Modeling the plantation area of geographical indication product under climate change: Gayo Arabica coffee (*coffea arabica*)

P Purba 12*, A C Sukartiko 1, M Ainuri 1

1 Department of Agro-industrial Technology, Faculty of Agricultural Technology, Universitas Gadjah Mada, Indonesia
2 Balai Pengujian dan Sertifikasi Mutu Barang, Dinas Perindustrian dan Perdagangan Aceh, Indonesia

*E-mail: pembina.purba@gmail.com

Abstract. The increase in temperature and changes in rainfall patterns over the long term can cause changes in the suitability level of the land to produce Gayo Arabica Coffee as a geographically indicated product in the future. Therefore, this paper aims to: (i) identify bioclimatic elements that affect the suitability of coffee grown areas; and (ii) finding out the impact on the suitability level of coffee grown areas in the Gayo highland. To achieve the research goals, data of bioclimatic elements from the Gayo highland and WorldClim were processed using ArcMap 10.3 and MaxEnt (Maximum Entropy) software to predict the possible effects of climate change on distribution shift of the Gayo Arabica Coffee grown areas. Based on the developed model, the suitability of the coffee grown areas is vulnerable to the effects of climate change in the future, indicated by a decrease in suitable grown-areas. Changes in a distribution shift of grown areas and required adaptation for short- and long-terms are discussed further in this paper.

1. Introduction

Coffee plants are highly dependent on the environment. The existence of this plant in the present and future will face various obstacles, one of which is climate change. Some papers showed that climate change can inhibit growth and decreases production and quality of coffee [1]. These changes in the future can also result in a shift in the spread of pests and diseases, later on affecting the coffee productivity [2]. The climate has significantly influenced the growth and reproduction of the plants, so this condition becomes a dominating variable in determining the geographical distribution of plant species [3]. The global climate has changed and is expected to continue to change throughout the twenty-first century, characterized by changes in temperature and rainfall, as well as increased extremes event in some areas [4].

The adaptation of agricultural systems to climate change is crucial for ensuring food safety, poverty alleviation, and sustainable use of natural resources [5]. The threat of climate change is increasingly exacerbated with long adaptation times and may also take decades [6]. The cultivation of Gayo Arabica Coffee, one of the Geographical Indication (GI) certified products also need adaptation to retain its quality characteristic in the future from the influence of natural factors such as climate.
Paying attention to the demand for high quality coffee that continues to grow globally, sustainable coffee sources, therefore, will be important to meet the demands, making potential areas of coffee plants need to be preserved. Many papers have mentioned the interactions among crops, environment, and its impact on the plant growth [7] [8]. The impacts caused by these environmental changes, therefore, can change the suitability of growing coffee plants area, including Gayo Arabica Coffee, and cause a shift in the plants distribution, a narrowing of the area, or even expansion, over the next few decades.

The species distribution model (SDM) is commonly used to predict the distribution of a species across geographic area and time using environmental data. A popular modeling technique currently used is the Maximum Entropy approach (MaxEnt), which was initially developed for ecological purposes [9] but has been widely used to assess the geographic and climate variability of commercial plants [10]. The MaxEnt model predicts habitat suitability of plant species by using correlation approach to evaluate environmental conditions that meet species ecological requirements [11] [12]. Recent studies on modeling the Arabica coffee distribution using the MaxEnt method have been applied on a regional scale, including the use of species distribution software to investigate the impact of climate on arabica coffee [11][13].

This research identifies the suitability of coffee growing area due to the climate change in Gayo highland using Geographic Information Systems (GIS) and MaxEnt. The study aims to: (i) identify bioclimatic elements that affect the suitability of coffee grown areas; and (ii) finding out the impact on the suitability level of coffee grown areas in the Gayo highland.

2. Materials and methods
The research was carried out in the three districts in the Gayo highland, i.e., Aceh Tengah, Bener Meriah, and Gayo Lues, at altitudes ranged from 900 to 1,700 m a.s.l, an optimal altitude range for growing arabica coffee [14]. The three districts are also the registered GI regions for Gayo Arabica Coffee. All data were collected, compiled, and spatially analyzed in 2019.

