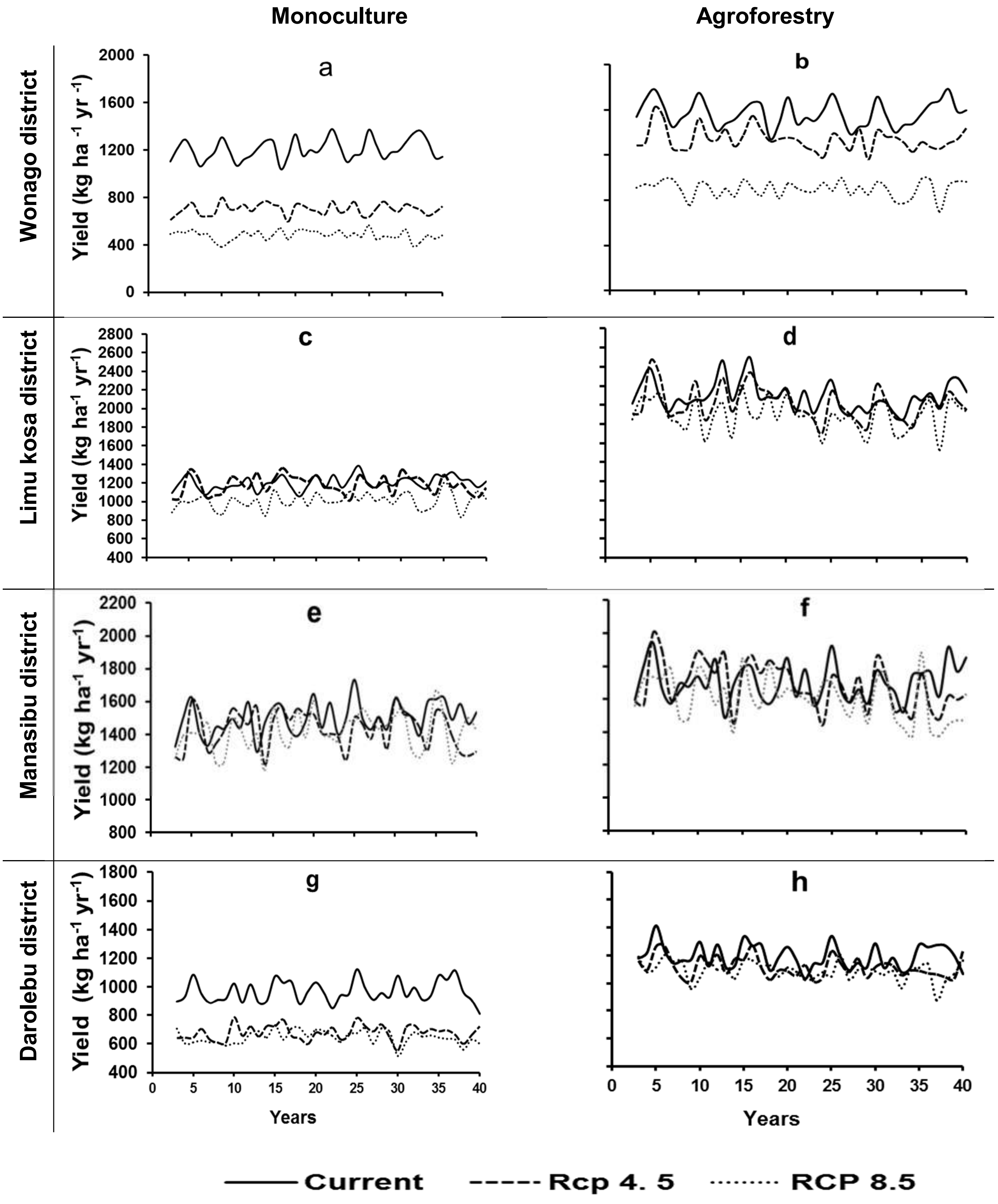

Figure 7. Coffee yield in monoculture and agroforestry systems in current and future climate change scenarios in the study districts

