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Abstract: The mountain chain of the Sierra Madre de Chiapas in southern Mexico is globally significant for its biodiversity and is one of the most important coffee production areas of Mexico. It provides water for several municipalities and its biosphere reserves are important tourist attractions. Much of the forest cover outside the core protected areas is in fact coffee grown under traditional forest shade. Unless this (agro)forest cover can be sustained, the biodiversity of the Sierra Madre and the environmental services it provides are at risk. We analyzed the threats to livelihoods and environment from climate change through crop suitability modeling based on downscaled climate scenarios for the period 2040 to 2069 (referred to as 2050s) and developed adaptation options through an expert workshop. Significant areas of forest and occasionally coffee are destroyed every year by wildfires, and this problem is bound to increase in a hotter and drier future climate. Widespread landslides and inundations, including on coffee farms, have recently been caused by hurricanes whose intensity is predicted to increase. A hotter climate with more irregular rainfall will be less favorable to the production of quality coffee and lower profitability may compel farmers to abandon shade coffee and expand other land uses of less biodiversity value, probably at the expense of forest. A comprehensive strategy to sustain the biodiversity, ecosystem services and livelihoods of the Sierra Madre in the face of climate change should include the promotion of biodiversity friendly coffee growing and processing practices including complex shade which can offer some hurricane protection and product diversification; payments for forest conservation and restoration from existing government programs complemented by private initiatives; diversification of income sources to mitigate risks associated with unstable environmental conditions and coffee markets; integrated fire management; development of markets that reward sustainable land use practices and forest conservation; crop insurance programs that are accessible to smallholders; and the strengthening of local capacity for adaptive resource management.

Response to Reviewers: Major revisions of the paper have been made following the guidance provided by the reviewer:

1) The paper has been shortened through elimination of some non-essential detail, especially in the introduction and the discussion of the adaptation options.

2) The methods section has been expanded through a more detailed explanation of the public participation process and of the analytical process. Substantial statistical analysis of the variability among different Global Circulation Models has been added. We now present confidence intervals of 15 GCMs in the maps of predicted future coffee suitability and also a map showing the agreement among models in Figure 3. We also show the prediction of coffee suitability by altitude for individual models, in addition to mean and confidence intervals. Error bars have also been added to the climate diagrams to reflect the variability among GCMs. We also explain in the Methods section why the use of 17 bioclimatic variables (some of which may be auto-correlated) is preferable when using MAXENT: it allows to retain the full set of information on bioclimatic requirements of coffee over the year, while the reduction of these variables to a smaller set of orthogonal variables might have led to loss of information and complicated the interpretation of the results. Moreover, MAXENT has been found to be relatively insensitive to overfitting.

3) The discussion of the adaptation options has been shortened, a Table summarizing the options has been added, and two non-essential figures (photos) have been deleted.

We hope and trust that these revisions adequately address the reviewer's concerns.

*Page with Personal Information

Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico

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Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico

Abstract

The mountain chain of the Sierra Madre de Chiapas in southern Mexico is globally significant for its biodiversity and is one of the most important coffee production areas of Mexico. It provides water for several municipalities and its biosphere reserves are important tourist attractions. Much of the forest cover outside the core protected areas is in fact coffee grown under traditional forest shade. Unless this (agro)forest cover can be sustained, the biodiversity of the Sierra Madre and the environmental services it provides are at risk. We analyzed the threats to livelihoods and environment from climate change through crop suitability modeling based on downscaled climate scenarios for the period 2040 to 2069 (referred to as 2050s) and developed adaptation options through an expert workshop. Significant areas of forest and occasionally coffee are destroyed every year by wildfires, and this problem is bound to increase in a hotter and drier future climate. Widespread landslides and inundations, including on coffee farms, have recently been caused by hurricanes whose intensity is predicted to increase. A hotter climate with more irregular rainfall will be less favorable to the production of quality coffee and lower profitability may compel farmers to abandon shade coffee and expand other land uses of less biodiversity value, probably at the expense of forest. A comprehensive strategy to sustain the biodiversity, ecosystem services and livelihoods of the Sierra Madre in the face of climate change should include the promotion of biodiversity friendly coffee growing and processing practices including complex shade which can offer some hurricane protection and product diversification; payments for forest conservation and restoration from existing government programs complemented by private initiatives; diversification of income sources to mitigate risks associated with unstable environmental conditions and coffee markets; integrated fire management; development of markets that reward sustainable land use practices and forest conservation; crop insurance programs that are accessible to smallholders; and the strengthening of local capacity for adaptive resource management.

Key words: adaptive resource management; *Coffea arabica*; coffee quality; crop suitability modeling; livelihoods diversification; MAXENT; natural disaster

Introduction

Over the next decades, the southern Mexican state of Chiapas will increasingly be affected by global climate change, though not quite as severely as the Yucatán and parts of southern Mesoamerica (Anderson et al. 2008; IPCC 2007). The predictions of global circulation models used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (IPCC 2007) concur that temperatures will increase and most models agree in predicting that rainfall will decrease in at least part of the region. The coastal region of Chiapas has repeatedly been affected by natural disasters including hurricanes and droughts over recent years (Saldaña-Zorilla 2008) and there is a consensus that the frequency and/or intensity of such events is likely to increase further in the future (IPCC 2007; Elsner et al. 2008; Webster et al. 2005).

In the mountain chain of the Sierra Madre de Chiapas (Fig. 1), high biodiversity and the provision of important ecosystem (especially hydrological) services for the surrounding lowlands coincide with a predominant land use – the cultivation of coffee (*Coffea arabica*) under shade – that may be severely impacted by climate change over the next few decades. In Mexico, coffee growing practices are not as intensive as in some other countries in Latin America (e.g. Guhl 2006). Moguel and Toledo (1999) estimated that still between 60 and 70% of the coffee areas in the country are under traditional management with relatively high levels of shade created by the canopy of a variety of shade tree species (Fig. 2). Numerous studies have established the important role that traditional coffee agroforests with complex shade canopies can play as wildlife habitat (e.g. Perfecto et al. 1996, Soto-Pinto et al. 2001, Philpott et al. 2008a), for pollination, pest control, erosion control, and other important ecosystem services (Perfecto et al. 2004, Soto-Pinto et al. 2000, Armbrecht and Gallego 2007; Philpott et al. 2008b). Recognizing the importance of traditional shade coffee systems for biodiversity and ecosystem integrity in the Sierra Madre, organizations including Rainforest Alliance, Smithsonian Migratory Bird Center and Conservation International have promoted shade use and other conservation measures, such as water, soil and forest protection, on coffee farms in this region over the past 15 years, with strong support and encouragement from the reserve administration (Comision Nacional de Areas Protegidas - CONANP).

[Figure 1 here]

[Figure 2 here]

The livelihoods of coffee dependent communities and the role played by coffee agroforests in the conservation of biodiversity and ecosystem integrity are now under threat. Studies from coffee regions in Mexico, Guatemala and Honduras indicate that temperatures have increased by 0.2 to 1°C and in some cases rainfall has declined by up to 15% over the last 2-3 decades (Richter 2000; Castellanos et al 2003; Baker and Haggar 2007; Haggar 2008). Some of the drier coffee regions in Mesoamerica may cease producing coffee by the end of the century (Baker and Haggar 2007; Haggar 2008). The threat to the coffee agro-ecosystem is compounded by the stress to livelihoods associated with participating in the global coffee market. Lin et al. (2008) pointed to the mutually reinforcing stresses of climate change and market forces that together have led to the simplification of many coffee production systems in the region. They argue that farmers who depend largely on a single crop (such as coffee) have less ability to cope with periodic crop failure than farmers who use traditional, more diversified farming systems. Eakin et al. (2006) discuss how smallholder coffee farmers in Mesoamerica have been adapting to volatile and declining prices and institutional change especially since the collapse of the International Coffee Agreement in 1989, highlighting the important fact that climate change is only one among several stressors to which coffee farmers need to continuously adapt. Indeed, coffee farmers still tend to perceive climate risks as less urgent than those posed by market volatility (Eakin et al. 2005; Gay et al. 2006). Saldaña-Zorilla (2008) observed that subsistence farmers in Mexico have increasingly adopted off-farm strategies such as emigration and urban employment to cope with climate and market risks. In the Sierra Madre, an exodus of smallholder farmers caused by decreasing coffee profitability could lead to the replacement of a farming landscape dominated by traditional shade coffee by cattle pasture and more intensively managed coffee or other monocultures – land use changes that already seem to be underway in Colombia (Guhl 2006).