2.1. Data Collection
Historical data on bioclimatic variables in the Gayo highland, were collected from Meteorology, Climatology and Geophysical Agency (BMKG) Indrapuri Station and from the WorldClim database (http://www.worldclim.org) [15]. A total of 9,280 coordinate points were extracted using ArcGIS 10.3 from the land use map of geographical indicated coffee developed by previous study [14]. The coordinate point data that was successfully extracted then stored as a database in CSV format, so that it can then be read through the MaxEnt software.

2.2. Environmental variables
Environmental variables (bioclimatic) are crucial in defining the environmental niche of plant species associated with the distribution of the coffee land suitability. The variables were chosen according to the climate conditions in Indonesia, including the Gayo highland area. A total of 11 bioclimatic variables were taken from the WorldClim dataset (www.worldclim.org/version2) as the ‘current period’. In the WorldClim database, the ‘current period’ is defined as the data in the period of 1970 to 2000. These current data has been widely used in generating distribution models of suitability area of plant species. Bioclimatic variables are generated from monthly temperature and precipitation interpolation obtained from available weather station at a spatial resolution of 2.5 arc minutes [15]. The environmental variables derived from the WorldClim, which has been widely used in the potential distribution predictions of plant species, can reflect characteristics of temperature and rainfall as well as characteristics of seasonal variations. Bioclimatic is a variable which ecologically essential for explaining the annual trend, season, and adaptation of species with extreme temperatures and precipitation. Bioclimatic is also suitable for describing the distribution of large-scale species such as the intercontinental and regional scale [16][17]. Therefore, these environmental variables were selected as the initial variables to be used in modeling on this paper (tabel 1).
Table 1. Environment variables are used for modeled Arabica coffee plantation area

| Code | Environmental Variables                                      | Unit       | % Contribution |
|------|-------------------------------------------------------------|------------|----------------|
| Bio1 | Annual Mean Temperature                                     | °C         | 0.1            |
| Bio2 | Mean Diurnal Range (Mean of monthly (max temp - min temp))  | °C         | 2.4            |
| Bio3 | Isothermality (Bio2/Bio7)                                   | -          |                |
| Bio4 | Temperature Seasonality (standard deviation *100)           | C of V     | 9.6            |
| Bio5 | Max Temperature of Warmest Month                           | °C         |                |
| Bio6 | Min Temperature of Coldest Month                           | °C         |                |
| Bio7 | Temperature Annual Range (Bio5-Bio6)                       | °C         |                |
| Bio8 | Mean Temperature of Wettest Quarter                        | °C         | 2.9            |
| Bio9 | Mean Temperature of Driest Quarter                         | °C         | 3.0            |
| Bio10| Mean Temperature of Warmest Quarter                        | °C         |                |
| Bio11| Mean Temperature of Coldest Quarter                        | °C         |                |
| Bio12| Annual Precipitation                                       | mm         | 40.0           |
| Bio13| Precipitation of Wettest Month                             | mm         | 26.1           |
| Bio14| Precipitation of Driest Month                              | mm         | 4.6            |
| Bio15| Precipitation Seasonality (Coefficient of Variation)       |            | 2.1            |
| Bio16| Precipitation of Wettest Quarter                           | mm         | 7.0            |
| Bio17| Precipitation of Driest Quarter                            | mm         | 2.3            |
| Bio18| Precipitation of Warmest Quarter                           | mm         |                |
| Bio19| Precipitation of Coldest Quarter                           | mm         |                |

The variables printed in bold were used in the model.

2.3. MaxEnt model
Projected climate in 2050 was carried out from WorldClim website to determine the distribution of species in the future under climate change. The chosen General Circulation Model (GCM) was IPSL-CM5A-MR, which has a good model at representing the climate in Southeast Asia [18]. The selected climate projection scenario was Representative Concentration Path (RCP) 4.5, a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change (IPCC) [19]. The RCP 4.5 concentration pathway assumes a moderate carbon emissions curve, which is stable up to 2050 [20]. This model is used in climate modeling to project the future climate. ArcGIS 10.3 software was used to convert these environmental variables into ASCII format.

