



# Land in Central America will become less suitable for coffee cultivation under climate change

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## Abstract

Coffee cultivation in Central America provides goods and services at local, national, and international levels. Climate change is likely to affect the magnitude and continuity of these benefits by reducing the land suitability for coffee cultivation. To quantify the impacts of climate change on land suitability, we use the Bayesian network model Agroecological Land Evaluation for *Coffea arabica* L. (ALECA) and estimate the land suitability for coffee production in 2000, 2050, and 2080 under three climate change scenarios based on relative concentration pathways (RCPs) 2.6, 4.5, and 8.5. Results indicate that even under the less severe climate scenarios, over half of the current coffee area in Central America will experience a decline in its land suitability for coffee production, from excellent or good to moderate and marginal, and that the change will not happen in the more distant future of 2080, but by 2050. Under RCP 8.5, most coffee areas become of marginal and moderate suitability. The findings show that the continuity of coffee cultivation in a large portion of coffee areas in Central America is under threat and that farmers and policy-makers should develop adaptation portfolios for their farms and regions in a timely manner.

**Keywords** *Coffea arabica* L. · Biophysical land suitability · Bayesian networks · Climate change · Probabilistic modeling · Perennial crop system adaptation

## Introduction

In the last two decades, the coffee sector in Central America has experienced low prices and outbreaks of coffee rust, crises that have threatened the sustainability of coffee production (Avelino et al. 2015; CEPAL 2002; PROMECAFE 2018). Climate models project drier and warmer climate conditions in the Northern, and wetter conditions in the Southern, areas of Central America (Hidalgo et al. 2017), which will affect the climate suitability for coffee (*Coffea arabica* L.). The continued change in climate is likely to exacerbate existing problems in the coffee sector and create new ones, making it more

difficult to sustain its production (Eakin et al. 2005; Frank et al. 2011; Reyer et al. 2017).

One option to explore the impacts of climate change on coffee yields and production across coffee regions would be to use sophisticated scientific tools such as crop models (Van Noordwijk and Lusiana 1998; van Oijen et al. 2010a). These models can provide a detailed assessment of the threat; however, coffee crop models are still limited in their ability to simulate coffee production beyond the plot scale, and many high-resolution data would be necessary as inputs, which are not readily available (van Oijen et al. 2010b). Thus, it is currently not possible to represent the existing complexity and variety of coffee systems with crop models at the spatial level required (Jose et al. 2004; Rao et al. 1997; Roupsard et al. 2009). Land evaluation is an alternative approach for assessing spatially explicit changes in coffee production suitability due to changes in climatic, soil, and topography-related factors (Brown et al. 2011; Lara-Estrada et al. 2017; Manandhar et al. 2014; Mighty 2015). Early warnings on expected changes in land suitability for coffee will enable farmers and agronomists to improve adaptation decisions and the planning of longer-term investments.

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Other previous studies have employed species distribution models to address the effect of climate change on climate suitability for coffee cultivation, using only climate data and the location of coffee areas (Chemura et al. 2015; Ovalle-Rivera et al. 2015; Schroth et al. 2014). These types of models were developed to study the dispersion patterns of wild species in nature using presence-absence data (Convertino et al. 2014; Guillera-Aroita et al. 2014; Phillips et al. 2006; Yackulic et al. 2013). Global studies indicate that in about half of the current coffee area, the climate will become less suitable for cultivation in the future (Bunn et al. 2014; Ovalle-Rivera et al. 2015). As a solution, these authors propose to shift the current coffee areas to higher altitudes to overcome climate change alteration. However, if other agroecological factors like soils, landforms, or land use are not considered, moving coffee areas to climatically more suitable areas may either not be possible due to land-use conflicts or not advisable due to unsuitable soil or landform conditions. Considering all relevant factors is necessary for actual agricultural planning (FAO 1976; McRae et al. 1981; Mighty 2015; Nzeyimana et al. 2014).

To address this gap, we used the Bayesian network model Agroecological Land Evaluation for *Coffea arabica* L. (ALECA) to evaluate the suitability of a given piece of land for coffee cultivation based on climate, soil, and landform information (Lara-Estrada et al. 2017). The model was specifically developed based on parameters reported in the coffee literature and empirical data and has been used to evaluate the current conditions for coffee production in Central America. In this paper, we assess the impact of climate change on land suitability for coffee cultivation in Central America with consideration of soil and landform factors. Furthermore, we briefly discuss the land evaluation approach in agricultural planning and propose adaptation strategies for those regions where a considerable loss of land suitability for coffee cultivation is expected in the future.

## Methods

### Study area

Our study covers the coffee areas in all coffee-producing countries of Central America. Guatemala has the largest coffee area, followed by Honduras, Nicaragua, El Salvador, Costa Rica, and Panama (Fig. 1) (PROMECAFE 2018). While the region contributes only about 10% to worldwide coffee production, the quality of the coffee is well appreciated in the coffee business (ICO 2015; McCook 2017). Both coffee production quantity and quality determine farmers' income in the market (Adams and Roldan 1980; Bolwig and You 2007).

The region has tropical and subtropical conditions and wet (rainy) and dry seasons with some variations in duration and

intensity depending on the location resulting from the oceanic influence and topography. Precipitation is the climatic variable with the highest variability, temperature variations for a given location are small during the year. The higher temperature changes are observed across altitudes (Imbach et al. 2017; Taylor and Alfaro 2005). Farmers cultivate coffee in the region under diverse agroecological conditions and production systems such as organic/conventional, low/high intensification, and full-sun monocrop/agroforestry (Blanco and Aguilar 2015; Hagggar et al. 2011; Infante-Amate and Picado 2018; Meylan et al. 2013; Muschler 2001; Somarriba et al. 2004). Regarding the aptitude of the region for coffee cultivation, land suitability evaluations indicate that about 59% of the region's coffee areas can be considered moderately to very good for coffee cultivation, and 14% as optimal (excellent); Costa Rica, Nicaragua, and Honduras have the highest regional shares of optimal areas (Lara-Estrada et al. 2017).

