Chapter 42
Predicted Impact of Climate Change on Coffee Supply Chains

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Abstract Global circulation models all forecast that climate change will increase mean temperatures and change precipitation regimes. As a result, traditional coffee growing regions may disappear and new regions may appear. At the same time, demand for high quality, responsibly sourced coffee continues to grow globally. For sustainable sources of coffee, participants in the global coffee supply chain need to know where coffee will grow in the future and how the suitability of these areas will change over time. With this information, the supply chain then needs to develop appropriate site-specific mitigation and adaptation strategies for both the short and the long term, to guarantee coffee supply as well as to support improved livelihoods for rural communities. In this paper, we firstly quantify the impact of climate change on the suitability of land to grow coffee in a case study in Nicaragua and on acidity content of beverage coffee in a case study in the Veracruz Department of Mexico. Secondly, we propose site-specific adaptation strategies and finally identify critical potential impacts of climate change on the overall supply chain and the implications for all actors in the system. We conclude the paper by identifying key directions for future research to seek mitigation and adaptation strategies at both the community and the supply-chain level.

Keywords Adaptation · Climate change · Coffee · Spatial modelling · Supply chains

Introduction

The global climate has changed over the past century and is predicted to continue changing throughout the twenty-first century. Global circulation models (GCMs) all point in the direction of higher mean temperatures and changes in precipitation

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regimes. Both indicate that there will be a drastic shift in current land use and crop suitability, in addition to general increases vulnerability to climate variability. Climate change, including changes in the baseline and increased variability and frequency of extreme events, will affect agricultural productivity, farm incomes, and food security (Fischer et al. 2002; Mata and Nobre 2006; Busuioc et al. 2007; Lobell et al. 2008; Battisti and Naylor 2009; UNFCCC 2007). The predicted changes in future climates have the potential to expose agricultural systems to conditions and extremes not experienced before. The impacts are likely to vary across geographical regions and between different agricultural systems. Some of the climate changes could have beneficial effects, while others are likely to be detrimental.

Many farmers continuously vary their annual crops, selecting them based on criteria including sustenance, market dynamics, productivity, and cultural preferences. In view of the short growth cycle of annual crops, in many cases substitutions can be made with a minimum of cost. Farmers therefore have the capacity to make changes that will likely outstrip the speed of climate change. It is noteworthy that market factors alone drive changes in cropping systems at a considerable rate, which in itself is both a problem and an opportunity. Whilst attention needs to be paid to adapting annual cropping systems to future changes in climate, we believe that more urgent action is required to address these issues as they apply to high-value perennial cropping systems. Cash crops such as coffee may also have large impacts on national economies: for example, they are the largest contributors to agricultural GDP in Latin America. In Nicaragua, coffee produces 14.3% (MAG-FOR 2006) of agricultural GDP. In Mexico, coffee production is considered as a strategic activity, since it is grown on 664,800 ha, giving labour to 700,000 families (ICO 2005). Coffee systems are characterized by requiring longer-lead times for both farmers and business partners to make changes. In these cases, decisions made today come to fruition in 8–15 years, when the climate is likely to have changed.

Laderach et al. (2008) predicted that climate change will shift the altitude range for coffee to higher elevations over time, with the optimal altitude shifting from 1,200 m at present to 1,400 m in 2020 and 1,600 m in 2050 in Central America. This scenario generates different impacts at different altitudes, with the winners being smallholders at altitudes currently too high for the production of speciality grade coffees and the losers those farmers currently at the lower viable bounds for production of speciality coffee. As part of this process, the viability of some of the most celebrated origins in the speciality coffee market today, including Antigua, Guatemala, and Las Segovias, Nicaragua, will be put at risk.

It is essential for vulnerable smallholder farmers, whose livelihoods will be most affected by climate change, to understand its likely impacts and develop strategies to adapt. Understanding the implications of these changes is also critically important to all stakeholders in the value chain. To ensure the livelihoods of millions of smallholder farmers and related rural industries, it is crucial to identify adaptation pathways for these production systems or identify opportunities for diversification into other high-value crops.

In this paper, we firstly quantify the impact of climate change on the suitability of land to produce coffee in a case study in Nicaragua, and on the acidity content of coffee in a case study in the Veracruz Department of Mexico. Secondly, we propose site-specific adaptation strategies, and finally, we identify critical potential impacts of climate on the overall supply chain and their implications for all actors in the system. We conclude the paper by identifying key directions for future research seeking mitigation and adaptation strategies at both the community and the supply-chain level.

Methodology

Evidence Data and Sampling Design

All the current coffee-growing areas in Nicaragua were mapped by Valerio-Hernandez (2002) using aerial and satellite imagery. The map shows that the coffee-producing areas range from altitudes of 100–2,000 masl. According to experts of CAFENICA, the principal regions that produce *Coffea arabica* lie between 500 and 1,400 masl. Below 500 masl, growers usually produce *Coffea robusta* and there are few coffee farms above 1,400 masl. We extracted the geographical coordinates of coffee farms in the 3,155 polygons that represent the Nicaraguan coffee zone, at 30 arc-sec spatial resolution (approximately 1 km). We obtained a total of 6,192 coordinates, of which 1,129 were for farms below 500 masl and 144 for farms above 1,400 masl. To avoid the introduction of noise due to *Coffea robusta* species or farms whose altitudes were not representative, we only used sites in the range 500–1,400 masl, a total of 4,919 coordinates.

In Veracruz, we used the data of the denomination of origin project conducted by the University of Chapingo (Pérez-Portilla et al. 2005). The sampling design was based on a selection of a statistical subset of the total population of farms. The coffee-producing regions of de Atzalan, Misantla, Coatepec, Huatusco, Córdoba, Tezonapa, and Zongolica, which represent 93% of the total producers of the state of Veracruz, were taken as the entire population of farms. Considering the number of farms per municipality and the project's limited budget, approximately one-thousandth part of the farms were sampled, a total of 73. A panel of seven cuppers in the cupping laboratory of Café-Veracruz, A.C., assessed the quality of the samples of coffee from each farm according to the Specialty Coffee Association of America SCAA standards.

