Climatic Change
DOI 10.1007/s10584-017-1949-5

Climate change and coffee: assessing vulnerability by modeling future climate suitability in the Caribbean island of Puerto Rico

Stephen J. Fain [1] · **Maya Quiñones** [1] ·
Nora L. Álvarez-Berríos [1] · **Isabel K. Parés-Ramos** [1] ·
William A. Gould [1]

Received: 4 November 2016 / Accepted: 14 March 2017

Abstract Coffee production has long been culturally and economically important in Puerto Rico. However, since peaking in the late nineteenth century, harvests are near record lows with many former farms abandoned. While value-added markets present new opportunities to reinvigorate the industry, regional trends associated with climate change may threaten the ability to produce high-quality coffee. Here, we discuss the history of coffee in Puerto Rico, outline important bioclimatic parameters, and model current and future habitat suitability using statistically downscaled climate data. Model projections suggest that warming trends may surpass important temperature thresholds during the coming decades. Under high (A2) and mid-low (A1B) emission scenarios for 2011–2040, Puerto Rico is projected to exceed mean annual temperature parameters for growth of *Coffea arabica*. Warming and drying trends may accelerate after 2040 and could result in top producing municipalities losing 60–84% of highly suitable growing conditions by 2070. Under the A2 scenario, Puerto Rico may only retain 24 km^2 of highly suitable conditions by 2071–2099. High temperatures and low precipitation levels can result in diminished quality and yields, as well as increased exposure and sensitivity to certain insects and diseases. The climate data and models used are based on best current understanding of climate and emission interactions with results best interpreted as projected climate trends rather than predictions of future weather. Planning, innovation, and adaptation provide promising avenues to address current and future socioecological challenges while building a model of sustainable and resilient coffee production in Puerto Rico and throughout the region.

This article is part of a Special Issue on "Vulnerability Assessment of US Agriculture and Forests developed by the USDA Climate Hubs" edited by Jerry L. Hatfield, Rachel Steele, Beatrice van Horne, and William Gould.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-017-1949-5) contains supplementary material, which is available to authorized users.

✉ Stephen J. Fain
sjfain@gmail.com

[1] 1201 Calle Ceiba, Rio Piedras, PR 00926, Puerto Rico

1 Introduction

Climate change is presenting challenges to agriculture and forestry worldwide. The Caribbean region has been deemed especially vulnerable due to its geographic and economic scale, exposure to extreme weather events, and reliance on tourism and imported goods (Mimura et al. 2007; Barker 2012; Gould et al. 2015). Regional climate models project a 2°–5 °C increase in annual mean temperature for the Latin American and Caribbean region (LAC) by the 2080s (Karmalkar et al. 2013). Climate projections averaged over large areas may assist in discerning large-scale trends useful for national and state level planning and policy, but may fail to provide small-scale farmers and land managers the level of detail needed to justify adaptive practices and investments (Mase and Prokopy 2014; Henareh et al. 2016). In Puerto Rico, downscaling of global climate models has revealed rates of anticipated warming and drying beyond that of projected regional averages (Henareh et al. 2016; Appendix I). Recent research highlights the need for more explicit analysis correlating downscaled climate projections with desired bio-climatic conditions to better understand cropping system vulnerabilities with local specificity (Mase and Prokopy 2014; Brown 2016). The objective of this paper is to begin addressing this gap by employing statistically downscaled climate data (Henareh et al. 2016) to model potential suitability for coffee growth in Puerto Rico at a 450 m resolution with the goal of supporting planning and management decisions.