### The model ALECA

Land evaluation systems in agriculture rate the biophysical qualities of the land for crop production, and because of their simplicity and explicit nature serve as tools for planning and management at local and national levels (Brown et al. 2011; Manandhar et al. 2014; McRae et al. 1981). ALECA is a Bayesian network (BN) model composed of two parts, (1) a graphical structure that consists of a set of agroecological variables linked by arcs, where the links define the conditional dependencies between variables; and 2) conditional probability tables that quantify the dependency between variables (Fig. 2). In BNs, the graphical structure and conditional probability tables can be determined by implementing machine learning algorithms from data, using literature, expert elicitations, or a combination (Aguilera et al. 2011; Marcot 2012; Rodorff et al. 2018). Literature and machine learning were used for ALECA (Lara-Estrada et al. 2017).

ALECA evaluates land suitability based on the agroecological variables mean annual temperature [°C], annual precipitation [mm], dry season length [months], slope [%], aspect [cardinal direction], pH in H<sub>2</sub>O, cation exchange capacity [Meq 100 g<sup>-1</sup>], and soil texture [categorical]. The variables were selected based on the results reported in the literature, correlations between variables, and data availability (Lara-Estrada et al. 2017). In ALECA, the suitability evaluation is inferred at three levels: variable, component, and land (Fig. 2). The variables are grouped into the components climate, soil, and landform. On Level 1, after entering the biophysical value of a given variable, a suitability function (S variables) assigns an individual suitability score to that value, ranging from 0 to 100%. Then, the suitability scores of each variable propagate to the corresponding component (Level 2), where an average component score is calculated. Finally, a weighted average is computed to estimate the overall land suitability (Level 3)

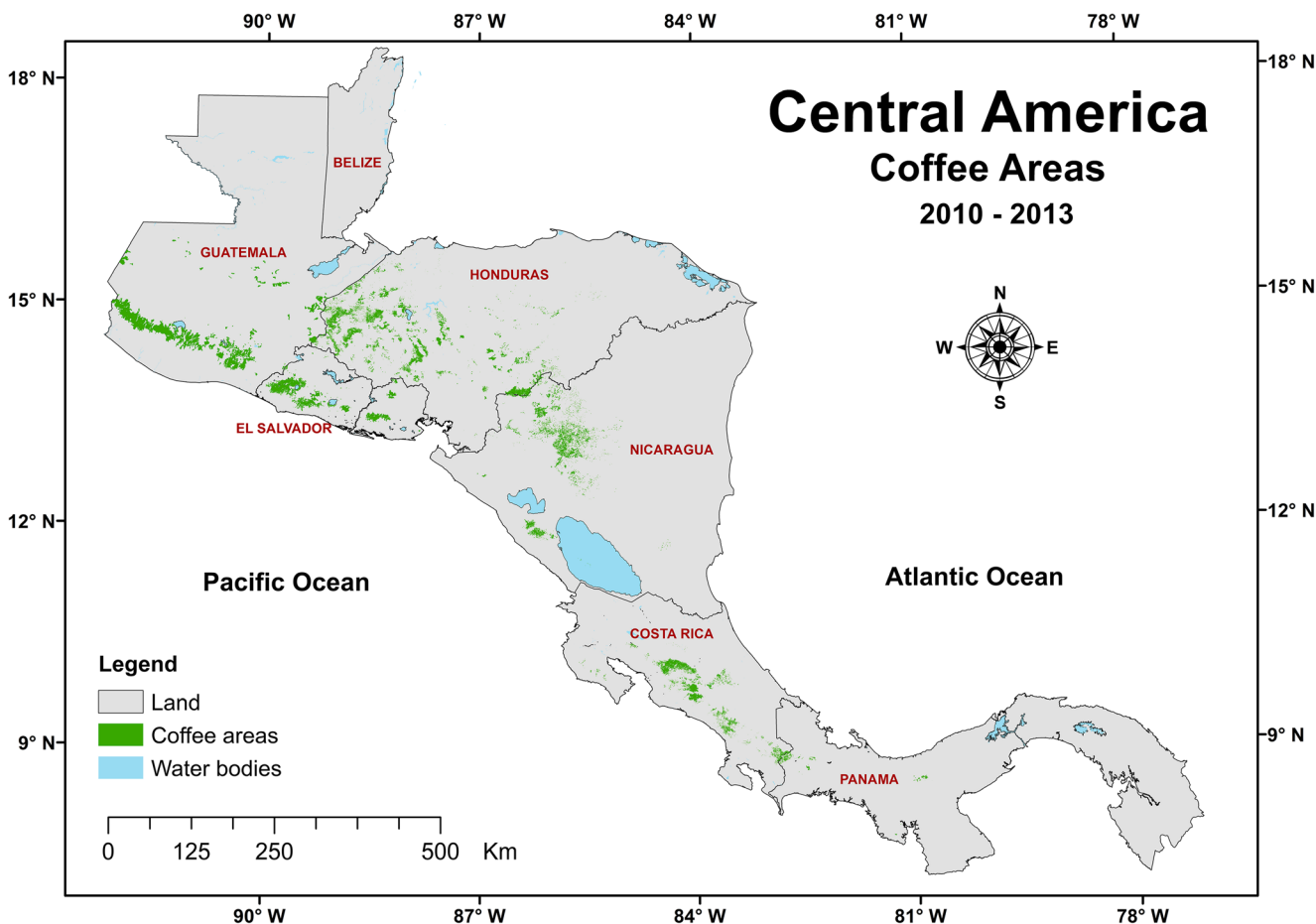
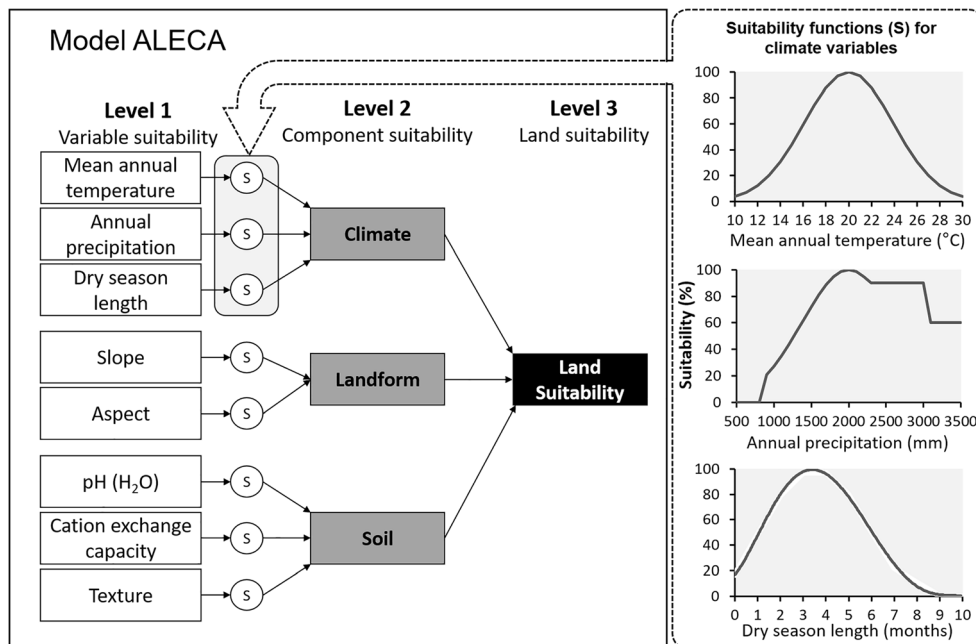