Historical Climate Data Collation

Historical climate data were obtained from the WorldClim database (Hijmans et al. 2005a, www.worldclim.org). WorldClim data were generated at a 30 arc-sec spatial resolution (1 km) through an interpolation algorithm using long-term average

Table 42.1 Bioclimatic variables with their coefficients of variation (CV) of 16 GCM models for Nicaragua and 17 GCM models for Veracruz. The CV indicates the variation between models (i.e. the greater the CV the more variability between GCMs)

ID	Variable	CV % Nicaragua	CV % Veracruz
Bio1	Annual mean temperature	2	2
Bio2	Mean diurnal range (Mean of monthly (max temp–min temp))	3	7
Bio3	Isothermality (Bio2/Bio7) ($\times 100$)	3	4
Bio4	Temperature seasonality (standard deviation $\times$ 100)	11	8
Bio5	Maximum temperature of warmest month	2	3
Bio6	Minimum temperature of coldest month	4	5
Bio7	Temperature annual range (Bio5–Bio6)	3	6
Bio8	Mean temperature of wettest quarter	3	2
Bio9	Mean temperature of driest quarter	2	4
Bio10	Mean temperature of warmest quarter	2	2
Bio11	Mean temperature of coldest quarter	3	3
Bio12	Annual precipitation	17	5
Bio13	Precipitation of wettest month	7	5
Bio14	Precipitation of driest month	55	53
Bio15	Precipitation seasonality (coefficient of variation)	8	7
Bio16	Precipitation of wettest quarter	10	5
Bio17	Precipitation of driest quarter	33	35
Bio18	Precipitation of warmest quarter	23	26
Bio19	Precipitation of coldest quarter	45	26

monthly climate data from weather stations. Variables included are monthly total precipitation, and mean monthly minimum and maximum temperatures. Hijmans et al. (2005a, b) used data from stations for which there were long-standing records, calculating means of the 1960–1990 period, and included only weather stations with more than 10 years' data. The database consists of precipitation records from 47,554 locations, mean temperature from 24,542 locations, and minimum and maximum temperature for 14,835 locations.

The data on which WorldClim is based in Nicaragua come from 277 stations with precipitation data, 218 stations with mean temperature data, and two stations with minimum and maximum temperatures. In the Department of Veracruz the analyses are based on 332 stations with precipitation data, 65 stations with mean temperature data, and 49 stations with minimum and maximum temperature.

The WorldClim database also includes 19 bioclimatic variables (Table 42.1) that are derived from monthly temperature and rainfall values to generate more biologically meaningful variables (Busby 1991). These variables are often used in ecological niche modelling (e.g. BIOCLIM, GARP). They represent annual trends (e.g. mean annual temperature, annual precipitation), seasonality (e.g. annual range in temperature and precipitation), and extreme or limiting environmental factors (e.g. temperature of the coldest and warmest month, and precipitation during the wettest and driest quarters).

We generated climate surfaces for each bioclimatic variable of Nicaragua and Veracruz from the original WorldClim dataset, and from them we used Arc/Info (ESRI, 9.2) to extract the data corresponding to each of the study farms.

Future Climate

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) was based on the results of 21 global climate models (GCMs), data of which are partially available through the IPCC website (www.ipcc-data.org.ch). The spatial resolution of the GCM results is, however, inappropriate for analysing the impacts on agriculture as in almost all cases the grid cells are 1 arc-degree (more than 100 km a side). This is especially a problem in heterogeneous landscapes such as those of the Andes, where, in some places, one cell can cover the entire width of the range.

Downscaling is therefore needed to provide higher-resolution surfaces of expected future climates if we are to forecast the likely impacts of climate change on agriculture. Two approaches are available for downscaling (1) re-modelling climate change impacts using regional climate models (RCMs) based on boundary conditions provided by the GCMs; or (2) statistical downscaling whereby resolution is reduced using interpolation and explicit knowledge of the distribution of climate at a fine-scale. Whilst the use of RCMs is more robust from the perspective of climate science, it requires a large amount of re-processing. Moreover, RCMs are only available for a limited number of GCM models, which makes it realistic to include only one or two RCMs in any analysis. In the context of this project, the use of RCMs for only one or two GCMs would make it impossible for us to quantify uncertainty in the analysis, which we believe makes them inappropriate. We have therefore used statistically-downscaled data derived from the larger set of GCMs to produce 10-km, 5-km and 1-km resolution surfaces of the mean monthly maximum and minimum temperature and monthly precipitation. In all cases, we used the IPCC scenario SRES-A2a ("business as usual").

Specifically, the centroid of each GCM grid cell was calculated and the anomaly in climate was assigned to that point. The statistical downscaling was then applied by interpolating between the points to the desired resolution using the same spline interpolation method used to produce the WorldClim dataset for current climates (Hijmans et al. 2005a, b). The anomaly for the higher resolution was then added to the current distribution of climate (derived from WorldClim) to produce a surface of future climate. This method assumes that the current meso-distribution of climate will remain the same, but that regionally there will be a change in the baseline. Whilst in some specific cases this assumption may not hold true, for the great majority of sites it is unlikely that there will be a fundamental change in meso-scale climate variability.

Suitability Prediction

We reviewed several prediction models such as ECOCROP, DOMAIN, BIOCLIM, MAXENT and CaNaSTA to select the most appropriate model to use in the analysis. ECOCROP (Hijmans et al. 2005b) is a crop database, with a description of the growing environment for various crops. There is also a crop prediction model with the same name (Hijmans et al. 2005b), which uses parameters in the FAO database to predict areas suitable for specific crops. ECOCROP is a very useful model for situations where there is no evidence data available for specific crops and one is forced to use environmental ranges instead. The results, however, are very general in nature and they can only be used to describe overall trends.