As the second most traded commodity in the world, *Coffea* is enormously important for the millions of people that depend on it directly and indirectly for their livelihood. Coffee production has now spread to 70 countries where, as in Puerto Rico, it is still predominantly grown in mountainous regions by limited resource, small-holding farmers (ICC 2009). *Coffea arabica* and *Coffea canephora* (Robusta) are the most cultivated species, both evolving as shade tolerant, understory plants within the tropics of eastern and western Africa and thriving within a relatively narrow range of bioclimatic parameters (Teketay 1999). *Coffea arabica* is used in specialty coffees, draws a higher price, and accounts for the majority of production in Puerto Rico and the world (Monroig 2015). It is also the more climatically sensitive of the two species, flourishing in annual mean temperatures between 18° and 22 °C (~64°–72°) (Davis et al. 2012), while *C. canephora* may thrive in temperatures up to ~27 °C (Bunn et al. 2015). *C. arabica* has been noted to grow in areas with annual mean temperatures up to 24°—26 °C (~75 °F) (Teketay 1999); however, prolonged exposure at or above 23 °C (~74 °F) can result in accelerated flowering and loss of quality. Exposure to temperatures above 30 °C (86 °F) can lead to abnormalities and severely stunted growth (DaMatta and Ramalho 2006). Differences in temperature tolerance relate to precipitation distribution throughout the year and average soil moisture content (Teketay 1999).

Annual precipitation of 1000 mm (~40 in.) is considered a minimum for *C. arabica* cultivation, although certain varieties have been documented to grow in areas with totals as low as 762 mm (30 in.) (Teketay 1999). Muñiz (1999) identified 1905–2540 mm as a desirable range within Puerto Rico. Periods of rainfall following a dry period can help synchronize flowering and promote clearly defined harvesting seasons. Coffee-producing countries with more than one wet and dry season will have correlating multiple harvesting seasons (Teketay 1999).

As with other crops, coffee grown in marginal bioclimatic conditions is more vulnerable to environmental stressors. Projected temperature and precipitation trends associated with climate change (Karmalkar et al. 2013; Henareh et al. 2016) may expose many coffee-growing regions in the LAC to diminished quality, yields, and increases in the occurrence of insect and disease outbreaks (DaMatta et al. 2006, 2007; Jaramillo et al. 2011; Davis et al. 2012; Baca et al. 2014; Bunn et al. 2015). Coffee production in Mesoamerica, Brazil, Southeast Asia, Africa, and other regions has already been negatively affected by conditions consistent with climate change (Davis et al. 2012; Baca et al. 2014; Bunn et al. 2015).

Analyzing the spatial extent and timing of future climatic stress on current coffee-growing regions may allow for economic analysis of potential losses as well as guiding the extent, timing, and nature of adaptive practices. Additionally, this study may serve as a model approach for coffee-growing regions across the tropics.

2 Methods

2.1 Background and study area

Although sources disagree on the exact date and origin, *Coffea* was likely introduced to Puerto Rico around 1736 and became an important source of foreign capital through much of the 17th and 18th centuries (Dietz 1986; Pumarada 1989). By 1899, Puerto Rico had become the world's sixth leading coffee producer with 41% of its cultivated area dedicated to coffee growth (Dietz 1986; Pumarada 1989). Approximately 768 km^2 were distributed in 21,693 plantations primarily in the western Cordillera Central (central mountain range of Puerto Rico), employing an estimated 200,000 people and yielding over 20 million kg a year (Pumarada 1989). The expansion of shade coffee cultivation from 70 km^2 in 1828 to 770 km^2 in 1900 played an important role in providing bio-sanctuaries for plant and animal species during the island's mass deforestation of the nineteenth century (Ewel and Whitmore 1973; Borkhataria et al. 2012).

As production peaked at the end of the nineteenth century, a series of circumstances aligned to undermine the island's burgeoning coffee industry. As a result of the Spanish American War, the U.S. took possession of Puerto Rico in 1898. The shift in power led to a loss of favored trade status with Spain and curtailed access to competitive European markets (Dietz 1986; Pumarada 1989). In the U.S., coffee culture had not yet evolved to support prices needed to make Puerto Rico's small-scale, artisanal style of premium *C. arabica* production economically viable (Pumarada 1989). As a result, exports fell to 5.5 million kg by 1901 (Pumarada 1989). Following this shift in market dynamics, hurricanes San Felipe and San Ciprian passed through western Puerto Rico in 1928 and 1932, devastating much of the remaining coffee sector and contributing to a general industry-wide decline (Dietz 1986; Pumarada 1989).