Because of the ecological importance, the long history of coffee production and its importance for smallholder livelihoods, and the strong linkages between land use and environmental conservation in the Sierra Madre de Chiapas, understanding the vulnerability of this region to climate change and developing ecosystem based adaptation options are particularly urgent tasks that could have a model character for mountain regions elsewhere. In the following sections we analyze current climate change scenarios for the Sierra Madre for the reference period 2040-2069 (further referred as 2050s). Based on a crop suitability model, published and ongoing studies and a stakeholder workshop that involved representatives from several local government agencies, the coffee sector, communities, conservation and scientific organizations, we discuss the range of potential impacts of climate change on coffee production, the communities dependent on it, and the repercussions that climate change driven land use change would have on the ecosystems of the Sierra Madre and other mountain regions in Mesoamerica. We identify adaptation options to increase the resilience of communities and ecosystems to climate change as well as research needs. While the paper focuses on the Sierra Madre de Chiapas, we draw on information from other parts of Mexico and Central America, and many of our conclusions can be locally adapted to be relevant to mountain ecosystems in Latin America more generally.

Site and methods

Site

The Sierra Madre de Chiapas is a largely forested mountain chain that separates the plains of Soconusco along the Pacific coast from the Central Valley where the state capital of Tuxtla Gutierrez is situated. Most of the chain is included in protected areas (Fig. 1), including the biosphere reserves La Sepultura (167,310 ha), El Triunfo (119,177 ha) and Volcán Tacaná (6,378 ha), the Forest Reserve La Frailescana (181,350 ha) and the State Reserve Pico de Loro El Paxtal (60,982 ha). The highest elevations are 2550 m in La Sepultura, 2750 in El Triunfo, and 4092 m in Volcán Tacaná at the border with

Guatemala (Fig. 1). The Sierra Madre is characterized by high biodiversity and species endemicity, hosting more than 2000 species of plants and at least 600 species of terrestrial vertebrates (Carabias et al. 1999 a,b). The Sierra Madre is also an important water catchment area for surrounding towns and agricultural plains. La Sepultura and El Triunfo Biosphere Reserves are divided into strictly protected core zones and buffer zones where agriculture and other land uses are permitted although forest conversion is prohibited. The core zones occupy 8.4% of La Sepultura and 21.6% of El Triunfo (Fig. 1). In the year 2000, the three biosphere reserves had a combined population of 27,454 the majority of which lived in the buffer zones (INEGI 2000).

Commercial Arabica coffee production began in the Sierra Madre about 120 years ago with German immigration (Richter 2000). The Sierra Madre now produces about 20% of the coffee of Chiapas (COMCAFE, pers. comm.) and is one of Mexico's most important coffee regions. Although an accurate map of coffee farms in the Sierra Madre does not exist, in part due to the difficulty of distinguishing heavily shaded farms from natural forest on satellite images (Fig. 2), a plot of coffee farm locations illustrates the importance of this land use at elevations above 500 m especially in the south-eastern part of the area, centered on El Triunfo and La Frailescana Biosphere Reserves (Fig. 3a). In mid-elevation (600-1400 m) areas, coffee accounts locally for up to 98% of the land cover (Philpott et al. 2008b). Cattle pasture has a longer history in the area than coffee and is more important at lower elevations and in the drier north-east (La Sepultura).

[Figure 3 here]

The degree of shading on the coffee farms of the Sierra Madre varies widely from heavy shade by forest remnant trees to uniform, planted shade on the more intensively managed farms. Unshaded coffee farms are rare (Philpott et al. 2008b). Preliminary data from a survey of 318 smallholder (< 5 ha) coffee farms suggest that farmers actively manage shade in response to a variety of pressures, including labor scarcity, economic needs and climatic variability (H. Eakin et al., unpublished).

Climate change scenarios

Projected climate conditions for the Sierra Madre for the period 2040 to 2069 ("2050s") were initially derived from the 17 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, two models (NCAR-PCM1 and BCCR-BCM2.0) were excluded after initial runs showed that their predictions diverged strongly from those of the other models and the analysis was repeated based on the remaining 15 models. The predictions for three available CO_2 emission scenarios were similar for the 2050s. Here we use the A2a scenario which assumes an increase of CO_2 levels that is above average but below the worst case scenario A1F1. A statistical downscaling method was applied to these data to produce 1 km resolution surfaces of the monthly means of maximum and minimum temperature and monthly precipitation. This method involved interpolating between the centroids of the GCM grid cells with the same spline interpolation method that was used to produce the WorldClim dataset for current climates (Hijmans et al. 2005) and adding the predicted climate anomaly for the respective grid cell to the WorldClim data points. This method assumes that the relative climate distribution will remain constant despite a change in the average climate for each GCM grid cell. Present climate is defined in the WorldClim database as the average climate between 1950 and 2000.

Crop suitability modeling

A total of 19 bioclimatic variables were generated by each GCM, describing the mean and extreme conditions of the future climate (Hijmans et al. 2005; Table 1). Each variable was averaged over the initially 17, then in the final analysis 15 GCMs to generate a mean climatic scenario as input to the software MAXENT (Philipps et al. 2006) in order to predict the shift in suitability for coffee production in the Sierra Madre resulting from climate change. The use of average predictions over several models, as in this paper, has been found to reduce uncertainty due to the cancellation of offsetting errors in the individual GCMs (Pierce et al. 2009). One variable, the precipitation of the driest month, was excluded because of its very high CV among GCMs, and because another variable, the precipitation of the driest quarter, is likely to contain very similar climatic information for the study region (Table 1). Although the remaining 17 bioclimatic variables are not independent of each other, we used the complete set of variables in the analysis because (1) they are useful to provide the best possible description of the climatic requirements of coffee over the year, (2) some authors have indicated that MAXENT reduces the risk of overfitting through variable weighting as explained below (Phillips et al. 2006; Phillips and Dudik 2008; Hijmans and Graham 2006), and (3) the alternative approach of reducing the set of 17 bioclimatic descriptors to a set of orthogonal variables (Dormann 2006) might lead to loss of information and would have complicated the interpretation of the results. Future suitability predictions were then assessed through each of the 15 GCMs via the software MAXENT (Phillips et al. 2006) and three 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; (2) the upper and lower 95% confidence intervals (C.I.) around the mean suitability change using all 15 models; and (3) the coefficient of variation (CV) among models.

[Table 1 here]

MAXENT is generally considered to be the most accurate model for the prediction of shifts in suitable growth ranges of species (Elith et al. 2006). MAXENT produces suitability maps showing the probability of encountering a species (here *Coffea arabica*) in a given grid cell in the present and a future climate (see Fig. 3). Similar to logistic regression, MAXENT weighs each environmental variable by a constant. The probability distribution of the present or future occurrence of a species (here *Coffea arabica*) in an area is the sum of each weighted variable divided by a scaling constant to ensure that the probability values range from 0 to 1. The program starts with a uniform probability distribution and iteratively alters one weight at a time to maximize the likelihood of reaching the optimum probability distribution. With the MAXENT software (version 3.2.19, available at http://www.cs.princeton.edu/~schapire/maxent/) we first identified interactions between current locations of *Coffea arabica* and its climatic conditions in the Sierra Madre. These interactions were then projected for the 2050s with the corresponding climate surfaces from the 15 GCMs. We extracted 6629 current locations of Arabica coffee farms in the Sierra Madre and the nearby Central Highlands from the

COMCAFE database of the Government of Chiapas (www.comcafe.gob.mx), using only sites with an altitude above 500 m.a.s.l. to exclude Robusta coffee (*Coffea canephora*) which replaces Arabica coffee at lower altitudes.