Fig. 1 Central American coffee areas. ICAFE (2013), MAG (2010), MAGA (2010), IAIP (2013), CATIE & MAGFOR (2012), and ANAM (2012)

Fig. 2 The graphical structure of the Bayesian network model ALECA (Lara-Estrada et al. 2017). The model infers the suitability at three levels: single variable suitability, component suitability (climate, landform, and soil), and overall land suitability for coffee. See Lara-Estrada et al. (2017) for the suitability functions for soil and landform variables



from the suitability scores of the components climate (weight = 49%), soil (36%), and landform (15%) (Lara-Estrada et al. 2017).

## Data

For current conditions (2000), the WorldClim dataset was used to obtain values for the climate variables (Chemura et al. 2015; Hijmans et al. 2005). Using the elevation data included in WorldClim, a spatial analysis was implemented to calculate the landform variables (ESRI 2012a, 2012b). The soil variables were obtained from the SoilGrids dataset<sup>1</sup> for 0–30 cm depth (Hengl et al. 2014). The individual datasets were merged into a single dataset at a 1 km × 1 km resolution.

To depict future climate conditions in 2050 and 2080, we used data from the model MPI-ESM-LR (ECHAM5) of the Max Planck Institute driven by the relative concentration pathway (RCP) scenarios 2.6, 4.5, and 8.5 (Jungclauss et al. 2006; Ramirez and Jarvis 2008). The data were downloaded at 30 s resolution (~1 km) (Ramirez-Villegas and Jarvis 2010) from the CCAFS GCM data portal<sup>2</sup>. The MPI-ESM-LR was chosen because its performance in the study region was better than the average performance of 20 other climate models (Conde 2011; Fuentes-Franco et al. 2015; Maloney et al. 2013; Schaller et al. 2011). All modeling and data only cover the coffee areas in the study region.

## Assumptions

We assumed that soil and landform variables would remain constant over time. Even though ALECA as a BN model can deal with data uncertainty (Aguilera et al. 2011; Lara-Estrada et al. 2018, 2017), we assumed no uncertainty in the input data to simplify the analysis. Coffee areas correspond to country coffee maps from the period 2010–2013 (Fig. 1) and are taken to portray the area for the year 2000 in the modeling. Because most of the coffee areas in the region are planted with Arabica varieties, and we were not able to extract non-Arabica areas, we assumed all coffee areas were planted with Arabica varieties. We assume that all Arabica varieties have the same suitability response to the agroecological variables. Even though the ALECA model does not consider interactions between agroecological variables and therefore cannot account for potential complementary or compensatory effects, the model performed very well in evaluating the current land suitability for coffee cultivation in the study region (Lara-Estrada et al. 2017).

<sup>1</sup> [www.soilgrids.org](http://www.soilgrids.org)

<sup>2</sup> <http://www.ccafs-climate.org>

## Estimating land suitability

We inferred the land suitability (LS) for coffee cultivation for coffee areas under current and future climate conditions. Possible values for LS range from 0 to 100%, with 100% denoting the highest suitable value. In addition, a categorical land suitability scale was used to put the values into perspective: ≤60% = unsuitable, > 60% = marginal, > 75% = moderate, > 85% = good, >90% = excellent.

We also estimated the rate of change of LS under current and future climate conditions for the coffee areas. For this, we used the *rate of change* used by the FAO to depict changes in the forest coverage between periods (Puyravaud 2003; Velázquez et al. 2002). In this study, the equation depicts the rate of change ( $R_c$ ) of coffee areas with a given land suitability between the years 2000, 2050, and 2080.

$$R_c = \left[ \frac{A_2}{A_1} \right]^{1/n} - 1$$

where  $A_2$  and  $A_1$  are the percent of areas with a given LS-score value at different years, and  $n$  is the number of years between the two years under comparison.