DOMAIN (Carpenter et al. 1993; Hijmans et al. 2005b) and BIOCLIM (Busby 1991) are fairly good models for conditions where evidence data are available. The algorithms used for both models are simple and tend to reduce and average the evidence information. The results are much more specific than the results for ECOCROP but are still rather general.

Maximum entropy (MAXENT) is a general-purpose method for making predictions or inferences from incomplete information. The idea is to estimate a target probability distribution by finding the probability distribution of maximum entropy, subject to a set of constraints that represent (one's) incomplete information about the target distribution. The information available about the target distribution often presents itself as a set of real-valued variables, called "features", and the constraints are that the expected value of each feature should match its empirical average ("average value for a set of sample points taken from the target distribution", Phillips et al. 2006). Similar to logistic regression, MAXENT weights each environmental variable by a constant. The probability distribution is the sum of each weighed variable divided by a scaling constant to ensure that the probability value ranges from 0 to 1. The programme starts with a uniform probability distribution and iteratively alters one weight at a time to maximize the likelihood of reaching the optimum probability distribution.

Crop Niche Selection in Tropical Agriculture, CaNaSTA (O'Brien 2004), employs Bayesian statistics. Bayesian methods provide a "formalism for reasoning under conditions of uncertainty, with degrees of belief coded as numerical parameters, which are then combined according to rules of probability theory" (Pearl 1990). A simple Bayesian model defines prior and conditional probability distributions and combines these to calculate posterior probabilities for each possible outcome. The probability distributions may be derived from data, be set by experts, or defined from a combination of data and expert opinion. The CaNaSTA algorithm, in addition to predicting presence or absence of a specific crop, also appraises its performance, and in the case of coffee, it predicts specific beverage attributes.

MAXENT is generally considered to be the most accurate model (Elith et al. 2006; Hijmans and Graham 2006) and we selected it for the analyses of the Nicaragua study after an initial iteration analysis in the study region using the

other four niche models (ECOCROP, DOMAIN, BIOCLIM, MAXENT). We used CaNaSTA for the analyses in Veracruz to predict the impact of climate change on coffee quality. CaNaSTA had been used previously in many agricultural applications including for coffee (Atzmanstorfer et al. 2006; Laderach et al. 2006a, b).

Projected climate conditions for the period 2040 to 2069 ("2050s") were initially derived from the 18 most reputable Global Circulation Models (GCM) used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007; http://www.ipcc-data.org). As explained below, (NCAR-PCM1 and BCCR-BCM2.0) were excluded in Nicaragua and one model (NCAR-PCM1) in Veracruz after initial runs showed that their predictions diverged strongly from those of the other models and the analysis was repeated based on the remaining models.

Future suitability predictions were then assessed through each of the GCM models via the software MAXENT (Phillips et al. 2006) and two measurements of uncertainty were computed (1) the agreement among models calculated as percentage of models predicting changes in the same direction as the average of all models at a given location, and (2) the coefficient of variation (CV) among models.

As mentioned, the initial analysis using 18 GCMs revealed that the predictions of NCAR-PCM1 differed strongly in Nicaragua and Veracruz and BCCR-BCM2.0 differed strongly in Nicaragua from those of the other models. According to these models, the suitability of coffee would increase by the 2050s. These predictions were significantly different from those of the other models according to Tukey's (1977) outlier test. Based on these tests, the two models in Nicaragua and one model in Veracruz were removed from the final analysis.

In MAXENT, we applied the logistic function, which gave us estimates between 0 and 1 of the probability of the presence in the climate change scenario. In CaNaSTA, we applied the score analysis, which gives an estimate between 0 and 1 probability of producing high quality coffee for the acidity indicator, which is important to the denomination of origin for specialty coffees in Veracruz. The results were overlaid with a filter of certainty of 80%, so that only results where CaNaSTA predicted over 80% probability were used.

Driving Environmental Variable Analysis

To determine the environmental variables that directly drive suitability, we conducted a step-wise forward regression. First, we calculated the change in climate and suitability for each of the coordinates. We calculated the change (difference) by subtracting the future climate (2050) from the current climate for each of the bioclimatic variables, and the suitability predictions. Applying a step-wise forward regression, each variable was added one at a time to the analyses to determine its importance in the change in suitability.

Results and Discussion

Predicted Climate Change in the Coffee Zones of Nicaragua and Veracruz (Mexico)

The most representative GCMs (16 in Nicaragua and 17 in Veracruz) of AR4 for the SRES-A2a (business as usual) emission scenario drew a trend of decreasing precipitation and increasing temperature for coffee-producing regions both in Nicaragua and in Veracruz by 2050 (Fig. 42.1). Total annual precipitation is predicted to decrease from 1,740 to 1,610 mm in Nicaragua and from 1,990 to 1,870 mm in Veracruz, while the maximum number of dry months stay constant at 5 months in Nicaragua and increase from 5 to 6 months in Veracruz. The mean annual temperature increases by 2.2°C in Nicaragua and Veracruz, while the mean daily temperature range rises from 10.4°C to 10.6°C in Nicaragua and from 10.8°C to 11.4°C in Veracruz.