In an effort to revive the industry during the 1970s and 80s, government-sponsored research and incentives moved farmers away from traditional, shade coffee cultivation techniques towards more intensive, full-sun farming (Perfecto et al. 1996 ; Borkhataria et al. 2012). Combined with an increase in agrochemical inputs and higher yielding varietals, this shift affected a steady increase in production with harvests regularly topping 12 million kg/year in the early 1990s. Hurricane George interrupted this upward trend in 1998, causing immense damage and resulting in a 38% harvest reduction the following season. Coffee harvests hit a historic low of 4 million kg in 2013, requiring the island to import over 11 million kg to meet local demand. Harvests for the 2013/2014 season were up only slightly to 4.6 million kg (Appendix II).

Along with market and climatic difficulties, Puerto Rican coffee farmers also confront higher production costs than many of their competitors due to higher costs of labor, fuel, equipment, and agrochemical inputs, which must be imported. Availability of labor is a persistent issue in the sector. Coffee picking is hot, hard, seasonal work often conducted on steep slopes. The urbanization of Puerto Rico has increasingly left few people within the rural Cordillera Central willing to pick coffee for minimum wage. Restoring harvests to levels experienced at the turn of the nineteenth century could provide a significant boost to the island's agricultural and general economy, but must be accomplished in concert with other priorities such as food security and ecological health.

2.2 Suitability model

To examine the extent coffee may be exposed to environmental stress from shifts associated with climate change, we conducted a spatially explicit, weighted overlay analysis to model current and future bioclimatic suitability in Puerto Rico. Weighted overlay analysis is a technique for integrating various types of spatial data within geographic information systems (GIS) by applying a common scale of values or weight (ESRI n.d.). Through literature review and consultation with local experts, bioclimatic parameters important for coffee growth in Puerto Rico were first delineated (Appendix III); then, geospatial datasets representative of these parameters were identified (Appendix III). Desired parameters were as follows: annual precipitation ranges of 1000–1905 and 1905–2540 mm, annual mean temperature range 18°–27 °C, selected soil series (Humatas, Alonso, Catalina, Daguey, and Los Guineos), and elevation range 182.99–914 m (Appendix III).

Using ArcGIS 10.2, precipitation, temperature, and elevation ranges were extracted from original raster datasets. Each range was transformed into vector format and joined together with the selected soil series vector dataset to calculate a coffee growth suitability index ranging from 0 (unfavorable) to 5 (optimal). All parameter sets were given a weight of 1 except the precipitation range 1905–2540 mm which was given a weight of 2 as it has been identified as locally optimal (Muñiz 1999). The resultant suitability model can be summarized in the following formula: selected soil series + elevations 182.99–914 m + temperature 18°–27 °C + precipitation 1000–1905 mm ($weight = 1$) + precipitation 1905–2540 mm ($weight = 2$).

Some land cover types (i.e., wetlands, inland water, natural barrens, and built-up surfaces) (Gould et al. 2008) and public protected areas (Quiñones et al. 2013) were excluded due to their lack of agricultural potential or protected status and were classified as value 0 in our suitability map. The weighted overlay analysis was performed 15 times for each projected precipitation and temperature data (Henareh et al. 2016) under three IPCC SRES emission scenarios (Nakicenovic et al. 2000): high (A2), mid-low (A1B), and low (B1) and five time periods (i.e., 1960–1990, 2011–2040, 2041–2070, 2071–2099). Emission scenarios are built on a range of assumptions regarding global economic and technological development, the continued use of fossil fuels, and greenhouse gas (GHG) mitigation policies. Final datasets were used to measure spatial extent, timing, and nature of bioclimatic stress on coffee in Puerto Rico.