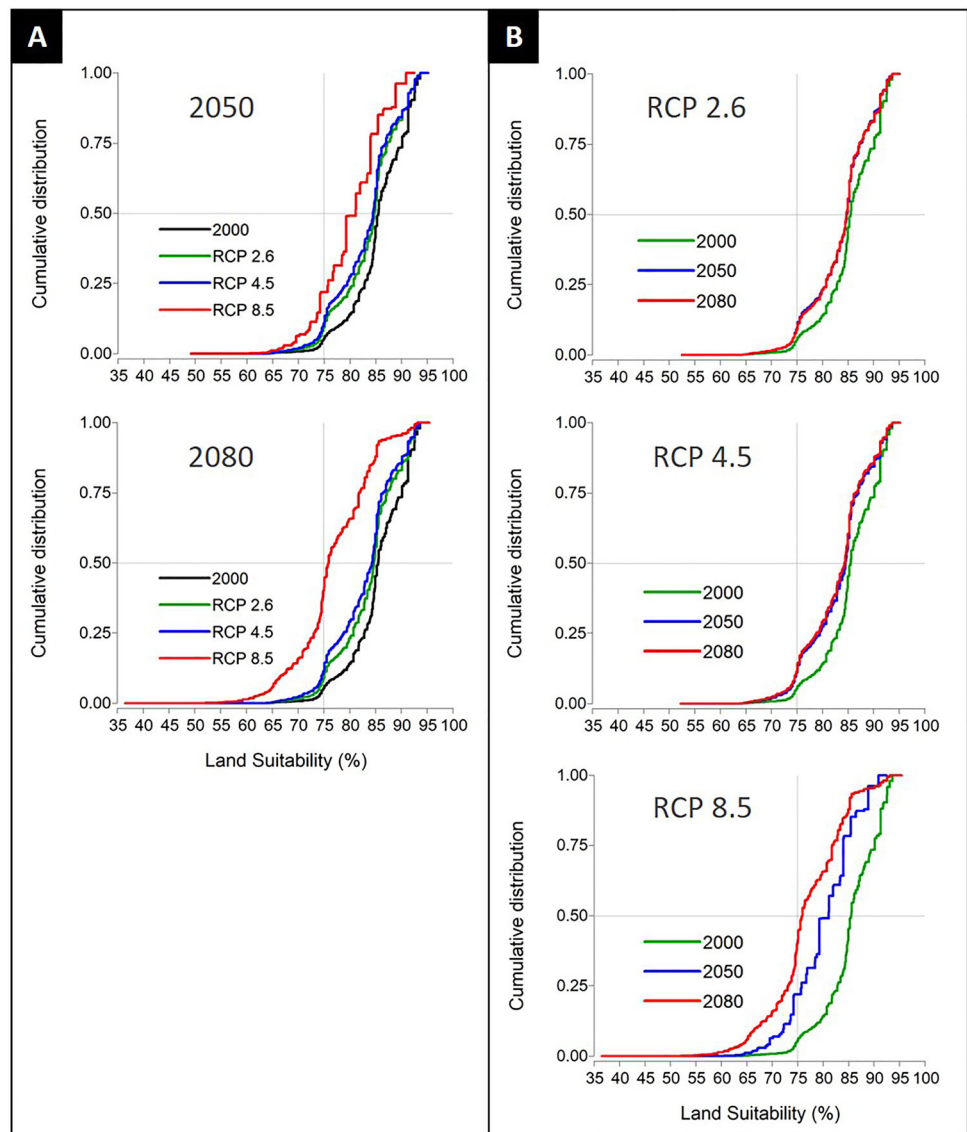
## Results

In our simulations, the land suitability for coffee cultivation decreased under all climate change scenarios in Central America. About half of the areas currently classified as excellent or good were downgraded to moderate or marginal under the less severe scenarios RCP 2.6 and 4.5, and they almost disappeared under the most severe scenario, RCP 8.5.

RCPs 2.6 and 4.5 show a similar trend in land suitability changes over time, but losses in land suitability scores are a little higher in RCP 4.5 (Fig. 3). In both scenarios, most changes occurred between 2000 and 2050, with only minor changes between 2050 and 2080. For RCP 8.5, the suitability losses were much higher (Fig. 3A) and more constant over time (Fig. 3B). Furthermore, the cumulative LS distribution functions reveal non-linear impacts of climate change across land qualities. The observed variations in the LS changes between periods are mainly caused by temperature and precipitation changes depicted in the CMIP5 data. For surface temperature, there is an overall rise close to the middle of the century in all RCPs, followed by an abated warming in RCP 2.6, a slightly abated warming in RCP 4.5, and a marked continuation of warming in RCP 8.5 until 2080 (Knutti & Sedláček, 2012). See Online Resource 1 for additional results on regional LS.

The unequal impacts of climate change on land suitability in the different periods are also shown in Table 1. The average annual rates of change ( $R_c$ ) in LS scores are generally higher

**Fig. 3** Current and future land suitability of coffee areas (*Coffea arabica* L.) under three scenarios of climate change in Central America. The data shown in panels A and B are the same; in **A**, the differences between climate change scenarios is highlighted; in **B**, the differences between the different time periods. Most changes occur between 2000 and 2050 for RCPs 2.6 and 4.5; for RCP 8.5, suitability losses are higher and more constant over time. Land suitability classes:  $\leq 60\%$  = unsuitable,  $>60\%$  = marginal,  $>75\%$  = moderate,  $>85\%$  = good,  $>90\%$  = excellent



between 2000 and 2050 than between 2050 and 2080. In addition, the  $R_c$  shows a particular pattern of changes across different land qualities. Areas with  $70\% \leq LS < 90\%$  have the highest rates under all the RCPs and periods. Negative changes occur in areas with  $LS > 80\%$  and positives in areas with  $LS$

scoring between 60 and 80%. Areas with  $LS$  scores below 60% display positive or negative changes depending on RCP and period. The  $R_c$  can help identify which  $LS$  coffee areas will be more affected and where actions need to be focused on coping with the adverse effects.