With regard to extreme conditions, maximum temperature of the hottest month is predicted to increase from 28.8°C to 31°C in Nicaragua and from 29.1°C to 31.9°C in Veracruz, while the warmest quarter will get hotter by 2.3°C in Nicaragua and by 2.4°C in Veracruz. The minimum temperature of the coldest month is predicted to increase from 14.4°C to 16.4°C in Nicaragua and from 11.5°C to 13°C in Veracruz, and the coldest quarter will be 2.1°C hotter in Nicaragua and 1.8°C in Veracruz. The wettest month is predicted to be somewhat drier with 270 mm instead of 280 mm in Nicaragua and with 360 mm instead of 370 mm in Veracruz, while in the wettest quarter the precipitation decreases by 60 mm in Nicaragua and by 42 mm in Veracruz. The driest month will be drier with 18 mm instead of 24 mm in Nicaragua and drier with 35 mm instead of 54 mm in Veracruz, while the driest quarter will be drier by 7 mm in Nicaragua and by 42 mm in Veracruz.
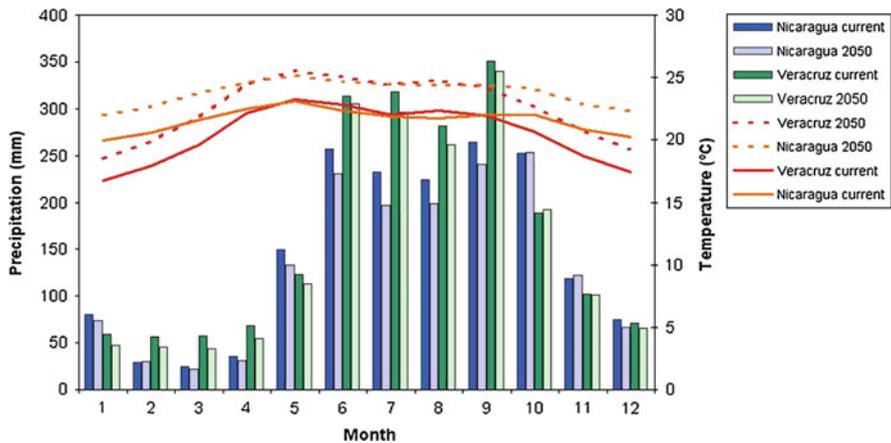

Fig. 42.1 Climate trend summary for current and future (2050) climate in Nicaragua and Veracruz

Overall, the climate will become more seasonal in terms of both variability through the year in temperature and in precipitation both in Nicaragua and in Veracruz. The predictions of the GCM models show a coefficient of variation (CV) of temperature of only 2.5% in Nicaragua and 3.8% in Veracruz, indicating uniform predictions between models with no outliers. The predictions of precipitation predictions have somewhat higher CVs, 9.9% for Nicaragua and 6.0% for Veracruz.

Impact of Climate Change on Coffee Suitability in Nicaragua

According to the MAXENT model, the most suitable coffee-producing areas in Nicaragua are currently Nueva Segovia, Jinotega, Madriz, Estelí, Matagalpa, Boaco, and smaller regions on the border of Masaya, Carazo, and Managua (Fig. 42.2). Their suitability is always between 50 and 80%. There are other areas in the same departments and in the departments of Atlántico Norte, Chinandega, León, and Chontales that are also suitable but at a lower degree (around 30–50%).
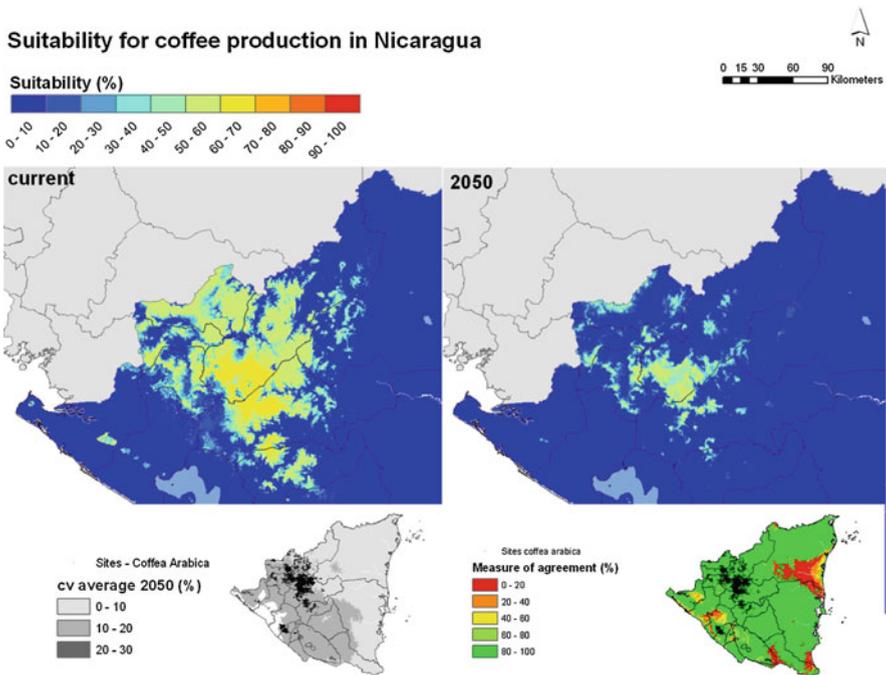
Fig. 42.2 Predicted (according to MAXENT) suitability for coffee production in the Nicaragua coffee-producing area today and in 2050 (*large maps*) and the coefficient of variation (CV) for the study area with the points representing the sampled *Coffea arabica* farms (*small map*)

MAXENT results indicate an important decrease in the suitability of coffee-producing areas in Nicaragua by 2050, equally distributed in areas that are highly and relatively suitable (Fig. 42.2). There is a general pattern of decreases in the area suitable for coffee and a decrease in suitability within these areas. Suitability for coffee will move upwards on the altitudinal gradient with climate change, with lower-altitude areas losing suitability the most. The areas that in 2050 will still be suitable for coffee production are mainly areas that currently show particularly high suitability. In 2050, the dominant area with suitability between 50 and 60% is in southern Jinotega, northern Matagalpa, and some other small areas in these departments. Areas with suitability between 30 and 50% will be in Nueva Segovia, on the border to Honduras, in Madriz, Atlántico Norte, and Boaco. The areas that will suffer the greatest loss of suitability loss (loss of 40–60%) are located in the departments of Nueva Segovia, Jinotega, Matagalpa, Boaco, and on the border of Carazo, Masaya, and Managua. The areas that lose least suitability (loss of 20–40%) are located in Estelí and Madriz. Some small areas that until 2050 will likely have an increase in suitability between 20 and 30% are located in Atlantico Norte, Estelí, Jinotega, and Madriz.

