Coffee Agroecosystems in Puerto Rico:

Trends in Management Practices, Climate Change Resilience, and Farm-size/Productivity Relationships in Coffee Farms in Puerto Rico

by

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Abstract

Agriculture, especially that employing agroforestry practices, provides food, materials, and income to people, while influencing the flora, fauna and ecosystem functions that are the source of life on Earth. Based on the environmental conditions and practices employed, farms vary in how much they support people and the environment. To better understand this relationship, this practicum focuses on reviewing agricultural census data and global climate data to see how management practices (shade or sun-grown coffee), farm size, temperature, and precipitation influence yield in the coffee agroecosystems of Puerto Rico. The results from this study present only a partial picture, and should be supplemented by studies on ecosystems services, impacts on farmer's livelihoods, and biodiversity.

We find that coffee agriculture in Puerto Rico is declining in total land area and total production. Sun-farms are generally larger than shade-farms and make up a greater proportion of farmland. Sun and shade farms do not differ in their total yield, defined as kilograms per area planted, however, shade farms do generally harvest a greater proportion of their total farm. The yield of sun and shade farms shows a positive linear relationship with total annual precipitation, and an insignificant negative linear relationship with average annual temperature and these were not influenced by cultivation methods. Of the variables we assessed, farm size and total annual precipitation are the strongest predictors of coffee yield in Puerto Rico. Both shade and sun farms show partial evidence of a positive polynomial relationship between farm size and yield.

Acknowledgments

This work would not be possible without the people and farmers of Puerto Rico who live and steward the land, are the focus of this work, and provided their time in the census process, the USDA Caribbean Climate Hub's researchers and scientists for conducting census fieldwork and providing data support, and the guidance, teaching, and support of Dr. Ivette Perfecto. Perfecto's extensive background in food/land sovereignty and coffee systems, through ecology, history, and social science, provided inspiration and invaluable education for me during my studies and in the completion of this practicum. To all these people, I am deeply indebted and thankful.

I would also like to acknowledge the insight and education I gained from all the researchers and faculty at SEAS whose teachings made this possible, inlcuding: Dr. Kyle Whyte for his discussions on responsibility and indigenous sustainability, Dr. Meha Jain for lessons on statistics in natural resources, Dr. Derek Van Berkel for guidance in modeling for landscape planning and visualization, and to the Perfectomeer lab for inspiration and helpful insight.

Finally, I thank my friends and family who supported me during my studies. A big thanks to Abigail Meyer, who provided so much support, and to Red, who gave me smiles from the side of my desk when I was stressed and reminded me to go on walks when we both needed them.

Table of Content

Background

Agriculture and the Environment

With 45% of earth's landcover in agriculture, and 75% heavily modified by humans, it is imperative that we understand and can support decisions in agriculture that are sustainable and equitable (IPBES, 2019; Vollrath, 2007; Wirsenius et al., 2010dietrich) . Agriculture currently accounts for 24% of global greenhouse gas emissions (IPCC 2014), with conventional agricultural also being linked to deforestation, soil degradation, declines in biodiversity and total insect biomass, and hazards to human health (Benton et al., 2002; Chaudhary et al., 2016; Hallmann et al., 2017). However, not all agriculture has these detrimental impacts. Farming methods can maintain ecosystem processes and have greater biodiversity, sequestering carbon and promoting biodiversity while supporting farmer livelihoods (Lewis et al., 1997; Mayorga et al., 2022; Padoch & Pinedo-Vasquez, 2010; Tsonkova et al., 2012). Biodiversity-friendly methods often reduce use of pesticides and petroleum-derived fertilizers through a technique called intercropping or polycultures. To best support the sustainability of agriculture systems and reduce negative impacts of people on the environment, we must determine which methods of cultivation are most resilient to climate change and can support people and wildlife. Scholars and agriculturalists have explored this through considering different models of agriculture and land-use planning. I will briefly touch on a few to provide context for the farming metrics that will be used in a case-study on coffee agroecosystems in Puerto Rico. These frameworks include land sparing-sharing, and the three modes of agriculture defined in van der Ploeg's The New Peasantries. Both frameworks establish a foundation for the utility in studying trends in yield, farm size, and ecosystem/biodiversity impacts.