**Table 1** The annual rate of change  $R_c$  of  $LS$  scores of coffee areas between the periods 2000–2050 and 2050–2080. Rates of change are highest for areas with  $70\% \leq LS < 90\%$  and generally higher in 2000–2050 than in 2050–2080. The rate depicts the intensity and direction: win [+ ] or loss [– ]

LS (%)	RCP 2.6		RCP 4.5		RCP 8.5		2000 (ha)
	2000–2050	2050–2080	2000–2050	2050–2080	2000–2050	2050–2080	
50.01–60	–1.80	–0.20	2.70	–0.79	6.01	8.27	18
60.01–70	2.10	0.05	2.27	0.30	3.97	0.94	22,400
70.01–80	0.46	0.17	0.73	0.11	1.33	0.37	261,443
80.01–90	–0.15	–0.07	–0.27	–0.11	–1.00	–1.60	630,264
90.01–100	–1.11	–0.23	–1.62	–0.12	–4.41	–0.28	145,639

In 2000, 145,639 ha of coffee areas in Central America were scored excellent, 235,415 ha good, 547,897 ha moderate, 130,793 ha marginal, and 18 ha unsuitable (Fig. 4, first map). The absolute LS losses of most coffee areas remain below 15% under RCPs 2.6 and 4.5 but reach 37% under RCP 8.5 (Fig. 4, other maps). Most coffee areas follow the general trend of increasing losses of land suitability from RCP 2.6 to 8.5 and 2000 to 2080, but there are exceptions in each country. Some coffee areas in Western Honduras, e.g., show higher losses under RCP 2.6 than under RCP 4.5 in 2050, some areas in Costa Rica experience an LS-score loss in 2050 but improve by 2080, and a fraction of coffee areas will experience positive changes under all RCPs and periods (green areas in Fig. 4). This is particularly promising for some areas in Guatemala, Honduras, and Costa Rica. See Online Resources 1 for regional maps on LS changes.

Table 2 provides a comprehensive overview of all estimated LS changes. Coffee areas classified as excellent in the year 2000 shrink by 56%, 63%, and 93% under the three different RCP scenarios, respectively. Most of these areas downgrade to the moderate or marginal categories. At the other end of the suitability scale, the picture is different: between 89 and 94% of currently rated marginal areas remain marginal under the three RCPs. Some upgrades were observed from marginal or moderate to excellent or good but remained below 5%. In all periods for RCP 2.6 and 4.5, 71% of areas currently rated unsuitable for coffee production experience an upgrade to marginal, and for RCP 8.5 to moderate, but since the actual unsuitable area is only 18 ha, the change is irrelevant to the whole picture. These improvements are observed in areas where the current low suitability is caused by colder conditions, shorter dry seasons, higher annual precipitation values, or a combination of all. Changes in climate to warmer and drier conditions improve the climate suitability for coffee in these areas. Areas that remain marginal or unsuitable are already warm and dry, so climate change does not improve the conditions for coffee production (Hidalgo et al. 2017).

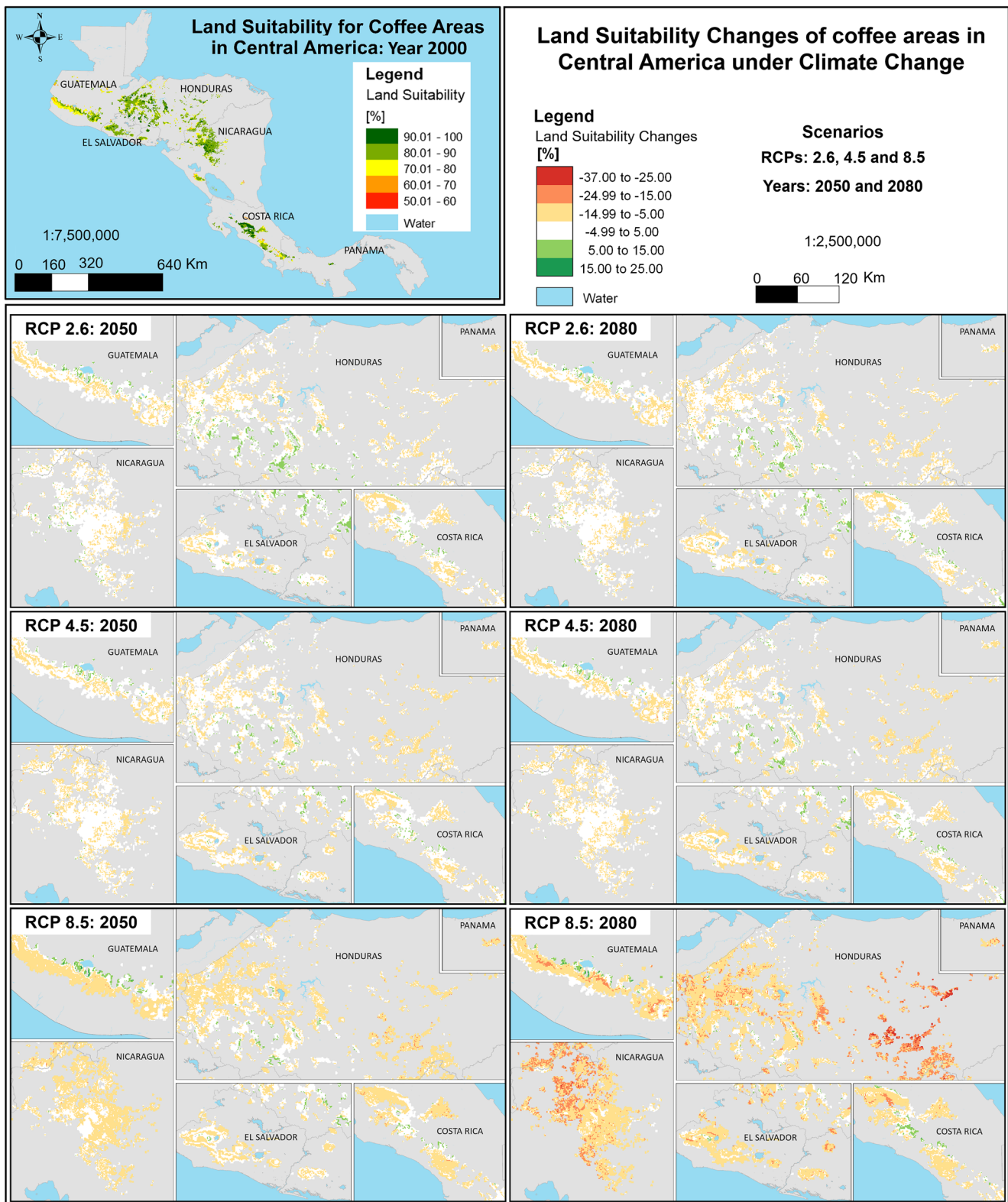
We can thus observe changes in both directions on the suitability scale, but changes are negative for a much larger area, with a decrease in highly suitable areas and an increase in moderately and marginally suitable areas. Therefore, the quantity and quality of the regional coffee production are under threat.