The coefficient of variation (CV) is a measure of the agreement between the bioclimatic variables produced by the different GCMs. CVs less than 20% are considered low. The mean CV of all bioclimatic variables for the 2050 predictions varies between 10 and 20% depending on the geographic location (Fig. 42.2, small grey map).

Currently 80% of the areas of the coffee producing departments in Nicaragua have a suitability of 0–40% to produce *Coffea arabica*, while 20% of the area shows a suitability of 40–100%. This means that only a fifth of the area is suitable for coffee production. By 2050, 96% of the area of the coffee producing departments in Nicaragua will have suitability of 0–40% and only the remaining 4% will have suitabilities of 40–100%. This means that the areas suitable for coffee production (suitability between 40 and 100%) will decrease by 16% and the areas no longer suitable for coffee production (suitability between 0 and 40%) increase by 16%. In other words, there will be substantial decreases in the total area suitable for coffee production.

According to MAXENT, with progressive climate change, areas at higher altitudes become more suitable for producing coffee (Fig. 42.3). We did not consider altitude as such in the suitability modelling so that we can consider it independently to forecast where coffee might migrate with climate change. Altitude and temperature have a fixed relation, called the lapse rate (0.6° per 100 m). The optimum coffee-producing zone in Nicaragua is currently at an altitude of elevation between 800 and 1,400 masl; by 2050, the optimum elevation will increase to 1,200 and 1,600 masl, which is consistent with the predicted temperature increase and the lapse rate. Between today and 2050, areas at altitudes around between 500 masl and 1,500 masl will suffer the greatest decrease in suitability and the areas above 1,500 masl the greatest increase in suitability. As the suitable altitude increases less and less land area to produce coffee will be available (Fig. 42.3, green line).

To develop adaptation strategies, it is important to know the most decisive climatic variables. Applying a step-forward regression analysis, we identified the
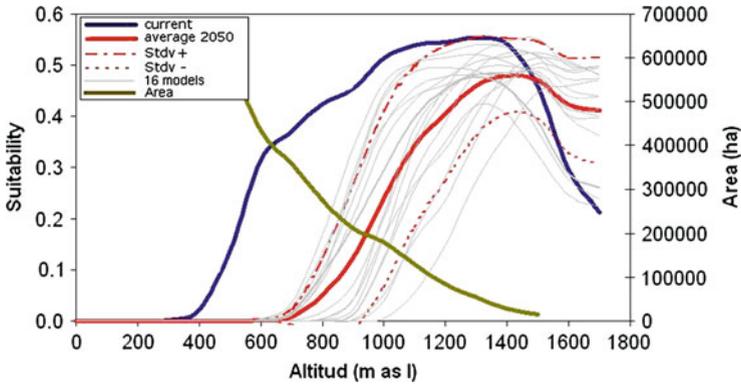
Fig. 42.3 Relation between current and future (2050) coffee suitability and altitude of coffee (*Coffea arabica*)

contribution of each of the 18 bioclimatic variables for the change in climate in the coffee-producing area. We analysed the sites predicted to increase in suitability separately from those predicted to decrease in suitability (Table 42.2). There were insufficient points predicted to increase in suitability to meet the requirements of the statistical tests, so it was not possible to determine the climatic variables for those sites. The most decisive climatic variable for the predicted decrease in suitability is the precipitation of the wettest month with a contribution of 42.8%, followed by the mean temperature of the warmest quarter with a contribution of 22%, the mean annual precipitation with a contribution of 8.8%, and the precipitation of the coldest quarter with a contribution of 6%.

Approximately 65% of the predicted decrease in suitability is due to precipitation-related variables. Overall, there is predicted to be less precipitation in the coffee-producing areas in Nicaragua by 2050. In the case of precipitation in the coldest and warmest quarters, there is not an absolute decrease predicted, which probably indicates an increase in evapotranspiration due to the increase in temperature and somewhat more water stress. Mean temperature of the warmest quarter contributes 22% of the variation. The remaining 35% contribution to the decrease in suitability is due to increasing temperature. The temperature variable that makes the highest contribution is mean temperature of the warmest quarter, which in Nicaragua is second quarter and falls together with the end of the dry season. This suggests that increased temperature and decreased precipitation imposes additional physiological stress on the plant, which it cannot resist.

Impact of Climate Change on Acidity Content in Veracruz

In Veracruz, the analyses focused on the sensorial attribute of acidity of the brewed coffee, which, together with aroma, is the most important attribute that distinguishes Veracruz coffee. The denomination of origin of Veracruz coffee is built on these two
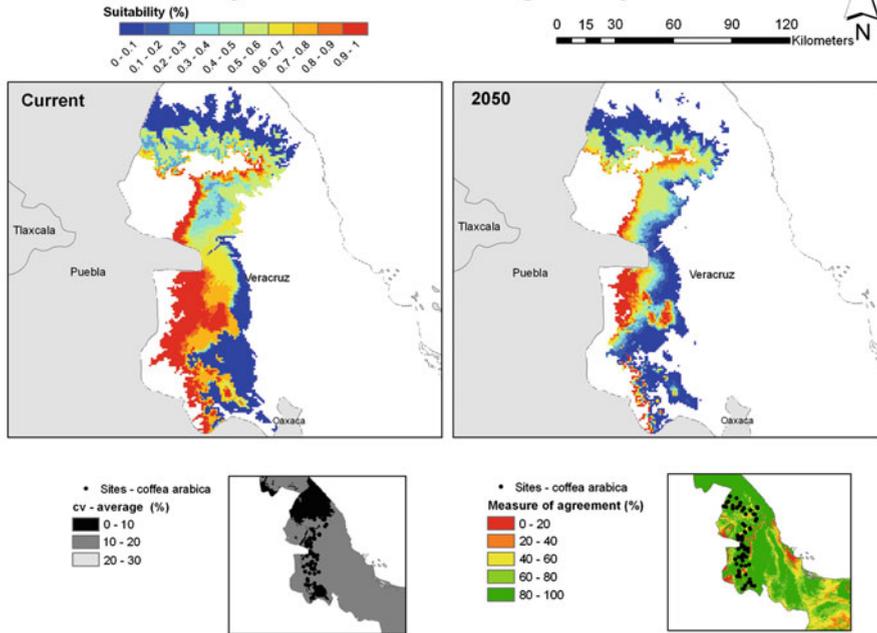
Table 42.2 Contribution of the different bioclimatic variables to the predicted change in suitability of *Coffea arabica* in the Nicaragua coffee-producing area