3 Results

Suitability model results for 1991–2010 mirror known growing regions in the western Cordillera Central (Fig. 1). The model also shows an area of high suitability in the southeastern portion of the island. Future model results indicate a dramatic loss in areas of high suitability (rating of 4 or 5) for coffee growth in Puerto Rico (Fig. 2).

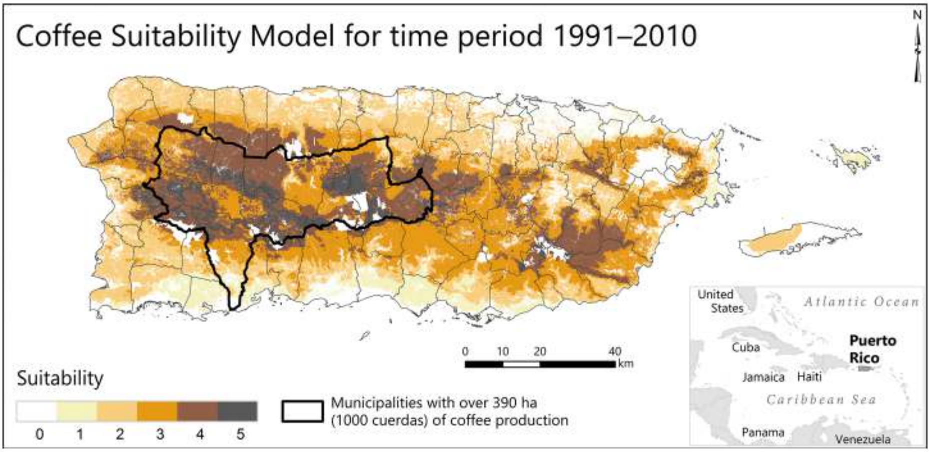

Fig. 1 Suitability index for coffee growth in Puerto Rico 1991–2010

Using 1991–2010 as a baseline of comparison, the top ten coffee-producing municipalities of Puerto Rico are projected to lose 47% of their high suitability range under the A2 scenario by 2040 as compared to a 21% loss under the lower emission B1 (Appendix IV). Declines in high suitability accelerate dramatically after 2040 under high (A2) and low (B1) scenarios, even as the difference between scenarios begins to emerge as critically important. This difference is demonstrated markedly by the municipality of Maricao, whose prime conditions may decline by 82% under the A2 scenario, as opposed to 29% under B1 by 2041–2070 (Fig. 2). Overall, the island's top ten producing municipalities may be facing a 60% decline in prime habitat under B1 scenarios and as much as an 84% decline under A2 projections for the same period. Under A2 scenarios, the entire island retains only 289 km^2 of highly suitable growing space during 2041–2070, further declining to ~24 km^2 by 2071–2099. By comparison, the island retains 680 and 329 km^2 for the same periods under B1 scenarios (Appendix V).

DaMatta and Ramalho (2006) found drought and unfavorable temperatures to be the major climatic limitation in coffee production. Analyzing precipitation and temperature shifts independently (Fig. 3) indicates that while mean annual precipitation is projected to decline across the entire island, areas of current coffee growth are expected to remain above the 1000 mm threshold cited as a minimum for growth of *C. arabica* (Teketay 1999). Depending on soil conditions, evapotranspiration rates, slope, seasonal distribution of rainfall, and other factors that affect soil moisture retention (e.g., shading, aspect), precipitation levels below 1905 mm in Puerto Rico may require some adaptive measures (Muñiz et al. 1999).

Temperature projections are another story. Model results indicate that Puerto Rico may lose all of its optimal *C. arabica* temperature range by 2041 with a correspondingly dramatic decline in optimal *C. canephora* range (Fig. 3). Only under the low emission scenario (B1) does the island maintain significant areas with annual mean temperatures below 27 °C. Under the A2 scenario, Puerto Rico may only retain 7 km^2 with mean temperatures below 27 °C by the end of the century. Even if other factors remain favorable, such temperatures could preclude growth of many traditional *C. arabica* varieties without significant environmental modifications.