A closer look at the changes in suitability for each variable in the climate component reveals that mean temperature suitability for coffee cultivation experienced the highest losses, from 10.24% under RCP 2.6 in 2050 to 47.27% in RCP 8.5 in 2080 (Table 3). The average precipitation suitability variability is much lower, with losses from 0.36 to 6.17% and lowest in dry season length suitability, ranging from 0.55 to  $-1.17\%$ . However, even if the mean changes in precipitation and dry season length are small compared to temperature, the standard deviation, minimum, and maximum of the three distributions

are very similar. This suggests that in some areas, the positive or negative changes in precipitation and dry season length will be much larger than the average, confirming our previous finding that some areas will experience land suitability changes in opposition to the regional average (cf. Fig. 4).

We looked at six representative coffee zones in Central America (described in detail in Lara-Estrada et al. 2017) to have a clearer insight into the dynamics of LS changes at the local level. Currently, the coffee area Tarrazú is considered excellent, Jinotega and Márcala as good, and El Paraíso, Masatepe, and Turrialba as moderate (Bertrand et al. 2006; Hagggar et al. 2011; Lara-Estrada et al. 2017; Teuber 2009). Figure 5 shows that most zones experience a downgrade in LS from 2000 to 2050 and 2080, but the magnitude differs between selected zones. Tarrazú, Jinotega, and Márcala downgrade the least with less than 4.5% on average. Tarrazú and Márcala may even experience some upgrades in LS under the less severe scenarios of RCP 2.6 and 4.5. Turrialba and Masatepe incur the highest losses in LS under the three RCPs, by 6–12% on average. Under RCP 8.5, all locations except Tarrazú experience considerable LS reductions, and some zones become marginal by 2080. These insights may enable local farmers, stakeholders, and institutions involved in coffee production to develop adaptation plans customized for every region.

The zones El Paraíso and Turrialba show high internal variability in LS scores, whereas others like Tarrazú or Masatepe have more homogenous profiles. Looking at the two representative zones in Nicaragua, Masatepe (461 m.a.s.l.) and Jinotega (1091 m.a.s.l.), one can also observe how the LS profiles, composed of soil, landform, and climate components, influence the future dynamic of LS-score changes. The landform and soil conditions are better suited for coffee cultivation in Masatepe than in Jinotega because the region has flatter slopes and better physical and chemical soil properties (e.g., slope  $2.17 \pm 1.6\%$  in Masatepe vs.  $6.77 \pm 4.06\%$  in Jinotega; CEC  $27.11 \pm 1.72$  vs.  $16.50 \pm 1.90$  Meq  $100\text{ g}^{-1}$ ). However, climatic conditions in Masatepe are less suitable for coffee because temperatures are higher and the dry season more prolonged (mean temperature  $24.26 \pm 0.35$  in Masatepe vs.  $19.85 \pm 0.96$  °C in Jinotega; dry season length  $5 \pm 0$  vs.  $3.03 \pm 0.2$  months) (Hagggar et al. 2011; Hengl et al. 2014; Hijmans et al. 2005). Coffee plantations in Masatepe thus experience temperature and water stress during the year and particularly in the dry season, which can lead to abortion or abnormalities in the flowering and fruiting stages, which impacts productivity and coffee quality. In the long term, these climatic stresses lead to a reduced life expectancy of coffee plants (DaMatta and Ramalho 2006; Melke and Fetene 2014); and therefore, coffee plantations may have to be replanted more frequently. This explains why climate change, even in the more benign RCP scenarios, leads to a rapid loss of land suitability scores in zones like Masatepe.