In order to understand the relative importance of different climatic drivers, we then carried out a forward, step-wise regression analysis with the suitability shift per data point as the dependent variable and the 15-model average changes in the bioclimatic variables between the present and 2050s as the independent variables, and calculating the relative contribution of each variable to the total predicted suitability shift in terms of the proportion of R-square explained when adding each variable to the linear regression model. This analysis was carried out separately for the data points showing positive and negative shifts in suitability.

As mentioned, the initial analysis using 17 GCMs revealed that the predictions of two models, NCAR-PCM1 and BCCR-BCM2.0, differed strongly from those of the other 15 models. According to these two models, the suitability of the Sierra Madre for coffee as it is grown today would decline to almost zero across all altitudinal zones by the 2050s. These predictions were significantly different from those of the other models according to Tukey's (1977) outlier test and were mostly caused by more pronounced predicted temperature increases. Based on these tests, the two models were removed from the final analysis, but it should be kept in mind that if they were right, the impact of climate change on coffee production and producers in the Sierra Madre would be far more drastic than the data that we present in the following sections suggest.

Assessment of climate change impacts and development of an adaptation strategy

Given the high uncertainty associated with how projected climate impacts will be experienced in the region, and the complex interaction between social and ecological responses to climate change, we incorporated expert knowledge into our assessment of impacts and adaptation strategies. The use of expert knowledge in climate impact assessment has been shown to provide insights into human behavior in face of environmental change – such as the importance of non-climatic factors in decision-making, or synergistic interactions between social change and climate impacts – that often remain hidden when impact assessments are based on modeling alone (Lorenzoni et al. 2000). The possible impacts on production systems, livelihoods and ecosystems were thus assessed through a stakeholder workshop that brought together about 70 local, national and international experts with a range of disciplinary backgrounds, government officials, private sector representatives, representatives from conservation and development organizations, and representatives of coffee communities in Tuxtla Gutierrez in November 2008. In addition to the knowledge experts brought to the table, the workshop participants were provided with downscaled climate change scenarios for the different altitudinal bands of the Sierra Madre and findings from published and unpublished scientific literature (undertaken by the workshop organizers).

The experts were indentified from a broad range of disciplines, including social scientists working on climate change impacts on coffee communities in the Sierra Madre and other parts of Mesoamerica as well as crop modelers, coffee quality experts, agro-ecologists and biodiversity specialists. The workshop was structured around initial presentations of research results, followed by a series of synthesis exercises. These exercises involved the formation of breakout groups in which the experts specified the climate impacts that have been observed or are expected and their impacts on coffee production, communities and the environment. Subsequent breakout groups identified the primary social actors (e.g., farmers, private sector companies, government, non-governmental agencies) in the Sierra Madre region, and, from the basis of their experience, the most likely opportunities and constraints for adaptation. For each of these groups of social actors, the experts then prioritized opportunities for supporting adaptation.

Results and discussion

Climate change and its impacts on coffee communities

The climate models show an overall temperature increase of 2.1 to 2.2°C within the coffee zone of the Sierra Madre by 2050. Annual precipitation is predicted to decrease by approximately 80 to 85 mm, or 4 to 5% of present rainfall, at all three altitudinal ranges (Fig. 4).

[Figure 4 here]

The MAXENT model results predict a strong decrease in suitability for Arabica coffee of the Sierra Madre (Fig. 3b,c), resulting from decreasing suitability at altitudes below 1700 masl where almost all coffee is presently grown, and drastic decreases below 1100-1200 masl. Suitability would only increase at the highest altitudes where coffee production is now limited by low temperatures (Fig. 5). Within a total area of 2.36 million ha, the area of high suitability for Arabica coffee (>60%) is predicted to decrease from presently 265,400 ha to 6,000 ha and that of low suitability (<40 %) is predicted to increase from presently 1.57 million ha to 2.04 million ha, suggesting that the Sierra Madre may cease to be an origin of specialty coffee (Fig. 3). However, even these numbers still underestimate the true impact of climate change on coffee suitability because they presume that coffee farming can actually move further up the mountains. In practice this will often not legally be possible because of established land use and property rights, the ban on forest conversion in the biosphere reserves and, in part, the core protection status of the highest parts of the Sierra Madre (Fig. 1). While Figure 5 shows considerable variability among GCMs in suitability profiles across altitudes, the prediction of an overall decline of suitability of the area is highly robust (Fig. 3 d,e) with a high level of agreement among models on the general trends, especially the strong decline of coffee suitability at lower elevations (Fig. 3f).

[Figure 5 here]

The regression analysis identified primarily the bioclimatic variables related to temperature increase and decreasing rainfall during the dry season as drivers of the predicted negative suitability shifts at altitudes below 1700 m (Table 2). The increases in mean temperature of the driest quarter and maximum temperature of the warmest month explained together 49% of the negative suitability shifts and decreasing precipitation of the driest quarter explained another 11% of the negative suitability shifts, suggesting that the decrease in dry season rainfall combined with higher evaporative demand would lead to drought stress at lower altitudes. The positive suitability shifts at the highest altitudes of the present growth range of coffee, on the other hand, were mostly driven by a combination of decreasing rainfall in the cold, wet season (probably indicating a positive effect of more sunny days at these high altitudes with their typically cloudy weather), and increasing temperature (Table 2).

[Table 2 here]

Although the MAXENT model does not use any crop specific information other than the present location of coffee farms, the predicted shifts are in general agreement with what is known about the impacts of increasing temperatures and decreasing, more seasonal and possibly less reliable rainfall on Arabica coffee. In coffee, a higher ambient temperature (as in a warmer climate or at lower altitude) results in faster ripening of the berries which translates into poorer cup quality (Vaast et al. 2006). Presently, Arabica coffee is grown above approximately 600 m altitude in the Sierra Madre (Fig. 3) and is replaced at lower altitudes by (lower value) Robusta coffee, cattle pasture and food crops. At low altitudes, coffee yields are negatively affected by increasing average and especially maximum temperatures (Fournier and di Stéfano 2004; Gay et al. 2006). The predicted temperature increase of 2.1-2.2°C would mean that conditions that are now found at 600 m altitude would then occur at 850 to 900 m and lower lying coffee areas would become marginal and most likely be converted into other land uses.

Coffees that meet the high quality requirements of the more lucrative specialty markets are presently found mostly upward of 1000 m. This limit will also tend to move upward, resulting in lower prices for many coffee producers who will then lose access to these higher paying markets and will have to compete on commodity markets with low-cost producers in countries like Brazil and Vietnam (Gay et al. 2006), while specialty coffee markets may satisfy their demand increasingly in other, less affected producer countries. Although the conditions for growing coffee would improve at altitudes above 1700 m due to the temperature increase and reduced cloudiness, the area of existing coffee farms that would benefit from these changes would be quite small and the potential for coffee expansion at this altitude would be minimal (Fig. 3).

Coffee farmers would also be affected by lower annual rainfall which, together with higher temperatures, would lead to overall drier conditions (Fig. 4; Table 2). The relationships between precipitation and coffee production are however complex. Increasing atmospheric CO_2 concentrations tend to increase the water use efficiency of

C3 plants such as coffee and will tend to offset the increased evaporative demand, though experimental data on the relative magnitude of these effects with coffee are not available. Moreover, the phenology of coffee is strongly dependent on rainfall distribution (Gay et al. 2006; Lin et al., 2008) and could be affected by decreasing rainfall during critical periods for crop development. For example, coffee flowering is triggered by rainfall events of at least 7-10 mm at the onset of the rainy season. If rainfalls are then not sustained or too heavy rainfalls occur, both the coffee flower and fruit can drop from the tree. The reduced fruit growth then results in fewer, smaller beans of lower quality (and thus poor prices). Less reliable rainfall patterns at the onset of the rainy season would lead to erratic flowering and fruit ripening, requiring more harvesting cycles, thereby increasing production costs (P. Vaast, pers com.). Coffee harvesting already represents up to 80% of production costs in Mexico (Gay et al. 2006). Moreover, in a drier, hotter climate the water supply for the traditional wet processing of coffee will become sparser and more likely to be subject to regulation.