2.4. Evaluation of the current and future potential habitat
This study used the Maximum Entropy model (MaxEnt version 3.3.3 K; [21]; http://www.cs.princeton.edu/wschapire/Maxent/). To evaluate the quality of the model predictions, the arabica coffee data were randomly divided into 75% for model training and 25% for training and testing data points, respectively [22]. The output was converted to raster format using the ArcGIS 10.3 software for further analysis. To calibrate and validate the robustness of the MaxEnt model evaluation, the threshold-independent Receiver Operating Characteristic (ROC) analysis was used. The Area Under the Curve (AUC) characteristic of the receiver operation was examined for additional precision analysis. The Jackknife test was used to assess the relative importance of variables. In general, the value of AUC can be in the range of 0.5 to 1.0. The AUC value was classified by [23] to assess the performance of the model, and the classification is used to assess the performance of the prediction model. The performance model was categorized low (0.60-0.70), moderate (0.71-0.80), good (0.81-0.90), and very good (more than 0.91) [23]. The closer the AUC to 1, the better the performance of the model.

MaxEnt estimates that a species probability of land suitability will be present based on a record of presence and randomly generates background points by finding the MaxEnt distribution. The final
distribution model was obtained based on the average logistics output of the ten executed replication, which was used to estimate the probability of presence as land suitability between 0 (not suitable) and 1 (high suitability) [21]. The MaxEnt model prediction was imported into the Geographic Information System (GIS), and the map was generated using ArcMap 10.3. The suitability of the land in the map was classified into five land suitability classes i.e., 'high suitability' (0.7-1), 'moderate suitability' (0.6-0.7), 'low suitability' (0.4-0.6), 'very low suitability' (02.0-0.4) and 'not suitable' (0-0.2) [24]. After using the current climate data to model the appropriate spatial level of land suitability for Gayo Arabica Coffee, modeling projections were conducted for future climatic scenarios in 2050 with RCP 4.5, to predict the suitable area for Gayo Arabica Coffee in the future.

3. Results

3.1. Model performance and contribution of environmental variables

The prediction accuracy of the coffee land suitability during the current period was found "good" (AUC mean = 0.814, figure 1). Among the eleven selected environmental variables, the contribution of the four variables, i.e., the annual rainfall (bio_12, 40%), the wettest month rainfall (bio_13 of 26.1%), the seasonal temperatures (bio_4, 9.4%), and the wettest quarter rainfall (bio_16, 7%), accounted in total for almost 82.7% of the model’s prediction (table 1). The Jackknife test also shows that the annual rainfall (bio_12), the wettest month rainfall (bio_13), and the wettest quarter rainfall (bio_16) were the main influential variables (figure 2). However, the average driest quarter temperature (bio_9) and precipitation of the driest month (bio_14) also showed a much higher increase compared with the other environmental variables (table 1). The condition indicates precipitation and temperature were played a vital role in predicting the probable distribution of Gayo Arabica Coffee suitability land.

![Figure 1. ROC curve and AUC value under the current period (10 replications)](image1)

![Figure 2. Jackknife test of variables importance for Arabica coffee](image2)
3.2. **Current potential distribution of predictable and potentially suitable future**

The current and projected potential distribution of Gayo Arabica Coffee were shown in figure 3. Land suitability habitat for the Gayo Arabica Coffee plantation shows the land suitability ranging from unsuitable to the high suitability located in Aceh Tengah, Bener Meriah, and Gayo Lues districts (figure 3.a). Aceh Tengah became the most significant coffee production area compared to the other two districts, currently due to its vast coffee plantation land. Current condition shows that Gayo Lues is the suitable area for Arabica coffee plants, indicated by the increasing yield in every year [25].

The predicted future potential suitability area distribution for the Gayo Arabica Coffee plantation under the RCP 4.5 climate change scenario was shown in figure 3.b. The developed MaxEnt model indicates that there was a significant difference between the current and the predicted suitable habitat area, with an increasing of unsuitable area in the observed regions.

![Figure 3. Map of the land-suitability model. a. Current; b. The future of the 2050s)](image)

4. **Discussion**

4.1 **Effect of bioclimatic variables on the suitability of coffee land in Gayo Highlands**

This study explores the effects of climate change, represented with the bioclimatic variables on the geographical range and suitable land suitability for the environment of the Arabica coffee plant in the Gayo highland using MaxEnt modeling. The MaxEnt model for the suitability of the Arabica coffee land provides an AUC value that predicts the distribution of potential land suitability under climatic conditions by 0.814, the result was consistent with previous research on the suitability land of coffee [26] [27].