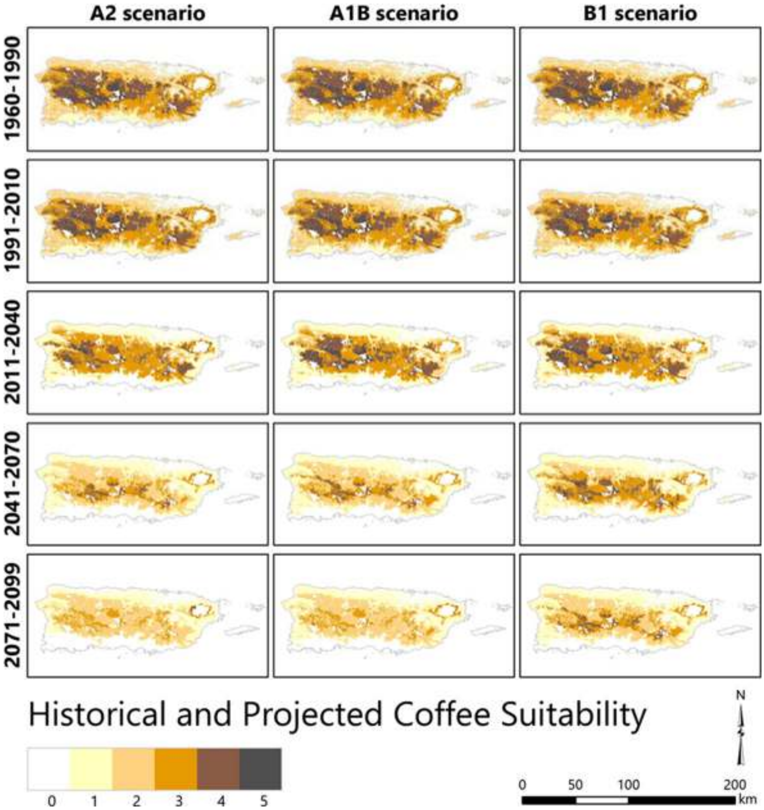

Fig. 2 Results of suitability model, 1960–2099 for IPCC SRES emission scenarios A2 (high), A1B (mid-low), and B1 (low) (Nakicenovic et al. 2000; Appendix I) based on data from Henareh et al. (2016)

4 Discussion: climate change effects on coffee growth

Projected losses in suitable habitat for *C. arabica* in Puerto Rico within the next 25 years merit further study and analysis. Our results indicate that much of the traditional *C. arabica* growing region may already be falling outside the proscribed optimal range of 18°–22 °C (Fig. 2). Optimal conditions for coffee growth are a dynamic combination of all bioclimatic factors as well as the particular requirements of the varietal of *C. arabica* or *C. canephora* being grown. This makes it difficult to define “hard” ecophysiological parameters for the species and may explain variations in the literature regarding desired temperature and precipitation levels. More research may be needed to understand important temperature thresholds for the specific set of varietals being grown in Puerto Rico.

Coffee farmers in many regions are increasingly relying on hybrid *C. arabica*/*C. canephora* varietals to increase plant resistance to heat, drought, and various insects (Romero et al. 2014). Combined with adaptive practices, such varietals may allow coffee farmers to continue growing high-quality coffee in the traditional areas of the western Cordillera Central until 2070. After 2070, differences in GHG emission scenarios begin to emerge as critical for the future of the island’s coffee industry. Only under the B1 (low emission) scenario does the island retain significant areas below annual mean temperatures of 27 °C. Adapting to higher