The changes in temperature and rainfall will also alter pest and disease pressures to which farmers will need to adapt their management practices. At lower altitudes, the fungal disease coffee rust (*Hemileia vastatrix*) may benefit from higher temperatures (Lamoroux et al. 1995). Higher temperatures will also allow the coffee berry borer (*Hypothenemus hampei*), which now causes little damage above 1500 to 1600 m, to expand its range upward (Gay et al. 2006; Baker and Haggar 2007). Where loss of profitability leads to abandonment or incomplete harvesting of coffee farms, a borer population could build up in un-harvested coffee berries and further increase the pest pressure in a positive feedback cycle.

Beside these more gradual changes in temperature and precipitation, several studies have predicted an increase in the frequency and/or intensity of extreme events, such as hurricanes and droughts, across Mesoamerica (IPCC 2007) and globally (Webster et al. 2005; Elsner et al. 2008). The coastal region of Chiapas has been affected by recurrent disasters, including hurricane Mitch in 1998 and hurricane Stan in 2005, which had devastating impacts on communities in the Sierra Madre, the latter causing thousands of victims, destroying coffee areas often irreversibly through landslides and causing soil erosion, flooding and damage to transport and processing infrastructure (Philpott et al.

2008b; Saldaña-Zorilla 2008). In Chiapas, Stan caused total economic damages estimated at 21 billion pesos, of which 3 billion pesos were in the agriculture sector (CENAPRED 2006) as well as a loss of 20% of the coffee harvest worth US$ 4 million to coffee cooperatives in the Pacific region of Guatemala (Baker and Haggar 2007; Haggar 2008).

While less spectacular than hurricanes, drought years affect coffee farmers not only through water scarcity and corresponding yield losses, but also through increased risk of wild fires. In the drought year 1998, a total area of 37,336 ha or 22% of the total area of La Sepultura was affected by wild fires, including 20% crown fires, destroying forest and coffee farms (CONANP et al. 2004). Dry season fires set mostly for pasture clearing and hunting are already a regular occurrence in La Sepultura (CONANP et al. 2004) and an overall hotter, drier climate with increased frequency of drought years would most likely alter the fire regime in the reserve. Conversions of coffee areas in response to decreasing profitability into regularly burned pasture or annual crops would reinforce this trend in a positive feedback cycle.

Finally, higher interannual variability in climate conditions and more climatic extremes, including an increased frequency or duration of El Niño events (Gergis and Fowler 2009), would also result in greater year-to-year fluctuations in quantity and quality of the coffee harvest. Such problems in production would negatively affect the ability of farmers and cooperatives to engage in and honor long-term sales contracts, possibly even affecting the viability of cooperatives if losses occur several years in a row. For example, in the dry Segovias region of Nicaragua that produces some of the best coffee of that country, farmers' profits fell from US$ 2,300 per hectare in the relatively wet (La Niña) year 2005-6 to US$ 600 per hectare in the subsequent dry (El Niño) year 2006-7 (Haggar 2008).

In summary, although climate change impacts will be differentiated by altitude and will further be modified by factors such as the position of coffee plantations on the rainfall gradient along the mountain chain from northwest to southeast, as well as by local topography and soil type, the overall trend will be for reduced revenue from diminished coffee quantity and/or quality, higher risk from drought, fire and rainstorms, increased costs for growing, harvesting and processing the coffee, as well as potentially higher cost of marketing coffee of more variable quantity and quality. In the absence of low-cost loans, small farmers in particular will have little capability to cope with these changes should they require investments in new coffee varieties, alternative crops, erosion and fire control, processing infrastructure, training and extension services to cope with new pest and disease pressures, and marketing stress. We might expect that social inequalities would widen and smallholder coffee farms be taken over by larger producers under such a scenario. Where unprofitable coffee farms are converted into other land uses, total coffee yield would decrease and employment opportunities for coffee workers, including many seasonal migrants, will be lost.

Impacts on the ecosystem

The predicted decrease in profitability and greater economic risk of coffee production may locally and temporarily have positive environmental impacts, but overall and over the longer term these impacts will likely be severe and negative. Many farmers will initially try to reduce production costs by using less labor, fertilizer and other inputs, similar to their responses to low coffee prices (Eakin et al. 2006). However, farmers who have the means to invest in new coffee varieties that are better adapted to a hot climate and have greater pest and disease resistance, water-saving processing infrastructure and increased erosion control will most likely attempt to recover their investments by increasing the overall management intensity of their coffee farms, reducing shade and increasing fertilizer levels. Also, while some unprofitable coffee farms may temporarily be abandoned, most will probably be converted into other land uses with the concomitant loss and fragmentation of (agro)forest habitat (Eakin et al. 2006; Hausermann and Eakin 2008). A dominant land use at lower altitudes and in the drier parts of the Sierra Madre is cattle pasture, and many communities currently have land use in both coffee and pasture. As coffee farming becomes more risky, such communities may expand livestock production, a way of adapting to weather and market related risks that has been observed elsewhere in Mexico (Eakin 2005). In Veracruz, some coffee communities producing at low altitudes responded to environmental and market stress by expanding their area under sugarcane (Hausermann and Eakin 2008). The loss of coffee areas at lower altitudes may also in some cases lead to increased demand for coffee land at higher elevations and thus increased pressure on forests there (Gay et al. 2006). Recent experience illustrates that coffee farmers in the Sierra Madre that were impacted by hurricane Stan tended to grow more food crops to increase their food security and were more likely to out-migrate than in average years (Eakin et al. 2008). As coffee incomes decrease, farmers may resort to illegal extraction of trees and non-timber forest products (e.g. *Chamaedorea* palm leaves) from community forests or even core protected areas, as has sometimes been observed at times of low coffee prices (CONANP, pers. comm.). The intensification or conversion of traditional shade coffee farms would negatively affect the biodiversity of the Sierra Madre, with most severe effects on amphibians and some reptiles that have very restricted distributions (Macip-Ríos and Muñoz-Alonso 2008). Landscape carbon stocks would decrease as carbon rich forest and shade coffee areas are converted into carbon poorer low shade, pasture and food crop systems. Where coffee farms are intensified or converted into food crops, increased erosion and fertilizer runoff may affect downstream water quality.

Elements of an adaptation strategy

In the absence of targeted adaptation measures, the predicted changes in temperature, rainfall and extreme events would have strongly negative effects on coffee production systems, the communities involved in it, and natural ecosystems in the Sierra Madre. The following sections outline elements of an adaptation strategy that the experts participating in the workshop believed would increase the resilience of communities, local institutions and ecosystems to extreme events, and strengthen their capacity to adaptively respond to gradual changes of a spatially and temporally differentiated climate with site adapted measures (Table 3).

[Table 3 here]

Carry out zoning according to risk and adaptation needs

The network of meteorological stations in Chiapas is relatively good (257 stations with precipitation data, 41 stations with mean temperature data, and 29 stations with minimum and maximum temperature) and should be used as a basis for the delineation of areas where different combinations of adaptation measures – such as erosion and pest control programs or change of coffee varieties – are indicated (Baker and Haggar 2007). Zones of low altitude where coffee will lose its viability regardless of adaptation measures and areas of steep slopes, valley bottoms subject to inundation and other sites where agriculture is becoming too risky given present and future patterns of extreme weather events should be identified and targeted for alternative livelihoods programs. The systematic analysis of meteorological information from various parts of the coffee region would also be an important input for crop insurance programs (see below). From interviews with farmers in the Sierra Madre and adjacent areas, Saldaña-Zorilla (2008) concluded that "most farmers want more public support for risk identification for house building and for cropping as, unlike in the past, they recognize their inability to forecast the increasingly variable climatic conditions in the region."