The results of this research predict that the potential suitability of the Gayo Arabica Coffee will be decrease based on future climate scenarios. Based on the variable analysis, annual rainfall (bio_12) has the highest contribution, followed by the wettest month rainfall (bio_13) and Seasonal temperature (bio_4) in influencing the suitability of the future coffee land. These results are in accordance with previous studies indicating that rainfall and temperature have the ability to disrupt the growth of phenology (a period of naturally occurring phases in plants) plants [28] so that they can affect the typical quality characteristics of products produced. Moreover, natural factors change in the form of climate and coffee quality in the future can affect the status of the Geographic Indication of Coffee Arabica Gayo.
The increase of Gayo Arabica Coffee yield in Gayo Lues shows the farmer awareness to improve their economic condition. The condition was also indicated by the increased plantation area, which gained from expanded coffee vegetation in the unproductive land and land conversion into coffee plants. This condition is characterized by the increasing area of the coffee plantations [25]. Higher coffee prices are also the reason for them to make coffee as a source of income. Nevertheless, the MaxEnt modeling showed that the land suitability area of coffee plants in Gayo highland will decrease in the future as a result of climate change and global warming, indicated with a decreased potential land suitability for coffee [29][30]. Previous research has concluded that global warming will greatly affect the distribution of species by causing expansion, displacement, or contraction in species ranges [27][31].

4.2 Adaptation of the unsuitability impact of coffee land on Gayo highland.
Considering the risk of climate change to the Gayo Arabica Coffee plantation, the adaptation strategy need to be planned. However, the developed planning adaptation for both short and long term strategies were tend to be differ [32]. The main focus of the current adaptation strategy is to increase the adaptive capacity of the farmers [33]. The utilization of relevant local climate information services can be a strategy addressing climate risk in the short term. Increasing farmers' knowledge of climate information will increase innovation to cope climate variability. For the unsuitable area, farmers must consider several other alternatives, such as changing the cultivation practices [34], immigrating to other regions, and to switch professions to other sectors [35]. For land that is less suitable to the suitable for coffee plants, agronomic management needs to be adjusted to anticipate the effects of climate change.

In some aspects, the effectiveness of individual adaptations is determined by the adaptation of the collective (the community). The role of farmers' collective action is very influential in overcoming climate change [36], so that long-term adaptation will be more effective by involving the community as well as considering short-term adaptation. In the future, local government policies must be made with a location-specific recommendations to enable adaptation in certain locations. Provision of shade plants, agronomic practices through the technical extension services, and other collective learning that focus on climate adaptation will be needed. The IPCC AR5 states that to adequately assess adaptation options, it is very important to have relevant information about the current and future climate. Adaptation of the impact of unsuitable coffee land in the Gayo highlands, that predicted to happen in the future, can be done according to the needs and adaptation options (table 2). Besides this adaptation, a better understanding of climate variability and its impact on unsuitable coffee land due to climate change is required.

| Table 2. The Gayo Arabica Coffee adaptation strategies in Gayo highland |
|-----------------------------|-----------------------------|-----------------------------|
| Vulnerability               | Adaptation options          | Practice                    |
| Decreased level of climate  | • Agronomic practices [37]  | • Multistrata rich shade    |
| suitability for cultivating  | • Transfer and adoption of  | management [35][37]         |
| coffee                       | emerged agricultural        | • Counseling provision for  |
|                              | technology [38]             | the farmers [38]            |
| Extreme weather events       | Reforestation [35][37]      | • Forests in degraded areas |
| that lead to floods and      |                             | [35][37]                    |
| landslides                   |                             | • Coffee agroforestry in    |
|                              |                             | degraded areas [35][37]     |
| Increased market risk        | • Strengthen community      | • Establishment of farmer    |
| related to yield variability  | organizations [35][38]      | organization [35][38]       |
| the produced coffee          | • Implementing a food       | • Establishing institutional |
|                              | security program [38]       | partnership [35][38]        |


5. Conclusion
The model generated in this study was a predictive model with a good performance in obtaining predictive values that affect the distribution of Gayo Arabica Coffee in Gayo highland using eleven environmental factors (bioclimatic). The results showed that highly suitable land would be reduced under future climate change scenarios (RCP 4.5) in the 2050s. The most influential bioclimatic variable were the annual rainfall, precipitation of the wettest month, and temperatures seasonal. Therefore, the impact of climate change on the suitability of coffee land in the Gayo highland need to be adapted to retain its GI status. The generated model in this study may provide relevant elements for management practice and adaptation strategies of current and future land use in Gayo highland.