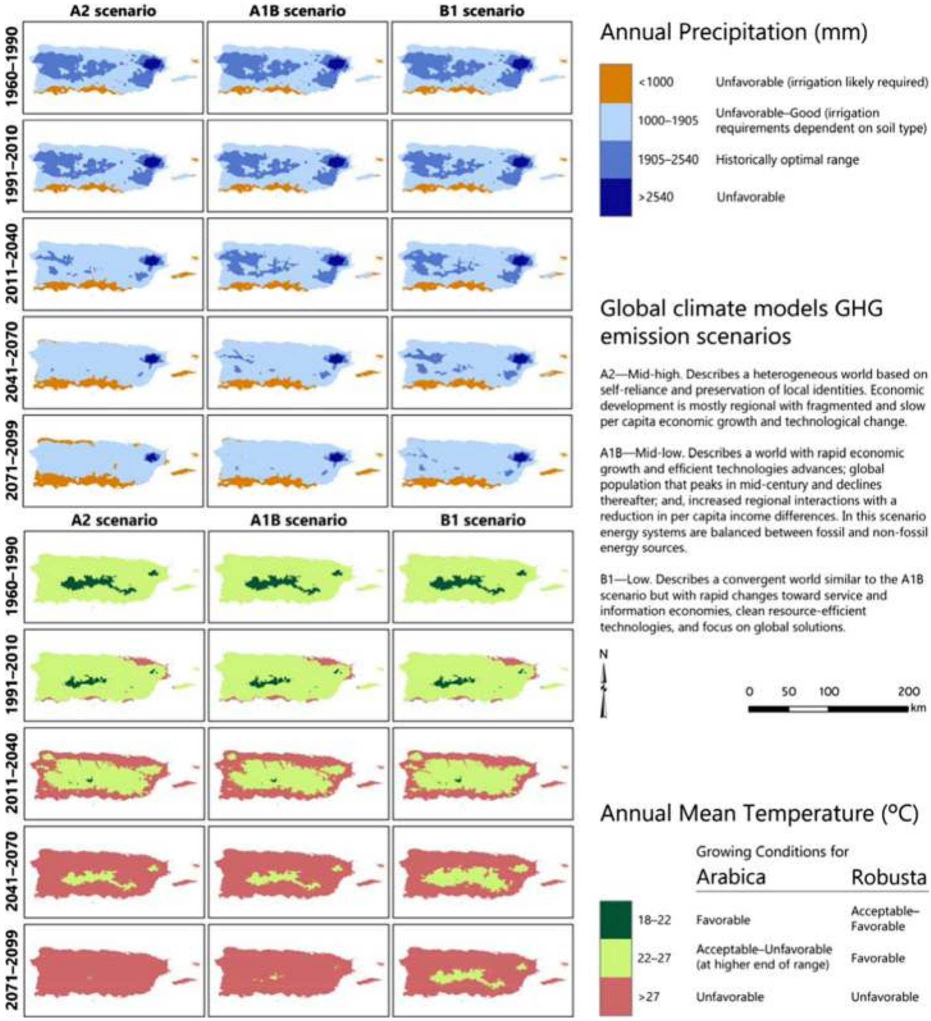

Fig. 3 Annual mean precipitation and annual mean temperature ranges for coffee production from 1960 to 2099 (Henareh et al. 2016) using three IPCC global GHG emission scenarios: mid-high (A2), mid-low (A1B), and low (B1) (Nakicenovic et al. 2000; Appendix I)

temperatures and lower precipitation could be a costly, time-consuming process that may be unfeasible for many farmers in the region.

4.1 Adaptive practices

While there are many adaptive practices coffee farmers can utilize to address various stresses associated with climate change, inter-cropping and the incorporation of shade trees have gained much attention for their multiple benefits. Shade trees have the potential to decrease ambient surface air temperatures by 2 °C or more (Jassogne et al. 2013), decrease runoff and erosion (Verchot et al. 2007; Philpott et al. 2008), protect plants from high solar radiation, wind, and heavy rain, as well as contributing to biodiversity, insect control, and pollination

(Perfecto et al. 1996; Beer et al. 1998). They also have the ability to mitigate greenhouse gas emissions by absorbing carbon dioxide (Albrecht and Kandji 2003), diversify sources of income, as well as provide wood products, energy, and increase food security (Rice 2008; Jassogne et al. 2013).