**Fig. 4** Changes in land suitability for *Coffea arabica* L. under climate change scenarios in Central America. Land suitability classes:  $\leq 60\%$  = unsuitable,  $>60\%$  = marginal,  $>75\%$  = moderate,  $>85\%$  = good,  $>90\%$  = excellent. Total coffee areas = 1,059,763 ha. Pixel size = 1 km

**Table 2** Estimated changes in land suitability under future climate scenarios for coffee areas in Central America. The diagonal values in italic show the area shares that remain in the same land suitability category from one period to the next. The values to the right of the italic values indicate a land suitability downgrade, the ones to the left a

suitability upgrade. The first row, e.g., shows that from the 100% of areas classified as excellent in 2000, only 45.36% will remain excellent in 2050, whereas 32.71% will be downgraded to good, and 21.92% to moderate under RCP 2.6. The values in brackets show the changes from 2000 to 2080

Land Suitability <sup>a</sup>	Excellent	Good	2050 (2080) Moderate	Marginal	Unsuitable
2000 \ RCP 2.6					
Excellent	<b>45.36 (43.90)</b>	32.71(30.09)	21.92 (25.96)		
Good	3.66 (2.37)	<b>52.60 (49.06)</b>	43.55 (48.33)	0.19 (0.24)	
Moderate	1.58 (0.84)	5.00 (3.19)	<b>77.94 (78.78)</b>	15.48 (17.20)	
Marginal		0.09 (0.02)	5.70 (6.12)	<b>94.20 (93.87)</b>	<0.01(<0.01)
Unsuitable				71.12 (71.12)	<b>28.88 (28.88)</b>
2000 \ RCP 4.5					
Excellent	<b>40.48 (37.49)</b>	31.33 (31.95)	28.20 (30.55)		
Good	1.38 (1.66)	<b>44.83 (40.76)</b>	53.50 (57.16)	0.28 (0.42)	
Moderate	0.41 (0.41)	2.13 (2.14)	<b>78.18 (75.04)</b>	19.28 (22.41)	
Marginal		0.06	5.04 (5.93)	<b>94.86 (94.04)</b>	0.05 (0.03)
Unsuitable				71.12 (71.12)	<b>28.88 (28.88)</b>
2000 \ RCP 8.5					
Excellent	<b>8.43 (7.23)</b>	32.21 (12.55)	59.05 (75.78)	0.31 (4.44)	
Good	1.01 (0.88)	<b>17.05 (2.09)</b>	79.00 (69.52)	2.94 (27.45)	(0.06)
Moderate	0.12 (0.12)	3.77 (0.59)	<b>56.08 (34.08)</b>	40.02 (63.62)	(1.59)
Marginal		0.66 (0.12)	5.01 (3.86)	<b>94.08 (89.49)</b>	0.25 (6.53)
Unsuitable			71.12 (71.12)		<b>28.88 (28.88)</b>

## Discussion

Given the magnitude of expected LS losses even until 2050, effective and timely adaptations are needed to sustain coffee production in Central America. Some authors suggest moving the coffee areas to higher altitudes or other areas that will

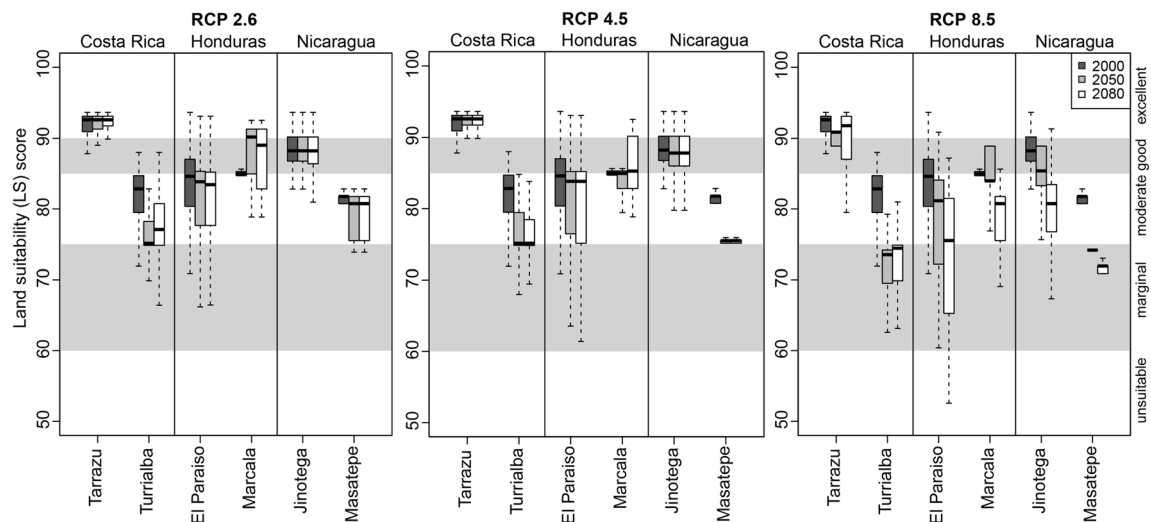
become suitable in the future (Läderach et al. 2010; Zullo et al. 2011). However, considering the financial state of the farmers and the coffee sector as a whole after the series of crises in the last years and decades, the existing land-rights issues, and national land-use regulations, this suggestion may not be easily realized (Boucher et al. 2005; Broegaard 2010;

**Table 3** Descriptive statistics of the actual climate data for the reference year 2000 and changes in suitability [%] for the climate variables under different climate change scenarios in the coffee areas in Central America.