Acknowledgments
The authors would like to thank the Meteorology, Climatology, and Geophysical Agency (BMKG) Indrapuri Station for providing the data and consultation. This research was financially supported by Universitas Gadjah Mada under the Rekognisi Tugas Akhir (RTA) project.

References
[1] Damatta F M and Ramalho J D C 2006 Impacts of drought and temperature stress on coffee Brazilian J. Plant Physiol. 18 55–81
[2] Jaramillo J, Muchugu E, Vega F E, Davis A, Borgemeister C and Chabi-Olaye A 2011 Some like it hot: The influence and implications of climate change on coffee berry borer (Hypothenemus hampei) and coffee production in East Africa PLoS One 6
[3] Bertrand R, Lenoir J, Piedallu C, Dillon G R, De Ruffray P, Vidal C, Pierrat J C and Gégout J C 2011 Changes in plant community composition lag behind climate warming in lowland forests Nature 479 517–20
[4] IPCC 2014 AR4 GCM data
[5] FAO 2016 State of the World’s Forests Rome
[6] Eskes A B and Leroy T 2008 Coffee Selection and Breeding. Coffee: Growing, Processing, Sustainable Production ((Wiley-VCH Verlag GmbH))
[7] Scheper J, Holzschuh A, Kuussaari M, Potts S G, Rundlöf M, Smith H G and Kleijn D 2013 Environmental factors driving the effectiveness of European agri-environmental measures in mitigating pollinator loss - a meta-analysis Ecol. Lett. 16 912–20
[8] Fortunel C, Paine C E T, Fine P V A, Kraft N J B and Baraloto C 2014 Environmental factors predict community functional composition in Amazonian forests J. Ecol. 102 145–55
[9] Van Gils H, Westinga E, Carafa M, Antonucci A and Ciaschetti G 2014 Where the bears roam in Majella National Park, Italy J. Nat. Conserv. 22 23–34
[10] Estes L D, Bradley B A, Beukes H, Hole D G, Lau M, Oppenheimer M G, Schulze R, Tadross M A and Turner W R 2013 Comparing mechanistic and empirical model projections of crop suitability and productivity:Implications for ecological forecasting Glob.Ecol.Bio. 22 1007–18
[11] Warren D L, Seifert S N, Warren D L and Seifert S N 2019 Ecological niche modeling in Maxent: the importance of model complexity and the performance of model selection criteria Ecological Society 21 335–42
[12] Davis A P, Gole T W, Baena S and Moat J 2012 The Impact of Climate Change on Indigenous Arabica Coffee (Coffea arabica): Predicting Future Trends and Identifying Priorities PLoS One 7
[13] Chemura A, Kutywayo D, Chidoko P and Mahoya C 2016 Bioclimatic modelling of current and projected climatic suitability of coffee (Coffea arabica) production in Zimbabwe Reg. Environ. Chang. 16 473–85
[14] Ellyanti, A K and H B 2012 Analisis Indikasi Geografis Kopi Arabika Gayo Ditinjau dari Rencana Tata Ruang Wilayah Kabupaten Agrista 16 46–61
[15] Hijmans R J, Cameron S E, Parra J L, Jones P G and Jarvis A 2005 Very high resolution interpolated climate surfaces for global land areas Int. J. Climatol. 25 1965–78
[16] Zhang L, Cao B, Bai C, Li G and Mao M 2016 Predicting suitable cultivation regions of medicinal plants with Maxent modeling and fuzzy logics: a case study of Scutellaria baikalensis in China Environ. Earth Sci. 75 1–12

[17] Choudhury M R, Deb P, Singha H, Chakdar B and Medhi M 2016 Predicting the probable distribution and threat of invasive Mimosa diplopticha Suavalle and Mikania micrantha Kunth in a protected tropical grassland Ecol. Eng. 97 23–31

[18] McSweeney C F, Jones R G, Lee R W and Rowell D P 2015 Selecting CMIP5 GCMs for downsampling over multiple regions Clim. Dyn. 44 3237–60

[19] Remya K, Ramachandran A and Jayakumar S 2015 Predicting the current and future suitable habitat distribution of Myristica dactyloides Gaertn. using MaxEnt model in the Eastern Ghats, India Ecol. Eng. 82 184–8