Make crop insurance available to small producers

While insurance is no substitute for adaptation, affordable crop insurance would help farmers to cope with increased frequency of extreme events such as hurricanes and droughts if accompanied by other measures to reduce their vulnerability to climate change. In recent years, the Mexican government has compensated farmers with a graduated payment for coffee commercialized below US$85/quintal (100 lb), which the agricultural ministry considers to be a threshold of economic viability for smallholder farmers (Eakin et al. 2006), thereby effectively providing an insurance for market volatility. Fair-trade or producer to consumer direct-trade programs are other ways to protect small farmers from low prices. On the other hand, the access for small farmers in the region to insurance for low coffee yields related to extreme weather events is very low (Saldaña-Zorilla 2008). The Mexican government withdrew from providing crop insurance (as well as credit and marketing services) in 1988, leaving these services to (more expensive) private providers and causing the insured crop area to fall from 40% in the 1980s to presently 10% (Saldaña-Zorilla 2008; see also Eakin 2000). The same author lists a number of government funds designed to reduce disaster risk in Mexico, but notes that these funds are practically unused in the Sierra Madre region despite high disaster susceptibility. He explains this paradox with "lack of state government coordination to apply for funding for preventive measures, together with insufficient organization among local leaders to demand them" and notes that farmers mostly rely on the assistance of relatives, neighbors and government, as well as emigration, to cope with disasters.

Test new coffee varieties

Baker and Haggar (2007) cite preliminary results of a consortium of research institutes including the Central American CATIE, PROMECAFE (Cooperative Regional Programme for the Modernization and Technological Improvement of Coffee Production) and the French CIRAD suggesting lower sensitivity of hybrids between local and Ethiopian coffee plants to a hotter, drier climate. These results require confirmation and field testing under a range of environmental conditions and management regimes across the region. Questions of access of Mexican producers to these new varieties are currently being discussed.

Promote traditional coffee shade

There are many reasons to promote the use of complex shade in coffee other than its important role as habitat for wild species (Lin et al. 2008). Across Mesoamerica, shade is used at low altitudes (i.e. 700-1000 m) to reduce excessive daytime temperatures. The widespread use of coffee shade in the Sierra Madre de Chiapas also at higher altitudes conveys some resilience to increasing maximum temperatures. Furthermore, Philpott et al. (2008b) showed that during hurricanes, farms with complex vegetation structure (rustic or traditional polyculture shade) had significantly smaller fractions of their farms affected by landslides compared with farms with a simpler vegetation structure (Fig. 6). As the frequency and severity of hurricanes increases, complex tree shade could be rewarded through reduced crop insurance premiums.

[Figure 6 here]

As especially in the second half of the 21st century the climate becomes increasingly drier, optimum shade management will become more complex and require research and monitoring. Ambiguous effects of shade on coffee yields during drought years have been observed elsewhere in Mesoamerica (Haggar 2008). Recent research on the effect of shade on coffee quality has also yielded complex relationships (Bosselmann et al. 2008), therefore programs to maintain and increase shade should be complemented by the testing and introduction of more drought and heat resistant coffee varieties (Baker and Haggar 2007).

Promote agricultural diversification

Lin et al. (2008) observe that increasing specialization on coffee as a single crop has made farmers more vulnerable to periodic crop failure. Diversification of crops is a strategy to reduce at the same time biological (e.g. pest outbreaks), market (i.e. price volatility) and climate risks, the latter especially if the different crops in a farming system have different susceptibilities to weather related factors. Planting alternative crops is a relatively common response by coffee farmers to low coffee prices; during the "coffee crisis", 28% of interviewed households in two communities in Veracruz reported adding an additional crop to their coffee based household economies (Eakin et al. 2006). The Mexican government now explicitly encourages crop diversification as a response to the coffee crisis, reversing its coffee policies of previous decades which encouraged specialization, although the precise incentives and technical support programs for diversification are not yet well defined (Eakin et al. 2006; Hausermann and Eakin 2008). A strategy of diversification of coffee farms should be pursued especially at lower altitudes (i.e. below about 900 m) where Arabica coffee will likely lose its viability as a crop over the next decades. However, recent top-down efforts to promote "reconversion" of coffee land to alternative uses in Veracruz have often met with failure (Hausermann and Eakin 2008), so efforts should be made to build on farmers' existing production knowledge and experience, and livelihood goals. Climatic conditions are suitable for a range of fruit trees, cocoa and Robusta coffee, though market potential and socioeconomic and environmental trade-offs have to be evaluated. At higher altitudes, farmers have fewer alternatives to coffee, especially for steep sites that require permanent soil cover. In La Sepultura Biosphere Reserve, a community enterprise for the production of *Chamaedorea* palm leaves for flower bunds, which like coffee are grown under forest shade, has been built up with support from the Global Environment Facility and now generates significant income, a strategy that is also being pursued successfully by coffee communities in Veracruz (Hausermann and Eakin 2008). Other communities and farms are complementing coffee incomes with the production of house plants including orchids and other flowers, and report that this income is often greater than their coffee income (S. Philpott, pers. obs.; H. Eakin, pers. obs.). Such alternative income opportunities (particularly those that also involve women more in the production process and strengthen their role in the rural society compared to the traditionally male dominated coffee system) are likely to expand and should be supported, especially through quality and supply chain management.

Another diversification option is the sustainable management of forest resources, focusing on the native pine forests of the Sierra Madre. The Mexican government already supports the development of management plans for production forests through CONAFOR, although there are no examples yet in the Sierra Madre. Research elsewhere in Mexico has shown that community forest management for production can be an effective forest conservation strategy (Ellis and Porter-Bolland 2008). Furthermore, environmental service payments from CONAFOR for carbon, watershed services or biodiversity for forest areas set aside by communities or individuals for conservation, and payments for the restoration of forest areas, can be seen as an additional diversification option (Muñoz-Piña et al. 2008). In a survey of 17 communities in La Sepultura Biosphere Reserve in late 2008/early 2009, 12 communities already received environmental service payments and/or support for fire control from the government but interest to solicit government support for additional conservation and restoration programs was identified in several communities (Conservation International Mexico, unpublished).

Restore degraded, flood-prone and ecologically sensitive areas

Hurricane Stan has destroyed extensive coffee and other farm areas in the Sierra Madre through landslides. Where most topsoil has been lost, these areas are not suitable for replanting coffee or other agricultural crops, but may still be able to support trees, including native pines which as pioneer species are well adapted to shallow, rocky soil. The same holds for farm land near rivers and in valley bottoms that was subject to flooding and where agriculture has become too risky under conditions of increasing hurricane frequency and intensity, creating opportunities for the restoration of riparian forests as corridors for species migrations and to reduce stream bank erosion and water temperatures (Pyke and Andelman 2007; Heller and Zavaleta 2009). Furthermore, there are still areas in need of restoration from the catastrophic fires of the El Niño year 1998 (CONANP, pers. comm.). As mentioned, government funds are available through CONAFOR to support reforestation but the small number of reserve management staff means that there is space for community based organizations and local NGOs to help affected communities and land owners to access these and support the implementation of restoration programs. Carbon markets offer additional funding options for restoration.

Develop and implement a comprehensive fire management plan

Wildfires are an important cause of forest loss in the Sierra Madre and will become an even greater threat to property and natural ecosystems in a future drier, hotter climate. Fires are usually set for hunting or clearing of pasture land and roadside vegetation but then spread uncontrolled (CONANP et al. 2004). The development and implementation of fire management plans is in many places a precondition for successful restoration projects. Although the Mexican government supports fire management through CONAFOR, few communities in the Sierra Madre have fire management plans and are organized and equipped to implement them (CONANP pers. comm.). This is another area where community based organizations and local NGOs could help close the gap between available government programs and their systematic implementation throughout the Sierra Madre.