Land Sparing – Land Sharing

The land sparing-sharing debate has been well discussed to support decisions in land-use, human livelihoods, and conservation (Fischer et al., 2013; Fischer et al., 2014; Perfecto et al., 2009; Phalan, 2018). The framework is representative of differing perspectives on conservation and human's relationship with the environment. In this framework, the balance of human wellbeing and ecosystem functioning / support for biodiversity is simplified to a balance of food production and biodiversity. In a reduced view, land-sparing represents agricultural intensification and land-sharing as agricultural expansion (Phalan, 2018). But it can also represent separation (land-sparing) or integration (land-sharing) of conservation and food production (Fischer et al., 2014). Land-sparing asserts that biodiversity and ecosystem function are best conserved with dedicated areas of limited human intervention where wildlife can thrive unimpacted by people. To achieve this, other areas of land are allocated for human uses, such as habitation, mining, forestry, and agriculture, and these are intensified for ultimate efficiency, often with negative impacts to the environment in these areas (Green et al., 2005;

Phalan, Balmford, et al., 2011). In this view, conservation and human-impacts are trade-offs separated by spatially explicit borders.

On the other hand, land-sharing advocates that humans are a part of ecosystems, and that human existence can act in synergy with ecosystem processes and biodiversity conservation. In this perspective, conservation goals are best achieved with practices in land-use that support ecosystem functions and wildlife (Cardinale et al 2012, Perfecto et al 2009). Borders between conservation areas and human areas are thus softer and support a coexistence between people and the biodiversity of earth. Land-sharing approaches have examples in traditional land-management and contemporary study and practice. These can include successional management, shifting-cultivation, agroforestry, alley cropping, and regenerative agriculture (Rhoades 2017; Padoch & Pinedo-Vasquez 2010, Berkes and Davidson-Hunt 2006; Sanchez 2019; Turner 1999).

The philosophical background for these perspectives can be further elaborated on in discussions on western conservation, colonialism, and indigenous knowledge and ways of knowing, but that will not be thoroughly discussed in this paper. Rather, we discuss measurable metrics of ecosystem impacts and support for human livelihoods.

To study production in the land sparing-sharing framework, researchers study yield. In the following case-study on coffee agroforestry in Puerto Rico, yield will be a primary metric for assessing productivity and support of human livelihoods, however, this will be contextualized by the documented ecosystem impacts of different methods of cultivation. Yield can be a misleading measurement. Fundamentally, it is a measure of the income-generating product of an agricultural harvest, but it does not directly consider other factors that could determine the viability of a farming enterprise, such as market factors, input costs, farmer health, labor costs, or farm resilience. Also, food-production is not necessarily the limiting factor for food-security (Tscharntke et al., 2012). Therefore, one must be cautious when taking the results from yield analysis at face value. Nonetheless, it is a close proxy for farm productivity and potential income. How yield is measured and calculated can vary, and exploring yield at various spatial scales provides insight into farming methodology and land utilization. In turn, understanding differences in farming methodology and land utilization can illustrate the costs and benefits of farming methods at the scale of individual farms, the surrounding landscape, and impacts to ecosystems and the diversity of life which live and migrate through these landscapes.

Modes of Farming

The land sparing-sharing framework illustrates a spectrum on which agricultural practices can fall. These practices are further complicated by the values and unique socio-cultural positions of farmers. This results in diverse methods in which people sustain themselves, their communities, and the people of the world along a spectrum of localized and globalized food systems. To define the practices and positionality of the worlds farms, van der Ploeg has defined three modes of agriculture (van der Ploeg, 2008). It is important to note that these modes are not prescriptive or concrete labels. The modes include Peasant Farming, Entrepreneurial Farming, and Large-Scale Corporate Farming.

Peasant farmers have historically been perceived as poor and uneducated laborers, but this doesn't acknowledge the reality of the underlying diversity, value-systems, priorities, and oppressive systems under which peasant farmers operate. The peasant farmer in this framework acknowledges peasant movements around the world, including indigenous stewards and community- and ecologically- oriented farmers. Peasant farmers are further characterized as contributing to localized food systems with the objectives of self-sufficiency, respect for the environment and local communities, and sparing scarce resources. Entrepreneurial farming, on the other hand, is a market-driven approach that focuses on increasing all production potential and using and contributing to financial and industrial capital. As opposed to peasant farming that focuses on autonomy and ecological sustainability, entrepreneurial farming focuses on balancing externalized inputs and farm outputs to maximize capital, often relying on industrial processes, inputs, and mechanization. Finally, large-scale corporate farming focuses on profit and economies of scale, fully leveraging financial and industrial capital to farm large swaths of land with minimal labor, extensive inputs, mechanization, output processing and refinement, and global supply chains.

Farmers often exist as more complicated and nuanced forms than these hyper-characterized modes of farming (fig. 1), often blurring the lines between these labels. While these terms and frameworks might assist in making predictions about the nature of farming practices, farmer's values, yields, and ecological impacts, they remain symbolic terms than may not relate to the self-identifying terms of farmers or the true nature of their values and practices.