[20] Krinner G, Germany F, Shongwe M, Africa S, France S B, Uk B B B B, Germany V B, Uk O B, France C B, Uk R C, Canada M E, Erich M, Uk R W L, Uk S L and Lucas C 2013 Long-term climate change: Projections, commitments and irreversibility Clim. Chang. 2013 Phys. Sci. Basis Work. Gr. I Contrib. to Fifth Assess. Rep. IPCC 9781107057 1029–136

[21] Phillips S B, Aneja V P, Kang D and Arya S P 2006 Modelling and analysis of the atmospheric nitrogen deposition in North Carolina Int. J. Glob. Environ. Issues 6 231–52

[22] Philipp S J and and Dudík M 2008 Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation Ecography (Cop.). 31 161–75

[23] Araújo M and Guisan A 2006 Araujo MB, Guisan A. Five (or so) challenges for species distribution modelling. Journal of Biogeography J. Biogeogr. 33 1677–88

[24] Yang X Q, Kushwaha S P S, Saran S, Xu J and Roy P S 2013 Maxent modeling for predicting the potential distribution of medicinal plant, Justicia adhatoda L. in Lesser Himalayan foothills Ecol. Eng. 51 83–7

[25] Pertanian K 2017 Outlook Kopi 2017 (Jakarta: Pusat Data dan Sistem Informasi Pertanian)

[26] Bunn C, Läderach P, Ovall e Rivera O and Kirschke D 2015 A bitter cup: climate change profile of global production of Arabica and Robusta coffee Clim. Change 129 89–101

[27] Yuan H S, Wei Y L and Wang X G 2015 Maxent modeling for predicting the potential distribution of Sanghang, an important group of medicinal fungi in China Fungal Ecol. 17 140–5

[28] Haggar J and Schepp K 2012 Climate Change, Agriculture and Natural Resources Coffee and Climate Change Impacts and options for adaption in Brazil, Coffee and Climate Change Impacts and options for adaption in Brazil, NRI Work. Pap. Ser. 4 50

[29] Magrach A and Ghazoul J 2015 Climate and pest-driven geographic shifts in global coffee production: Implications for forest cover, biodiversity and carbon storage PLoS One 10 1–15

[30] Hailu B T, Siljander M, Maeda E E and Pellikka P 2017 Assessing spatial distribution of Coffea arabica L. in Ethiopia’s highlands using species distribution models and geospatial analysis methods Ecol. Inform. 42 79–89

[31] Li R, Xu M, Wong M H G, Qiu S, Sheng Q, Li X and Song Z 2015 Climate change-induced decline in bamboo habitats and species diversity: Implications for giant panda conservation Divers. Distrib. 21 379–91

[32] Vermeulen S J, Aggarwal P K, Ainslie A, Angelone C, Campbell B M, Challinor A J, Hansen J W, Ingram J S I, Jarvis A, Kristjanson P, Lau C, Nelson G C, Thornton P K and Wollenberg E 2012 Options for support to agriculture and food security under climate change Environ. Sci. Policy 15 136–44

[33] Lasco R D, Habito C M D, Delfino R J P, Pulhin F B and Concepcion R N 2011 Climate change adaptation for smallholder farmers in Southeast Asia Philippines

[34] Thornton P K, van de Steeg J, Notenbaert A and Herrero M 2009 The impacts of climate change on livestock and livestock systems in developing countries: A review of what we know and what we need to know Agric. Syst. 101 113–27

[35] Läderach P, Villegas J R, Navarro-racines C, Zelaya C, Valle A M and Jarvis A 2017 Climate
change adaptation of coffee production in space and time 47–62

[36] Sumaryanto, Irawan B, Sawit H, Setyanto A, Situmorang J and M S 2011 Dampak Perubahan Iklim Jakarta: Kementerian Pertanian

[37] Rahn E, Läderach P, Baca M, Cressy C, Schroth G, Malin D, van Rikxoort H and Shriver J 2014 Climate change adaptation, mitigation and livelihood benefits in coffee production: where are the synergies? *Mitig. Adapt. Strateg. Glob. Chang.* 19 1119–37

[38] Baca M, Läderach P, Haggar J, Schroth G and Ovalle O 2014 An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in mesoamerica *PLoS One* 9