Increase water efficiency in coffee production and processing

The wet processing of coffee on individual farms, as is common in the Sierra Madre, uses large amounts of water from natural water courses (Bello Mendoza 2002). Traditionally, the effluents with their load of organic residues are returned untreated, although several organizations have promoted the use of infiltration pits in the Sierra Madre. With decreasing runoff in a drier climate, the systematic use of such simple water protection measures will become even more essential. Mexican law now requires that water is returned to natural water bodies in the same condition as it has been extracted, prompting especially larger coffee farms to use processing technologies that require drastically reduced water volumes and produce much smaller amounts of waste water. Such technologies could be made accessible to smaller farmers through subsidized loans from government and private sector, as well as inclusion in the government's program of payments for watershed services. In Nicaragua, water-efficient coffee wet mills for small farmers have been developed that cost less than $1000 per mill (CAFENICA 2008).

Strengthen community organization and capacity building

The strengthening of community organizations and their integration into information exchange networks would facilitate group learning and decision making about natural resource management, including forest conservation and fire control, as well as crop diversification, the testing and adoption of new coffee varieties, and more effective product commercialization. In view of the greater variability in quantity and quality of coffee yields in the future, larger producer organizations and networks will be better able to honor commercial contracts and negotiate favorable terms and prices. Stronger farmer organizations could engage more effectively with municipal governments and micro-watershed councils on questions of their interest, including the design and funding of disaster prevention measures, livelihood diversification, marketing, and accessible crop insurance. Unfortunately, farmers in Mexico tend to have a negative perception of farmer organizations, associating them with fraud and political manipulation (Eakin et al. 2005, 2006), and such experiences and preconceptions need to be overcome by strengthening organizational capacity and documenting positive examples. Here again is a role cut out for community based organizations and local NGOs to support the development and adaptation process, with back-stopping from the national and international research and development community.

Conclusions

In the future, the coffee communities in the Sierra Madre de Chiapas and other parts of Mesoamerica will most likely be impacted by even more frequent and severe hurricanes and droughts than in the recent past. These natural disasters will be aggravated by a gradual increase in temperature and changes in rainfall that will make some areas unsuitable for coffee and will force producers in other areas to adapt to a new set of environmental conditions. In a pessimistic scenario, this adaptation process will lead to the emigration of many smallholder farmers, the large-scale abandonment of unprofitable shade coffee farms and expansion of regularly burned cattle pasture and fields of row crops at the expense of forest and shade coffee. Owing to a drastic reduction and fragmentation of (agro)forest cover, the Sierra Madre de Chiapas – and other (agro)forested mountain chains in Mesoamerica – may lose much of their biodiversity and environmental services along with the livelihoods of their traditional communities and their role as suppliers of high-quality coffee (Saldaña-Zorilla 2008).

In an optimistic scenario, communities will adapt to their changing environment with a variety of techniques. Depending on their specific circumstances, they may adopt coffee varieties that are less susceptible to high temperatures and drought or switch to other tree crops where coffee is no longer viable. They may continue to use or (where possible) increase structurally diverse tree shade in their coffee farms to reduce temperature extremes and hurricane damage. Water saving processing technologies may help them to cope with increased water regulation. They may protect their incomes from extreme weather events through subsidized crop insurance, diversification of their crops and the discontinuation of cropping on sites prone to flooding and landslides where they may restore natural forest with government support. And finally, they may maintain a portfolio of income sources including environmental service payments for forest conservation and restoration, sustainable forest management, and diversified agroforestry systems that provide income under variable weather conditions and habitat for the region's rich biodiversity. This scenario is more likely to occur with strong community organizations that favor group learning and information exchange and that facilitate the access to markets for a wider range of products and services. Such organizations will not be passive recipients of information and government programs, but will engage actively in the political discourse over development options with municipalities and other government agencies and form partnerships with NGOs and private sector. Although additional research is needed to inform climate change adaptation in the Sierra Madre and other coffee regions of Mesoamerica, this work should begin soon and involve all relevant stakeholders in mutually reinforcing partnerships (Agrawal 2008).

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Tables

Table 1: Bioclimatic variables used by MAXENT to predict the shift in suitability for Arabica coffee due to climate change between the present and the 2050s in the Sierra Madre de Chiapas, Mexico, and the coefficient of variation (CV) among the 15 Global Circulation Models used in the study

No.	Variable	CV%
BIO1	Annual mean temperature	2
BIO2	Mean of monthly diurnal temperature range	3
BIO3	Isothermality (BIO2/BIO7 * 100)	3
BIO4	Temperature seasonality (standard deviation *100)	11
BIO5	Maximum temperature of warmest month	5
BIO6	Minimum temperature of coldest month	4
BIO7	Temperature annual range (BIO5-BIO6)	3
BIO8	Mean temperature of wettest quarter	3
BIO9	Mean temperature of driest quarter	4
BIO10	Mean temperature of warmest quarter	2
BIO11	Mean temperature of coldest quarter	3
BIO12	Annual precipitation	6
BIO13	Precipitation of wettest month	5
BIO14	Precipitation of driest month	69*
BIO15	Precipitation seasonality (coefficient of variation)	7
BIO16	Precipitation of wettest quarter	7
BIO17	Precipitation of driest quarter	37
BIO18	Precipitation of warmest quarter	24
BIO19	Precipitation of coldest quarter	24

* BIO14 was excluded from the analysis owing to its high variability among the Global Circulation Models.

Table 2: Contribution of different bioclimatic variables to the predicted shift in suitability for *Coffea arabica* in the Sierra Madre de Chiapas, Mexico, between the present and the 2050s, separating locations with decreasing and increasing suitability[a]

Variable	Adjusted R^2	R^2 due to variable	% of total variability	Present mean	Change by 2050s
Locations with decreasing suitability (n=5846, 88.2% of all observations)					
BIO9 – Mean temperature of driest quarter	0.0866	0.0866	28.0	20.9 °C	+ 2.1 °C
BIO5 – Max temperature of warmest month	0.1515	0.0649	21.0	30.7 °C	+ 2.5 °C
BIO17 – Precipitation of driest quarter	0.2996	0.0332	10.7	99 mm	– 24 mm
BIO3 – Isothermality	0.1777	0.0262	8.5	71 %	– 2.4 %
BIO4 – Temperature Seasonality	0.1980	0.0203	6.6	1358	+ 251
BIO19 – Precipitation of coldest quarter	0.2137	0.0157	5.1	142 mm	+ 2 mm
Locations with equal or increasing suitability (n=783, 11.8% of all observations)					
BIO16 – Precipitation of wettest quarter	0.2003	0.2003	44.7	874 mm	– 51 mm
BIO19 – Precipitation of coldest quarter	0.3664	0.0798	17.8	213 mm	– 0.5 mm
BIO13 – Precipitation of wettest month	0.2866	0.0481	10.7	329 mm	– 13 mm
BIO8 – Mean temperature of wettest quarter	0.2385	0.0382	8.5	19.9 °C	+ 2.4 °C
BIO9 – Mean temperature of driest quarter	0.3957	0.0293	6.5	18.4 °C	+ 2.4 °C

[a] Variables explaining less than 5% of total variability are not listed.