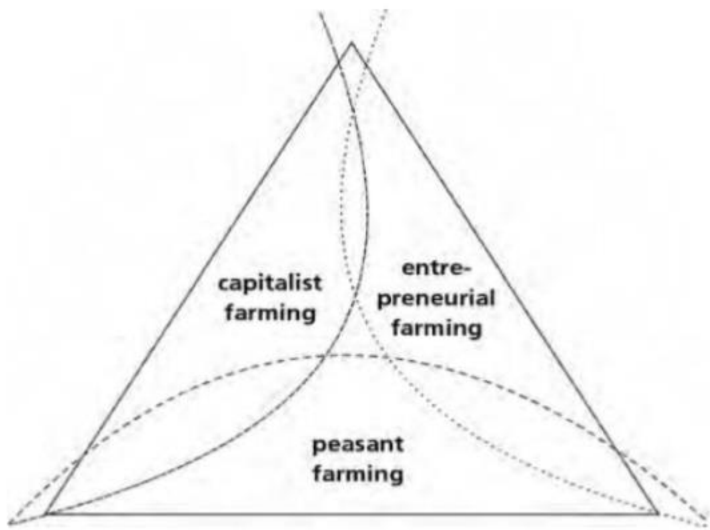

Figure 1. Modes of Farming from The New Peasantries: Struggles for Autonomy and Sustainability in an Era of Empire and Globalization by Jan Douwe van der Ploeg. Illustrates the three modes of farming and how individual farming operations can exist on a continuum between these modes.

These values and practices often correspond with different scales of land management. Along these modal lines yield and farm size vary. Farm size is a complex metric because it is tied to investment strategies, farmer income, and farmer expenses, and it can be difficult to untangle from confounding legacies of oppression and socioeconomic disparities. Farm size trends are emblematic of the transition from labor-intensive and biodiversity-friendly methods towards mechanized and industrial agriculture (van der Ploeg, 2008). In this way, however, farm size may act as a predictor of farmer positionality and modes of farming.

While farm size is related to farming practices, organizational structure, and values, it can also predict yield. Farm size has shown an inverse relationship with yield, or productivity, known as the inverse-farm-size-productivity relationship (Ali & Deininger, 2015; Chayanov, 1926; Sheng et al., 2019; Sial et al., 2012; Vollrath, 2007). On the other hand, there is evidence of larger farms being more productive, such as in Muyanga & Jayne's review of farms in Kenya (Muyanga & Jayne, 2019). This explains how, in some cases, the inverse farm size relationship is not necessarily linear, often taking a polynomial "u-shape"(Sheng et al., 2019). These conclusions have led to suggestions that policy should support small farms. Other's rebut this, arguing that reports indicating an inverse-farm-size-productivity relationship are missing important indicators and ignore the plight of the underpaid farm workers on more labor-intensive small farms (Muyanga & Jayne, 2019; Ritchie, 2021). However, smaller farms can better support biodiversity, ecosystem functioning. (Perfecto &

Vandermeer, 2010; Ricciardi et al., 2021; Ricciardi et al., 2018). Farmer values influence this relationship, too, such as in peasant farmers who choose smaller farms with labor intensive and ecologically synergistic practices due to a high value placed on self-reliance, support for local communities and environments. Evidently, our understanding of the relationship of farm size with productivity should be placed in context of how they interact with environmental impacts, farmer livelihoods, and climate resilience.

Therefore, we will explore how farm size relates to yield and ecosystem/biodiversity impacts. It is important to understand these trends, especially as they relate to biodiversity and climate change resilience to best support farmer decisions and that agricultural policy.

Climate Impacts on Agriculture

Climate impacts agriculture. Changes in precipitation, temperature, and extreme weather events increase pest and pathogen abundance and cause damage to crops and livestock (Lehmann et al., 2020; Mall et al., 2017; Rojas-Downing et al., 2017). We need to understand what management methods and farm sizes can best mitigate these issues. Theory predicts that more biodiverse farms will be more resilient to climate change, with shade trees moderating microclimates and water availability, acting as wind breaks, and providing a diversity of crops, timber, and forest products, which can provide economic buffers for farmers. On the other hand, wealthier farmers, which are often monoculture entrepreneurial and corporate farms, have the funds to moderate climate impacts with irrigation, infrastructure, fertilizers, and pesticides. Nonetheless, how farms respond to temperature and precipitation is important to understand. Further, evaluating the current suitability of existing farms in the climatic landscape and which crop cultivars can best adapt to future climate scenarios can inform agriculturalists and policy-makers.