Variable	R^2 adjusted	R^2 due to variable	Percentage of total variability	Current mean	Change by 2050
Locations with decrease in suitability (n = 4902, 99.8% of total observations)					
BIO13 – Precipitation of wettest month	0.2591	0.2591	42.8	279 mm	−10 mm
BIO10 – Mean temperature of warmest quarter	0.3924	0.1333	22.0	22.6°C	+2.3°C
BIO12 – Annual precipitation −132 mm	0.5862	0.0532	8.8		1,742 mm
BIO19 – Precipitation of coldest quarter	0.4287	0.0363	6.0	192 mm	+23 mm
BIO4 – Temperature seasonality	0.5123	0.0326	5.4	935	+111
BIO16 – Precipitation of wettest quarter	0.4797	0.0192	3.2	759 mm	−55 mm
BIO18 – Precipitation of warmest quarter	0.4605	0.0184	3.0	428 mm	+21 mm
BIO6 – Minimum temperature of coldest month	0.4421	0.0134	2.2	14.4°C	+1.9°C
BIO17 – Precipitation of driest quarter	0.5330	0.0119	2.0	88 mm	−7 mm
BIO5 – Maximum temperature of warmest month	0.5971	0.0109	1.8	28.8°C	+2.2°C
BIO8 – Mean temperature of wettest quarter	0.5211	0.0088	1.5	21.9°C	+2.4°C
BIO9 – Mean temperature of driest quarter	0.6001	0.0030	0.5	21.4°C	+2.1°C
Others	0.6054	0.0002	0.8		
Total variability explained		0.6054	100.0		

characteristics. According to the CaNaSTA analysis, the areas currently suitable to produce coffee berries with high acidity in Veracruz are located northward along the mountain chain from Zongolica in the south through Córdoba and in the regions of Tlaltetela to Atzalan in the north (Fig. 42.4). At higher altitudes towards the west lie the areas with the highest suitability (70–100%) running from Córdoba in the south up to Coatepec in the north. Descending the altitudinal gradient to the east towards Gulf of Mexico, suitability for producing coffee with high acidity falls to low to medium (20–40%). Between Tlaltetela in the centre and Atzalan in the north, there is the same east-to-west pattern of increasing suitability towards higher altitudes. Overall, the southern parts of Veracruz are less suitable for the acidity characteristic.

CaNaSTA predicts that by 2050 the areas with higher suitability will decrease drastically and the highly suitable areas for the acidity characteristic will move towards higher altitudes. Between Tlaltetela in the centre and Atzalan in the north, areas that are currently suitable to produce coffee with high acidity will become limited, although areas at higher altitudes may become more suitable by 2050. In the southern part, between Zongolica and Tlaltetela, the areas that are highly

Fig. 42.4 Predicted (>80% certainty according to CaNaSTA) production suitability for coffee beans with high acidity content in Veracruz for current and 2050 conditions (*large maps*) and the coefficient of variation (CV) for the study area with the coordinates of the sampled *Coffea arabica* farms (*small map*)

suitable are predicted to decrease and move to higher altitudes. The north will maintain areas of high, medium, and low suitability, whereas in the south, areas of both high and low suitability will predominate.

The mean CV for all bioclimatic variables for the 2050 predictions varies between 0 and 10% (Fig. 42.4, grey map). This indicates that there is very little variability between the GCMs for Veracruz and one can be confident in the predictions.

Currently, CaNaSTA predicts, with a certainty above 80%, that 45% of the coffee areas in Veracruz have a suitability of only 0–40% to produce *Coffea arabica* with high acidity contents, while 55% of them will have a suitability of 40–100%. This means that rather less than half of the area is suitable to produce of high-acidity coffee. By 2050, 77% of the area of the coffee producing departments in Veracruz will have suitability between 0 and 40% and only the remaining 23% will have a suitability of 40–100%. This means that the areas suitable for high-acidity coffee will decrease by 32% and the unsuitable areas will increase by 32%. That is, there will be a substantial decrease in the areas suitable areas to produce high-acidity coffee.

As climate change progresses, areas at higher altitudes will become suitable for producing high-acidity coffee (Fig. 42.5). The optimum coffee-producing elevation

for high-acidity beans is currently above 1,100 masl, but by 2050, the optimum elevation will increase to above 1,600 masl. Between today and 2050, areas at altitudes between 900 masl and 1,500 masl will suffer the highest decrease in suitability while the areas above 1,800 masl will have the highest increase in suitability. As the suitable altitude increases less and less land area to produce coffee will be available (Fig. 42.5, green line) (Table 42.3).
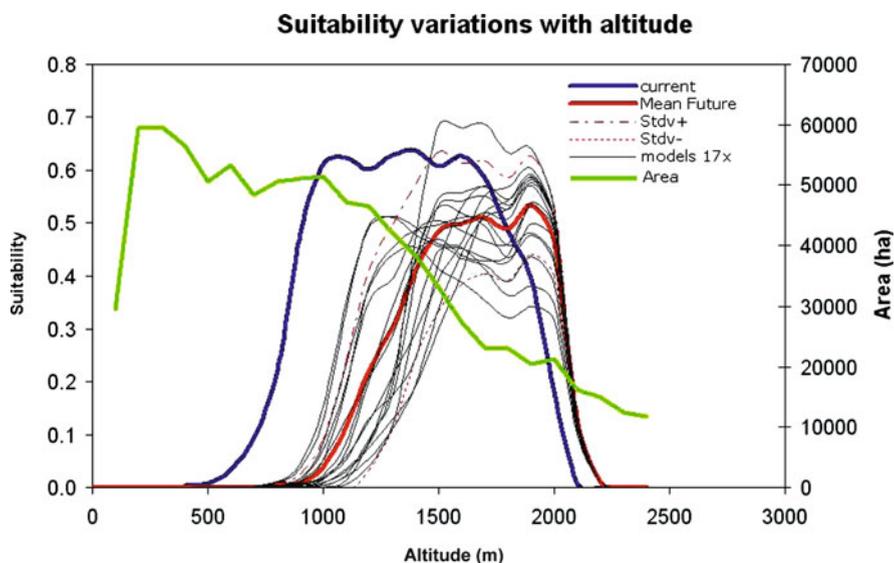