Table 3: Overview of climate change adaptation options for the Sierra Madre de Chiapas, Mexico

Activity	Stressors to be addressed	Caveats
Carry out zoning of vulnerability and adaptation needs	Increased risk of extreme weather events, decreasing coffee suitability at lower altitudes	Uncertainty of climate models, especially in mountain environments
Promote crop insurance for small farmers	Increased risk of extreme events	Could in certain cases delay the adoption of necessary adaptation measures
Test/introduce coffee varieties with greater tolerance of high temperatures and altered pest/disease pressures	Temperature increase and its effects on coffee production and quality	Varieties are still in development and not readily available to Mexican producers
Promote structurally diverse coffee shade	Greater maximum temperatures, increasing risk of rainstorms and landslides	Complex relationships between shade and coffee under drought conditions, labor requirements for shade management
Promote diversification of land use systems and income sources, including payments for environmental services (PES)	Increased variability of coffee production and quality and increased risk of crop failure, interacting with market risks	Need to avoid prescriptive, top-down approaches, requires careful market analysis for new options, sustainable funding for PES
Reforest degraded and risk prone sites	Extreme weather events leading to flooding, landslides and fires	Small number of government staff to support projects, therefore need for institutional partnerships
Promote fire management	Increased fire risk	ditto
Increase water efficiency in coffee production and processing	Lower average rainfall, increased drought risk	Requires low-cost credit especially for small farmers
Strengthen community organization	Increased market risk related to greater variability of coffee production, changes to traditional livelihoods	Widespread negative perception of farmer organizations among farmers

Figures

colour figure

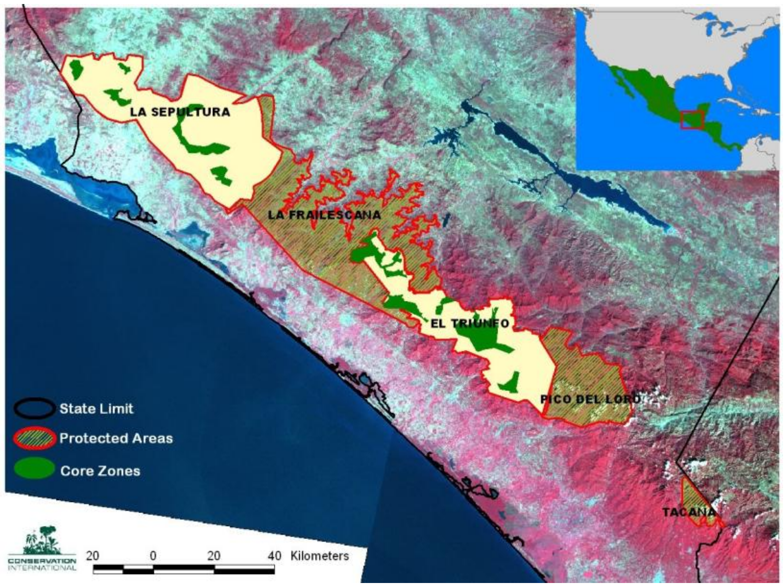

Figure 1: Protected area system of the Sierra Madre de Chiapas, Mexico

Figure 2

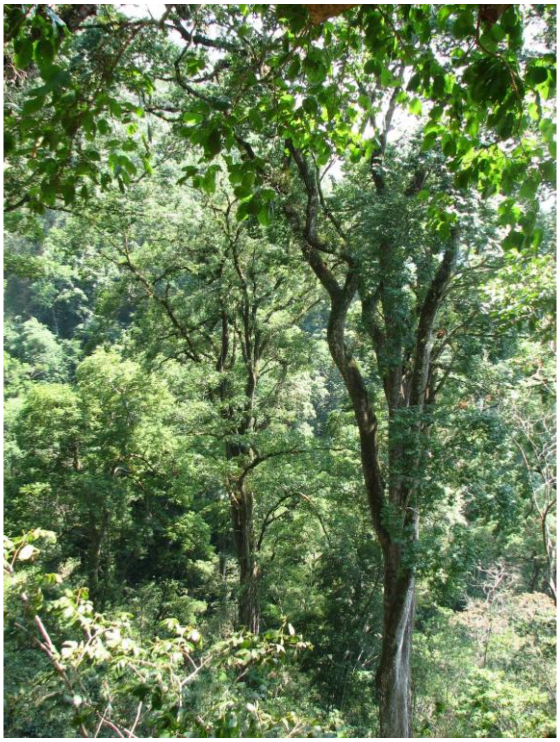

Figure 2: Coffee farm under forest shade in El Triunfo Biosphere Reserve, Sierra Madre de Chiapas, Mexico

Figure 3

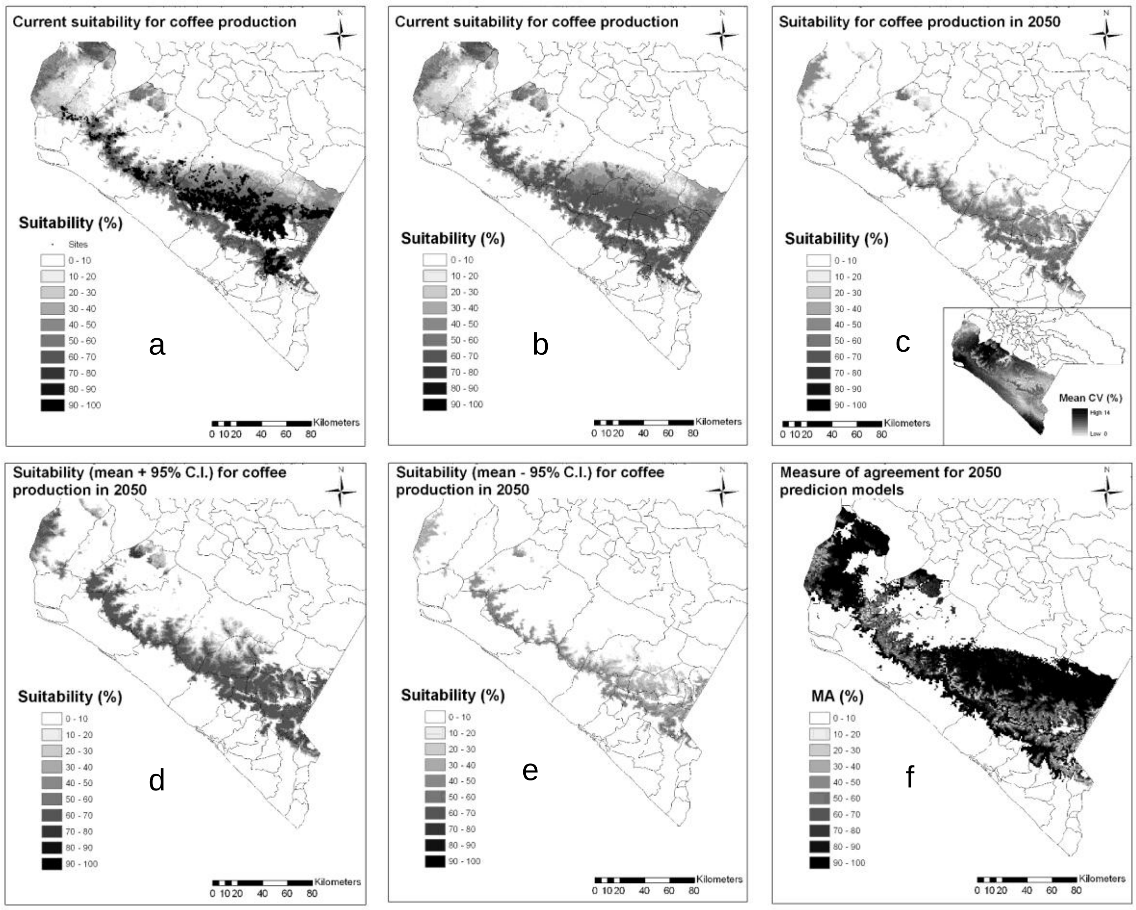

Figure 3: Change in the suitability for coffee production of the Sierra Madre de Chiapas, Mexico, from present to the 2050s, as predicted through MAXENT. The present climate is defined as the average climate between 1950 and 2000, and the 2050s climate as the average climate between 2040 and 2069. (a) Overlay of coffee farm locations with present suitability distribution; (b) present suitability distribution showing the probability of encountering coffee farms in a location based on the adjustment of a distribution model with 18 bioclimatic variables to the observed coffee farm locations; (c) modeled suitability distribution for the 2050s based on the distribution model and the predicted change in climate from 15 Global Circulation Models (GCMs). The inset shows the mean CV across the 15 models and 18 bioclimatic variables; (d-e) modeled suitability distribution for the 2050s plus and minus 95% confidence intervals of the mean as shown in figure c; (f) percent agreement between the suitability predictions of 15 individual GCMs and the mean of all 15 models.