Following a series of studies indicating decreased tree cover on coffee farms could increase yields in Puerto Rico (Abruna et al. 1959; Arrillaga 1942), intensive full-sun techniques were encouraged and began to affect significant change during the 1980s. From 1982 to 2007, shade-grown coffee production in Puerto Rico declined by 70% (Borkhataria et al. 2012). This “modernization” of the industry appeared to be effective as coffee became the most economically important crop from 1982 to 1998 with yearly harvest regularly topping 11 million kg/year (Borkhataria et al. 2012; Appendix II). However, this shift in cultivation practices significantly increased the crop’s vulnerability to storm damage (Philpott et al. 2008) as was demonstrated in 1998 when Hurricane George heavily damaged much of the island’s coffee-growing region.

While the ecological benefits of shade coffee production are evident (Perfecto et al. 1996; Jha et al. 2011), the economic viability in Puerto Rico has been questioned. High production costs on the island necessitate high yields to ensure profitability. More study is needed to quantify the costs of any potential yield reductions versus benefits gained from wood, fruit, and other inter-crop products (Rice 2008; Jassogne et al. 2013). Intensive, full-sun cultivation methods often rely on costly agrochemical inputs, irrigation, and fossil fuels. These higher operational and environmental costs must also be considered in any cost/ benefit analysis. Directing industry subsidies and educational programs toward practices that preserve and enhance ecosystem services may help close the gap between climate-smart, ecologically friendly practices, and profitability.

Commercial coffee farmers in Puerto Rico are adapting to labor shortages by establishing new farms and processing facilities in the coastal lowlands to facilitate mechanized harvesting. Higher temperatures and low rainfall are characteristic of the coastal lowlands in Puerto Rico with temperature and precipitation levels increasingly falling outside preferred parameters (Fig. 3). Some mechanical harvesters are limited by slope (10%) and require much wider spacing between individual plants and rows (R. Alvarez, July 29th, personal communication). Growers within Puerto Rico’s mountainous region are experimenting with various techniques to improve harvesting efficiency including handheld “mechanized harvesters” and terracing (A. Rodríguez, personal communication, May 25th, 2016).

Terracing is a particularly promising adaptive strategy in the steep, mountainous terrain of central Puerto Rico due to its multiple benefits which include the following: easing maintenance and harvesting, reducing runoff and erosion, and increasing soil moisture retention (Altieri and Koohafkan 2008). As with the planting of shade trees, the instillation of irrigation systems or transitioning to more resilient varietals, terracing requires a level of initial capital outlay that may be beyond many small-holding coffee farmers. Government programs intended to defray such adaptive costs and encourage investment in resilient cultivation techniques must be accessible to be effective. Extensive bureaucratic processes and requirements can limit program participation to a self-selecting group of growers familiar with navigating such systems, leaving many farmers ostracized and without the ability to make needed adaptations.

4.2 Model limitations

Climate projections are not predictions of future weather, but rather probable projections of long-term climate trends based on best available climate science and the ability to predict future socio-ecological and technological scenarios (Hawkins and Sutton 2009). As a result, they carry many uncertainties. Nevertheless, they provide the best available data for assessing potential climate change effects on various systems and processes, such as species distributions (e.g., Li et al. 2015), terrestrial and marine ecosystems (e.g., Hooidonk et al. 2015), and adaptation and mitigation planning (e.g., Whateley et al. 2014).

The temperature and precipitation data used in this analysis are based on the IPCC Special Report on Emission Scenarios (Nakicenovic et al. 2000) using Coupled Model Intercomparison Project 3 (CMIP3) model ensembles. Both emission scenarios and model ensembles were updated in the IPCC Fifth Assessment Report (2013) to ease modeling the potential effects of policies and technology. Hayhoe (2013) found that CMIP3 models in Puerto Rico overestimated projected decreases in wet season rainfall and in extreme precipitation events compared to CMIP5 models using the new Representative Concentration Pathway (RCP) scenarios. They also reported that some global circulation models (GCMs) fail to simulate the structure of precipitation patterns in the central and eastern Caribbean accurately. Dynamically downscaled climate projections for Puerto Rico based on CMIP5 RCP scenarios are in progress as of the publication of this article and may provide more robust climate projections for the island.