Fig. 42.5 Relation between current and future (2050) coffee acidity and altitude of the coffee

Table 42.3 Contribution of the different bioclimatic variables to the predicted change in production for *Coffea arabica* beans with high acidity content in the Veracruz coffee-producing area

Variable	R^2 adjusted	R^2 due to variable	% of total variability	Current mean	Change by 2050
Locations with decrease in suitability (n = 73, 100% of observations)					
BIO9 – Mean temperature of driest quarter	0.4400	0.4400	68	18.2°C	2.5
BIO8 – Mean temperature of wettest quarter	0.5436	0.1036	16	21.9°C	2.3°C
BIO5 – Max temperature of warmest month	0.6025	0.0589	9.1	29°C	2.8°C
BIO2 – Mean diurnal range	0.6229	0.0204	3.2	10.8°C	5.7°C
BIO6 – Min temperature of coldest month	0.6470	0.0158	2.4	11.4°C	1.4°C
BIO19 – Precipitation of coldest quarter	0.6312	0.0083	1.3	187 mm	−20 mm
Total variability explained		0.6470	100.0		

Close to 100% of the decrease in suitability is due to variables related to temperature. According to the climate predictions, temperature will increase in the coffee-producing areas in Veracruz by 2050. Mean temperature of driest quarter is the major driving variable accounting to 68% of the total variation and precipitation of coldest quarter the only precipitation related factor. The coldest quarter coincidences with the main harvest period. We therefore conclude that increasing temperature and decreasing precipitation have an overall negative impact on acidity content of coffee beverage. A statistically significant relation between elevation – which is a proxy for temperature – and acidity had been observed previously in the Orosi coffee-producing area in Costa Rica (Avellino et al. 2005).

Implications for Coffee Supply Chains and Possible Adaptation Strategies

Thus far we have focused on the impact of climate change at the farm level. From a livelihood and rural development perspective, this is critical. However, coffee farmers in Nicaragua and Veracruz do not operate in isolation, but rather as participants in multi-actor supply chains that link tropical countries with global coffee markets. A full assessment of the implication of climate change to implement effective mitigation strategies needs to include both on- and off-farm actors and the often substantial investments they have made.

At a supply-chain level, two general areas of climate effects emerge (a) the absolute capacity of the regions to produce coffee and (b) the quality of the coffee produced. Both topics have important implications in terms of infrastructure investments, the role of specific actors, the selection of target market niches, and the identification of key areas for research, investment, and policies in the future. The changes in the suitability of a particular area to grow coffee are site-specific because each site or area has its own very specific environmental conditions. In Nicaragua, according to the MAXENT prediction, by 2050 there will be areas that lose 40–60% of their suitability (e.g. the departments of Nueva Segovia, Jinotega, Matagalpa, Boaco), while others only lose 20–40% of their suitability (e.g. areas in the departments of Estelí and Madriz), and there are some small areas that may even become more suitable (e.g. areas in Atlántico Norte, Jinotega, and Madriz).

The first step in adaptation is to reduce the vulnerability of the coffee farmers to climate change. In this regard, use of technical "no regret" measures that strengthen the resilience of the system (e.g. sound agronomy, sustainable management of natural resources) will be beneficial to growers and their livelihoods and may also minimize the effects of climate change.

The solution to site-specific changes is site-specific management. In areas that will become unsuitable to grow coffee, farmers will need to identify alternative crops. In areas that will remain suitable for coffee but with some reductions in

suitability, agronomic management might be adapted to buffer the impacts of climate change. Drought resistant varieties, irrigation, and shade cover, which can decrease average temperatures by up to 4°C (Vaast et al. 2006), are all useful practices that can be implemented. Areas where coffee is not grown today, but which in the future will become suitable for coffee, need strategic investments to develop coffee production. Environmental viability needs to be taken into account, since higher altitudes are often forest reserves that provide environmental services to the lowland population and to agriculture.

In regions that may be forced to abandon coffee, existing supply-chain actors need to think carefully about what their role in this transition may be. There are substantial investments in coffee processing and drying facilities but it might be possible to use some of these facilities for other, non-coffee, crops that are better adapted to projected future climates. In addition to physical infrastructure, many coffee-growing regions boast a highly qualified and specialized group of business services focused on coffee. If they continue to specialize in coffee, they will need to adapt and move to other regions, or, if they choose not to move, they will need to begin to work on other crops. This combination of physical and human capacity is a current strength of coffee-growing areas and may well be leveraged to help identify and promote a planned transition to other income sources.

A second major area of climate change impact is coffee quality. Coffee quality is assessed by what is known as "cup quality", where coffee samples are scored by tasters on a 0 to 100 point index based on taste and aroma characteristics (Lingle 2001). For example, the denomination of origin, which provides a price premium for Veracruz coffee, is built on the high acidity content and the distinct aroma of the coffees produced there. As climate changes, the areas in which coffee of this quality can be produced are projected to decline. This, too, has implications for market actors. Some actors may decide to leave the region altogether while others may struggle to find ways to continue to differentiate the Veracruz product on other factors. Taking a long-term view, the strategic challenges for the entire coffee supply chain with regard to climate change are:

- If possible, how best to shift infrastructure, knowledge, andkey capacities from current growing areas towards emerging growing areas
- How to identify and strategically develop alternative crops and livelihood opportunities for producer communities, regions, and countries that provide a viable option to increasingly marginal coffee production
- How to adapt marketing strategies and niche selection currently based on quality differentiation to other characteristics or find other suitable coffee areas
- How to make these transitions work in terms of logistics and processing capacities

None of these questions can be answered easily, and all will require effective collaboration among chain actors as the climate changes and coffee markets continue to evolve.