Figure 4

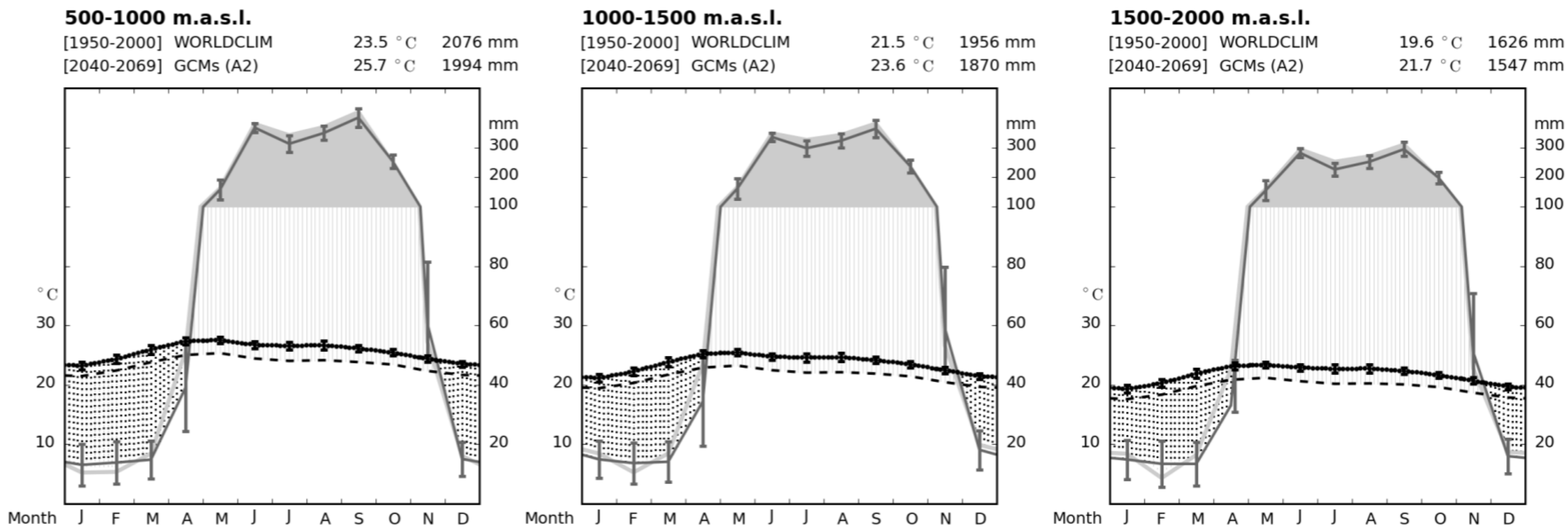

Figure 4: Climate scenarios of the Sierra Madre de Chiapas, Mexico, for the present and the 2050s for three altitudinal zones. The present climate is defined as the average climate between 1950 and 2000, and the 2050s climate as the average climate between 2040 and 2069. The climate diagrams of the current climate were derived from the WorldClim dataset (Hijmans et al. 2005) and overlaid with monthly means of future temperature and precipitation calculated from 15 GCMs. Bold black dashed lines represent current temperature, bold black dotted lines are projected temperatures in the 2050s. Light gray lines and polygons represent current precipitation, dark gray lines show future precipitation. Vertical lines are error bars calculated as plus or minus one standard deviation of the 15 GCM projections. The wet and dry seasons are indicated by the precipitation curve falling above or below the temperature curve, respectively.

Figure 5

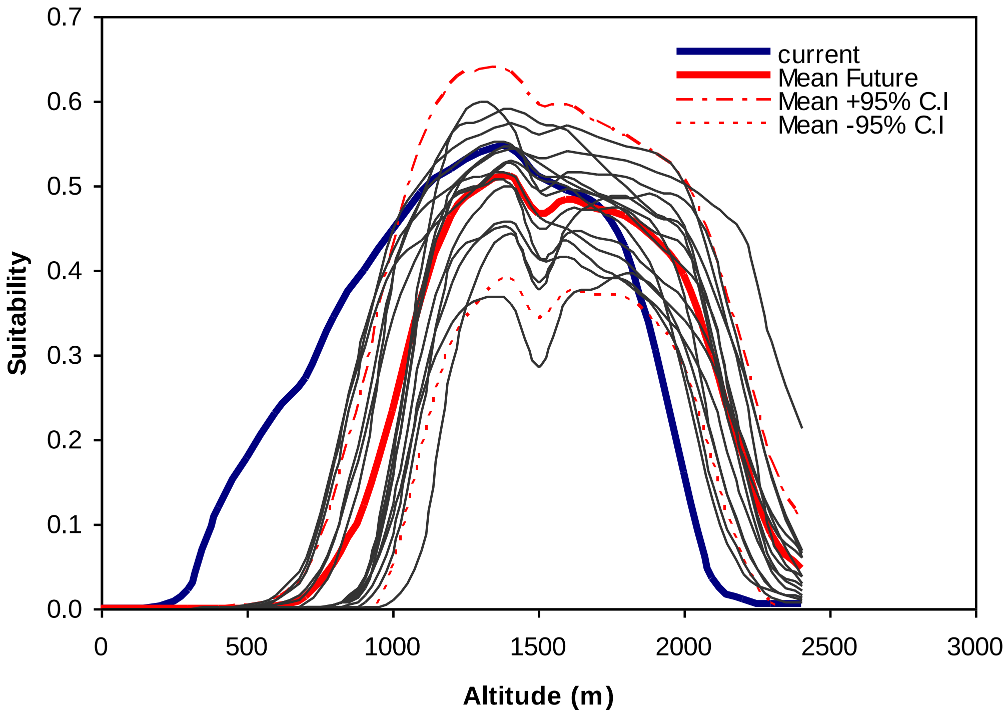

Figure 5: Altitudinal shift in suitability for Arabica coffee in the Sierra Madre de Chiapas, Mexico, as a result of climate change between the present and the 2050s as predicted by MAXENT using 15 Global Circulation Models (GCMs). The predictions of individual GCMs are shown as thin lines. The red lines show the mean and the 95% confidence intervals (C.I.) of the 15 models. The present climate is defined as the average climate between 1950 and 2000, and the 2050s climate as the average climate between 2040 and 2069.

Figure 6

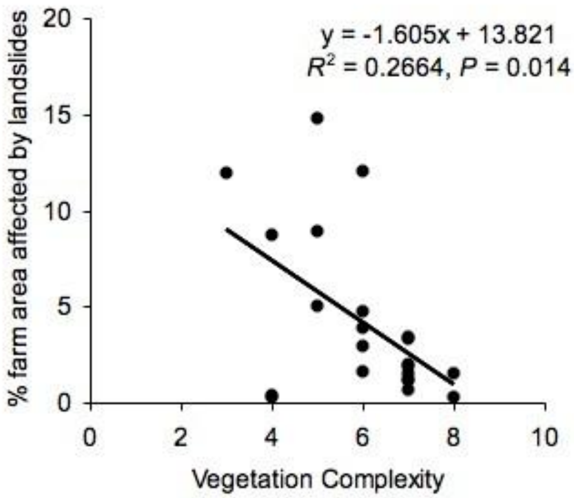

Figure 6: Percent coffee farm area affected by landslides as a function of vegetation complexity in coffee farms. Rustic and traditional polyculture farms have higher vegetation complexity scores (7-8), commercial polycultures mid-range scores (5-6), and coffee farms with simple shade have lower scores (3-4) (from Philpott et al. 2008, modified).