Mean temperature suitability for coffee cultivation experiences the highest losses, precipitation, and dry season length suitability variability is much lower

RCP	Year	Variables	Units	Mean	SD <sup>a</sup>	Min	Max
2000		Mean Temperature	° C	20.95	1.84	8.90	28.00
		Annual Precipitation	mm	2,139.92	670.56	819.00	5,390
		Dry Season Length	Months	3.53	1.43	0.00	6.00
Changes in suitability: RCP 2.6	2050	Mean Temperature		-10.24	11.31	-53.73	71.04
		Annual Precipitation	%	-0.36	10.23	-34.75	49.57
		Dry Season Length		0.32	7.10	-40.04	40.04
	2080	Mean Temperature		-9.34	10.73	-53.73	70.15
		Annual Precipitation	%	-1.50	8.05	-38.19	44.84
		Dry Season Length		0.39	8.36	-40.04	40.04
RCP 4.5	2050	Mean Temperature		-10.35	11.32	-53.73	56.24
		Annual Precipitation	%	-3.10	8.01	-39.28	32.12
		Dry Season Length		-0.55	7.43	-40.04	40.04
	2080	Mean Temperature		-12.37	12.73	-57.76	72.66
		Annual Precipitation	%	-3.07	8.48	-37.72	44.94
		Dry Season Length		0.05	8.84	-40.04	40.04
RCP 8.5	2050	Mean Temperature		-23.33	17.35	-71.15	74.8
		Annual Precipitation	%	-2.19	10.36	-30.6	37.05
		Dry Season Length		1.77	9.18	-30.88	40.00
	2080	Mean Temperature		-47.27	21.37	-86.15	89.76
		Annual Precipitation	%	-6.17	10.20	-65.77	39.75
		Dry Season Length		0.13	12.29	-75.15	40.00





**Fig. 5** Changes in land suitability scores from 2000 to 2080 in six representatives (i.e., well known or well studied) coffee zones in Central America under different climate change scenarios. Most zones experience a downgrade in LS from 2000 to 2050 and 2080, but the magnitude differs

Charlip 1999; Zeledon and Kelly 2009). A more feasible solution for small- and medium-scale farmers in the region is to increase current coffee areas' resilience. Haggard and Schepp (2012), for example, mention a series of adaptation strategies that include technical (e.g., agroforestry and income diversification), financial (climate insurance), and organizational aspects (joint efforts and planning) that coffee farmers and farmers' organizations can consider and implement to improve their level of resilience to climate change.

The effects of climate change can also be alleviated by a change in farming practices, such as adjusting the shade of trees in the coffee plantations to improve the microclimate and soil conditions, irrigation, fertilization, soil conservation practices, or better-adapted coffee varieties (Meylan et al. 2017; de Souza et al. 2012; Vaast et al. 2016). Agroforestry is already used in the coffee areas in the region as a strategy to improve microclimatic and soil conditions under suboptimal conditions (areas at low altitudes) (Harvey et al. 2017), which explains the presence of a considerable proportion of the current coffee area under marginal LS conditions. Conservation practices of soil and water could be adopted to improve other biophysical conditions (Blanco and Aguilar 2015; Harvey et al. 2014), and the planting of coffee varieties better adapted to shade, drought, and warming conditions may improve the resilience of coffee farms under marginal and moderate LS conditions (Bertrand et al. 2011; Montagnon et al. 2012).

The selection of farming adaptation practices and final strategies at the farm level should be tailored to the region and reflect the severity of the expected changes (Vermeulen et al. 2013). Coffee farmers in areas where only a slight decrease in land suitability is expected, like Tarrazú, Jinotega, and Marcala, may only need to adjust at a varietal, or shading,

or intensification level. Farmers in coffee areas with medium LS losses may need to make further adjustments like introducing shade trees of higher economic value (producing timber and fruits), adding market value to the coffee (certification, postharvest processing), and improving the efficiency of farming practices. In the areas with the highest LS losses, where climate will become unsuitable for *Coffea arabica* L. cultivation, changing to other crops like *Coffea canephora* (robusta coffee) or cocoa is an option that may allow the farmers to continue cultivating without changing their whole operations.

Climate change is expected to progressively increase the occurrence and severity of the most important pests and diseases like the coffee berry borer (*Hypothenemus hampei*) and the coffee rust (*Hemileia vastatrix*) over time (Jaramillo et al. 2011, 2009; Merle et al. 2020; Ward et al. 2017). Some even consider the past outbreak of coffee rust in Central America as an early warning of what may become more recurrent in the future (Avelino et al. 2015). On the other hand, the occurrence of diseases favored by cold conditions like leaf spot (*Mycena citricolor*) will probably decrease (Avelino et al. 2007). Adaptation strategies and practices need to be incorporated into farm planning, not only against latent threats like pests and diseases, but also for expected changes in biophysical conditions, price crises, local land-use changes, market or financial opportunities, and farmers' socioeconomic conditions and preferences (Vega and Somarriba 2005; Waldick et al. 2017).

Land evaluations like the one we presented here can support the planning and decision-making processes at the farm, local, national, and regional levels (Bizikova et al. 2015).

Stakeholders can use these results or even the model ALECA itself to explore how changes in the soil, landform, and climate variables affect the aptitude of their land for coffee cultivation instead of relying on general tendencies (Brown et al. 2011). At the governmental level, based on the rates of change, spatial distribution, and severity of the LS changes to be expected in the coffee areas in the Central America region, policies, and programs oriented to support the coffee farmers should include technical and financial tools as well as a legal framework for planning and implementing region-specific adaptation strategies. Finally, because of the magnitude of the changes in the land suitability across the coffee areas in the region, it is possible that even if all possible adaptation actions are implemented and coffee production continues in the region, the quantity and quality of the coffee will change.

## Conclusions

The suitability of current coffee areas in Central America to produce coffee will decrease at an alarming rate under climate change. Highly suitable areas will decrease in size, while the size of only marginally suitable areas will increase. Under the most severe climate change scenario (RCP 8.5), most of the current coffee areas will become marginal or unsuitable for *Coffea arabica* L. cultivation. Given the expected speed of land suitability downgrades in the period 2000–2050 and the perennial nature of the coffee plant, adaptation actions need to be implemented urgently. They should be customized to the specific coffee areas and the expected changes there. High-resolution land evaluations like this one may support stakeholders in this endeavor by giving an estimation of not only the expected change in overall suitability for coffee cultivation but also of the single component changes that showcase what factors adaptation measures need to target to be most effective.

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## Declarations

**Conflict of interest** The authors declare no competing interests.

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