The climate projection data used here contains uncertainties related to the statistical downscaling and interpolation process used to create the raw projected data and the post-processed raster datasets used in our analysis. The GCM’s were downscaled using the asynchronous regional regression model (ARRM), which outputs the downscaled climate model data to individual weather station locations. Disparate results have been reported for the same output locations in Puerto Rico when using two different statistical downscaling methods (Henareh et al. 2016). Furthermore, the downscaled projection data show an increase in the difference between observed and projected values for the 1991–2010 period compared with 1960–1990 (Henareh et al. 2016).

Interpolating climate data across a complex landscape with high topographic variability, as is the case with Puerto Rico, can increase errors and uncertainty (Daly et al. 2002). To account for this, Henareh et al. (2016) used the climatically aided interpolation method to apply the projected changes from the downscaled data to a Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate dataset for Puerto Rico created from weather station observations from 1963 to 1993 (Daly et al. 2003). While this PRISM dataset is reported to have some cross-validation errors (Daly et al. 2003), it showed improved performance over simpler interpolation methods and greater spatial detail than previously published maps (Daly et al. 2003).

Uncertainties in specific models and methods notwithstanding, all data used in this analysis are based on accepted methods for minimizing uncertainty. Current global emission levels are most closely aligned with A2 (high) scenarios (Fuss et al. 2014). Given the potential effects of even the low emission scenarios (B1), employing adaptive strategies in planning and management practices may be necessary to mitigate future risk for coffee farmers.

5 Conclusion

Building a sustainable and climate resilient coffee sector in Puerto Rico could provide a much-needed economic boost to the island. However, efforts to do so must be balanced with the island’s pressing need to reduce its dependency on imported food and consider the significant risks posed by climate change in the coming years. Large portions of the traditional coffee-growing region of Puerto Rico may be exposed to increases in annual mean temperature within the next few decades. Global GHG emissions are currently trending toward the high end of IPCC scenarios. If this continues, the time period 2041–2070 could represent a tipping point in which mean temperatures over the entire island could exceed optimal parameters for *C. arabica*. Scientific consensus regarding the dynamic processes through which GHGs accumulate in the atmosphere and in turn affect global climate is still evolving. As such, specific temperature and precipitation projections may be modified in coming years; however, significant warming, drying trends are likely to remain.

As history attests, Puerto Rican coffee farmers are accustomed to adapting to both market and environmental stresses. Nevertheless, responding to the significant environmental challenges associated with climate change may require a new level of public and private cooperation designed to empower agricultural communities with the social, intellectual, and economic resources necessary to adapt. Integrated knowledge sharing networks are needed to facilitate an effectual exchange of information between farmers, scientists, and policy makers. Adaptive capacity may be further enhanced by increasing resources available to farmers and agricultural advisers regarding climate change risks, viable adaptation and mitigation strategies, education on and access to climatic data, as well as trainings on sustainable land management practices. Cooperatives can be a strong tool for providing these services by hedging individual risk to growers and providing valuable forums for peer-to-peer knowledge sharing related to specific adaptive practices that are proven to function at the local level.

Producers may also need increased economic support from local and federal government entities to begin implementing needed adaptations. This support could come in the form of incentives for sustainable practices, payments for ecosystem services, or subsidized low interest loans. Support services for the Puerto Rican coffee industry would do well to consider projected climate trends when planning financial assistance as well as research, education, and communication programming.

Acknowledgements The authors would like to acknowledge the following for their indispensable help and expertise in completing this paper: Lisette Fas, Alfredo Rodríguez, Víctor Vega López, Carlos Flores, Salvador Baiges, José García Peña, Yaniria Sánchez de León, Mariangie Ramos Rodríguez, and Azad Henareh. We would also like to thank all reviewers and the International Institute of Tropical Forestry staff for their support.

Compliance with ethical standards

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