The results of this work are in convergence with previous authors, following the pattern of coffee yield reduction. However, the results presented here suggest that coffee yield under agroforestry systems is less impacted by climate change as compared to monoculture systems. The Yield-SAFE model suggests that the presence of trees is effective in reducing soil evaporation and coffee transpiration (Figure 8) when compared to monoculture systems, especially under climate change. The tree presence reduces air temperature, radiation reaching the soil, lowers wind speed and therefore reduces vapor pressure deficit and the latest developments of Yield-SAFE improvements (Palma et al. 2016) allow the interpretation of this dynamics. The model is suggesting the same consistency with some authors. For example, Pezzopane et al., (2011) reported that shade trees can reduce the movement of wind energy that carries water away from soil and leaf surfaces thereby reducing the amount of water lost through evapotranspiration.

Moreover, over story shade trees in coffee production are also helpful for reducing sunlight radiation reaching the coffee leaf and soil surfaces thereby reducing evapotranspiration and creating conducive-climate that better suited for coffee growth and development (Alemu, 2015; Wubet et al., 2003). Air temperature above the coffee bushes is also modified by the over story shade trees and this can also reduce evapotranspiration (Lin, 2010; Alemu, 2015).

Under future climate, soil water content in agroforestry systems seems to be higher when compared to monoculture (Figure 8). This dynamic is mainly associated with lower soil evaporation, coffee transpiration and total evapotranspiration from the microclimate system (Figure 8). Lin (2010) corroborate this tendency by showing that growing of shade trees with coffee can dramatically reduce soil evaporation and coffee plant transpiration and therefore agroforestry seems to be a better option under future climate with high evaporative demands.