Successful adaptation of the coffee chain in the face of climate change will require more investment in building collaborative networks, sharing knowledge more widely and making shared strategic investments merely to stay in business. The current structure of the conventional coffee chain is not conducive to these kinds of decisions with the notable exceptions of examples of transparency in small, specific differentiated niches or high-quality niches. In the future, the use of methods such as farmer field schools and other collective learning vehicles focused on multi-actor climate adaptation around specific issues of productivity or quality will be needed. Recent collaboration between the Kenya Tea Development Agency, Unilever, and the Rainforest Alliance on how to promote sustainable tea production with more than 500,000 tea farmers provides one potential model from which to build (Hiller et al. 2009).

Despite the potential to establish successful adaptation strategies between specific buyers and producer organizations, the major challenge is how to generate collective action across the chain to find lasting solutions to these global issues in the coming years. The coffee chain as such needs to become more aware of the potential effects of climate change on the entire system and find ways to encourage strategic research and adaptation strategies at different scales. The data presented in Nicaragua and Mexico show that time is relatively short and the stakes are high.

Determine Risk and Opportunities at Farm Community Level

The AdapCC initiative has developed a participatory methodology of risk and opportunity analysis (ROA) to identify site-specific vulnerabilities of smallholders and possible adaptation pathways (Schepp et al. 2008). The methodology used the climate scenarios of the present study and estimated possible losses and damage for smallholder families as a consequence of climate variability.

The ROA process seeks to identify adaptation strategies at local level. In so doing, the approach aims to develop, test, and implement these site-specific adaptation strategies to support small-scale farmers' future production and their livelihoods.

We have shown that by 2050, Nicaragua will lose between 20 and 60% of the areas that are currently suitable to grow coffee. The ROA process identified the climate risks that smallholder producers already perceive as threats are extreme weather events, increasing temperatures and less rainfall causing droughts, and increased pressure from pests and diseases. All these factors subsequently lead to declining yields and fruit quality, and lower incomes (Schepp et al. 2008). Through the ROA analysis, farmers identified immediate no-regret measures such as (1) improved agro-forestry management to reduce the effect of higher temperatures and water scarcity; (2) capacity building to increase coffee growers' awareness of climate change and promote improved management, (3) foster the compilation

and evaluation of climate data to monitor the impact of climate change on coffee in their specific region.

Key Future Research Directions for Community and Chain-Level Mitigation and Adaptation Strategies

The results we present here show potentially drastic changes in the suitability for coffee production in the study regions in Mexico and Nicaragua. Thousands of smallholder farmers depend on coffee for their income, and the likely societal impacts in these regions are particularly worrying as the coffee industry (from production, including the support of a large labour market, through to rural service providers and local and regional buyers and exporters) is an important component of the local economy. Outside of the region, this will have implications on coffee prices, and the global supply of beans, especially for the gourmet market.

This study suggests that there are a number of actions required, on both research and in terms of enabling the affected communities to adapt. In terms of research, we suggest a number of further refinements and additional research components that require attention:

- Our models only take into account the climate; research should also include constraints of soils, pests, and diseases
- Analyses need to be expanded to include economic impact analyses, using general equilibrium models, which take into account possible substitute crops, and incorporate livelihood components including also analysis of the impacts on gender and diversity
- Besides climate, there are many other important factors that drive change such as markets, social and cultural preferences, and policies that should be incorporated into the modelling
- Regional climate models (RCMs) could be used to improve the certainty of future climate scenarios and
- The use of multi-stakeholder learning mechanisms to identify, test and scale up appropriate adaptation strategies in coffee growing regions tied to a greater sector-wide understanding of the potential impacts of climate change

Despite a number of research questions that remain unresolved in our analysis, the results nevertheless suggest the need to use these results to establish adaptation measures for the communities that will be affected. The impacts demonstrate that areas suitable for coffee will decrease substantially by as soon as 2020. Production investments in coffee have a 10–15 year time horizon, hence farmers and other chain actors today should be making decisions based on long-term scenarios of change, such as those demonstrated here.

In areas that will be negatively affected, the first stage of adaptation will involve agronomic interventions that buffer the negative impacts, including change of

varieties and the establishment of shade trees (including fruit trees, other tree crops, and timber species). The latter may form the basis for a transition towards crop substitution in areas where particularly severe negative impacts are predicted within the next 15 years, thus providing a seamless adaptation strategy that moves producers out of coffee. National and sub-national policies should be put in place to provide site-specific recommendations, and incentives for enabling adaptation. These may include provision of shade planting material, and promotion of agronomic practices through technical extension services. Attention should also be paid to the entire supply chain rather than focusing only on the production system. Coffee provides multiple employment and secondary income opportunities in rural areas, and hence entire societies must adapt. Despite uncertainties attached to the analyses, the results merit careful consideration, and action in the region to address the challenges we have identified.

Conclusions

This paper predicts severe impacts of climate change on both overall suitability for coffee production in Nicaragua, and coffee beverage quality in the Mexican department of Veracruz by 2050. Due to the long lead-time of perennial cropping systems and the complexity of global supply chains for coffee, it is urgent to identify appropriate adaptation strategies. These strategies must operate locally but be connected with the global supply chain. Farmers will need to develop site-specific adaptation strategies tailored to their environments, while other supply chain actors will need to invest more in building collaborative networks, sharing knowledge more widely and making shared strategic investments merely to stay in business. Researchers must better integrate climate science with analyses of economic, environmental and social impact. These will be needed on regional, national, and local scales to quantify the impact of climate change on relevant social, economic and environmental variables that lead to the development of appropriate adaptation pathways.

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