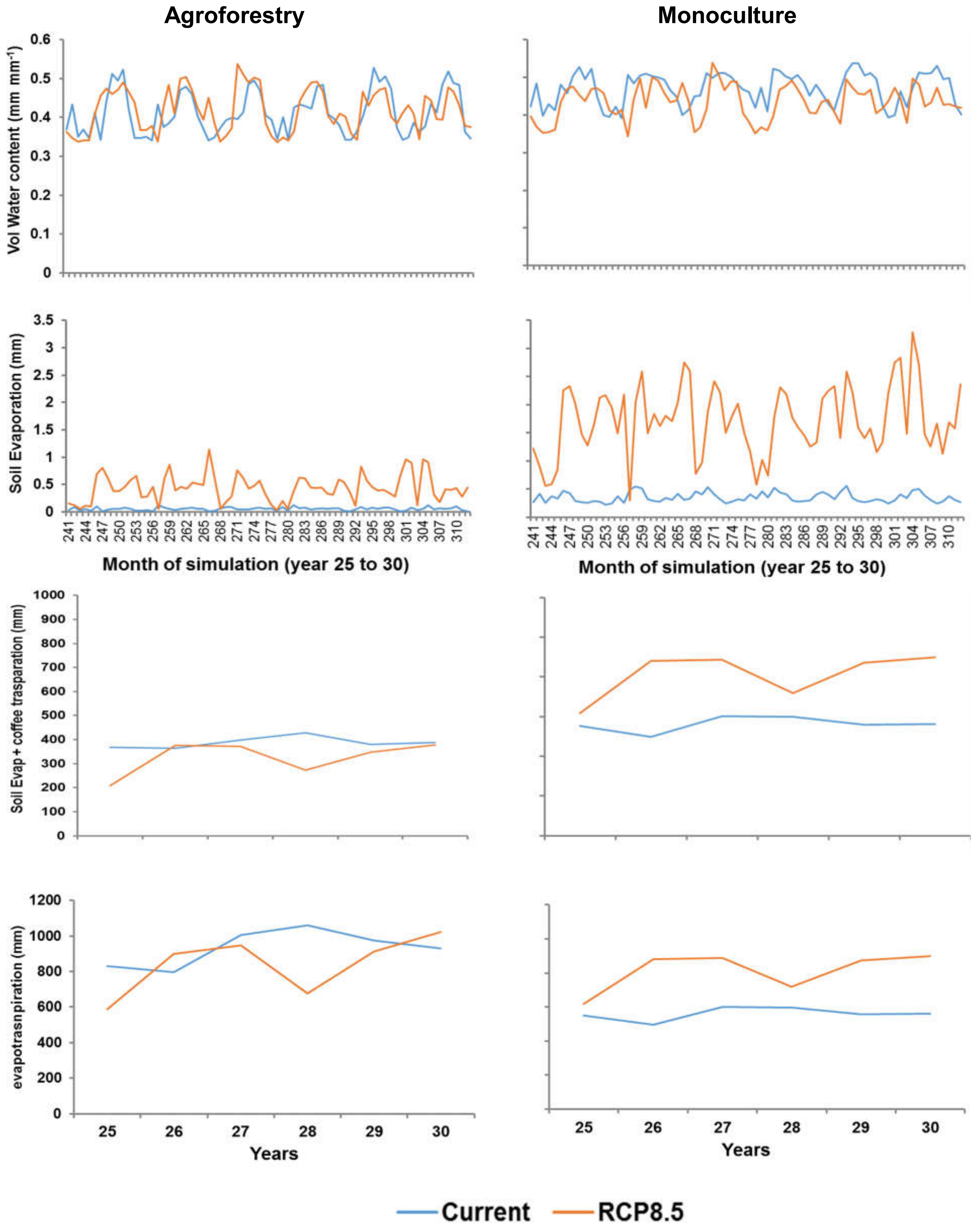

Figure 8. Comparison of water dynamics between agroforestry and monoculture under current climate and the representation concentration pathway (RCP 8.5) in Wonago district

4. CONCLUSION

The daily time-step process based model Yield-SAFE was used to simulate yields of *Coffee Arabica* under agroforestry and monoculture systems. This work is the first time that this model is used with coffee, showing an interesting performance in terms of validation with reference data. Such robustness allows the use of the model to estimate yields under future climate scenarios. With a detailed methodological description to take advantage of the CORDEX world consortium that is delivering climate change datasets, this work explored these datasets to be used with Yield-SAFE, allowing the understanding of the effects of changing minimum and maximum temperature, precipitation, radiation, wind speed and relative humidity according to existing future climate scenarios on coffee production in Ethiopia. It was also essential for understanding the impacts and changes of soil dynamics such as soil evapotranspiration, crop transpiration, volumetric soil moisture and total evapotranspiration on coffee productivity under changing climate.

Coffee yield under agroforestry and monoculture systems have different sensitivity to future climate change in the study districts as they have different soil types and climate conditions. Yield of coffee under agroforestry and monoculture systems in the Wonago (South Ethiopia) and the Darolebu (East Ethiopia) districts seem to be more sensitive to future climate change whereas in the Limu kosa (Southwest Ethiopia) and the Manasibu (West Ethiopia) districts the negative impacts are relatively smaller.

In all districts, coffee yield under agroforestry system seems to be more resilient when compared to monoculture systems in future climate scenarios. It seems to be clear that this is due to the presence of the trees. The effect of trees on coffee has been reported by experimental data of previous authorships, but this work provides a preliminary description of the processes involved when the trees reduce radiation reaching the soil and, with the recent algorithms implemented accounting for reducing wind speed and lowering temperature, reducing vapour pressure deficit of the system. The reduction of soil evaporation, crop transpiration and soil water loss from high temperature, radiation exposure, and wind speed that would be expected from future climate scenarios, seems to promote a better resilience (less impact of climate change) of coffee production under shade of trees (agroforestry system). Therefore, this system seems to be a key adaptation for mitigating the negative impacts of future climate in coffee production. We also suggest that coffee growth variables should be taken from permanent plots as inputs for the model, for better Yield-SAFE model prediction for coffee yield.

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ANNEX I. Program developed in Python programming language to retrieve the daily climate for the latitude and longitude of each of the study areas

```
from netCDF4 import Dataset
import numpy as np
import datetime
import csv
import cgi
import sys
import os
import math

def get_Rlat_Rlon(X,Y,arrLonLatRlonRlat):

    Lons=[]
    Lats=[]
    RLons=[]
    RLats=[]
    c=0
    for row in arrLonLatRlonRlat:
        if c>0: #header
            Lons.append(float(row[0]))
            Lats.append(float(row[1]))
            RLons.append(float(row[2]))
            RLats.append(float(row[3]))
        c +=1

    res=[]
    res.append(0)
    res.append(0)
    dist=100000000000
    for idx in range (len(Lons)-1):
        calcDist = math.sqrt(pow((Y-Lats[idx]),2)+pow((X-Lons[idx]),2))

        if calcDist < dist:
            dist = calcDist
            res[0] = RLons[idx]
            res[1] = RLats[idx]

    return res

fs = sys.argv
if len(fs)<6:
    print "You need to add arguments: lon lat variable iniYear Filename"
    print "for example:"
    print "accessNCFiles.py 36.52 7.48 pr 1996 pr_AFR-44_MOHC-HadGEM2-ES_historical_r1i1p1_SMHI-RCA4_v1_day_19960101-20001230.nc"
    sys.exit()
lon      = float(fs[1])
lat      = float(fs[2])
variable = str(fs[3])
iniYear  = int(fs[4])
fileName = str(fs[5])

print "Folder: " + os.path.dirname(os.path.realpath(__file__)).replace("\\","/") + "/"
folder = os.path.dirname(os.path.realpath(__file__)).replace("\\","/") + "/"

nc_file = folder + fileName
f = Dataset(nc_file, mode='r')
lons = f.variables['lon'][:]
```

```
lats = f.variables['lat'][:]
time = f.variables['time'][:]
var = f.variables[variable][:]
Date = datetime.datetime(iniYear, 1, 1, 00, 00)# y,m,d,h,s
south_north = len(f.dimensions['rlat'])
west_east = len(f.dimensions['rlon'])

lonlatrlonrlat = []
for x in range(west_east):
  for y in range(south_north):
    r=[]

    r.append(lons[y][x])
    r.append(lats[y][x])
    r.append(x
    r.append(y)
    lonlatrlonrlat.append(r)

rlonrlat = get_Rlat_Rlon(lon, lat,lonlatrlonrlat)

print " A extrair dados para o ponto [rlon, rlat] = ", rlonrlat
res=[]

for day in range(0,len(time)):
    if variable =="pr":
    cxvvv
     res.append([Date.day,Date.month,Date.year,var[day,rlonrlat[1],rlonrlat[0]] * 86400])
    elif variable in ('tasmin', 'tasmax', 'tas'):
      res.append([Date.day,Date.month,Date.year,var[day,lat,lon] - 273])
    elif variable in ('rss',"rsds"):
      res.append([Date.day,Date.month,Date.year,var[day,lat,lon] * 0.0864])
    elif variable == "evspsbl":
      res.append([Date.day,Date.month,Date.year,var[day,lat,lon] * 86400
    elif variable in ('hurs','hursmax','hursmin'):
      res.append([Date.day,Date.month,Date.year,var[day,lat,lon] ])
    elif variable == "sfcWind":
      res.append([Date.day,Date.month,Date.year,var[day,lat,lon] ])

    Date = Date + datetime.timedelta(days=1)
#
outFileName = folder + 'results_' + variable + "_" + str(iniYear) + "_" + str(lon) + "_" + str(lat) + ".csv"

outFileHandle = open(outFileName, 'w')
for i in res:

  s =",".join(map(str, i))
  outFileHandle.write(s+"\n")
outFileHandle.close()

f.close()

print "Done"
```