Coffee Agroforestry

The tropical forests in which coffee is grown are biodiverse yet often imperiled. Coffee farming has been a model system for understanding biodiverse forms of land management (Jha et al., 2014; Perfecto et al., 1996), often due to traditional and indigenous practices of land stewardship (Toledo & Moguel, 2012).

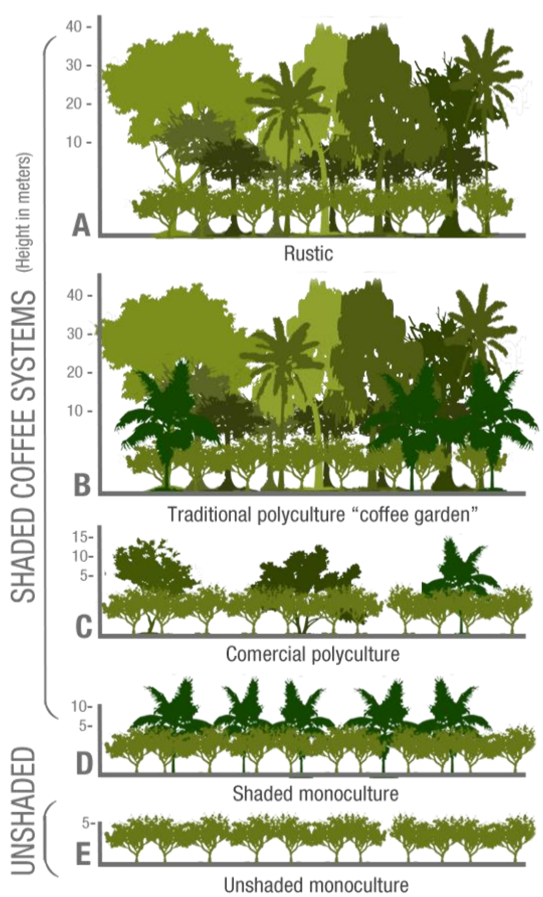

Figure 2. The continuum of coffee cultivation methods, illustrating complexity, height of canopy and diversity from unshaded monoculture, shaded monoculture, commercial polyculture, traditional polyculture,

and rustic practices. From (Agnoletti et al., 2022) an adaptation of (Moguel & Toledo, 1999)

Coffee agroforestry, like most forms of agroforestry, exist on a continuum from extensive to intensive agriculture (fig 2). The way that coffee is farmed has changed greatly over the past 40 years. More extensive traditional practices have been exchanged for intensive conventional practices. This wide spectrum in which agroforestry systems can exist is often simplified to either sun or shade farms. Shade coffee farms are an example of an intercropping polyculture. Intercropping is where two or more crops are grown together, as opposed to a monoculture of a single crop. In shaded coffee agroecosystems, coffee plants are either grown within an intact tropical forest (Rustic or "Traditional Polyculture"), or shade trees are planted within a coffee monoculture (commercial polyculture or shaded monoculture). This intercropping can also include other crops such as citrus trees, root crops, bananas, and plantains (Borkhataria et al 2012; Perfecto et al 2019).

Agriculture and coffee farming have a long history in Puerto Rico, dating back to the early 18th century. Here we look at how coffee farming practices have changed and what those impacts may look like in the future with changes in economic and climatic stressors.

History of Coffee in Puerto Rico

Puerto Rico's tropical climate brought intense interest from colonizing European nations who sought to use the area for accruing wealth. Spanish subjugation of the island and its Taino people began with Christopher Columbus's second arrival in 1493. After a genocidal displacement of indigenous communities, Spanish colonists mined gold and started plantations of cash crops such as sugar cane and coffee, relying heavily on slave laborers, first the indigenous Taino, and later peoples brought forcibly from Africa. The Spanish colonial plantation era began in 1736. Production boomed through the 1800's until a major hurricane hit in 1899 reducing coffee production dramatically. Coffee production has remained relatively low compared to the early Spanish colonial era, especially following US annexation from Spanish rule and subsequent occupation. Tariffs and the enforcement of the US minimum wage are partly responsible for this continued decline. (Perfecto personal comm. 2021; Perez 2004). Operation Bootstrap, a collection of economic development policies implemented jointly by the US and Puerto Rican governments changed the agricultural landscape in Puerto Rico. With a linear perspective on economic development, the US sought to industrialize the island by creating factories and denigrating the role of farmers in society. This led to a rapid decline in the total number of farmers, and a large exodus of Puerto Ricans to the United States. Further, a rise in coffee production in Latin America, the Jones Act which constrained shipping to US built ships, and the impacts of Hurricanes San Ciprian (1932), George (1998), Maria (2017), and Fiona (2022), have led to a decrease in the number, size, and total production of coffee farms in Puerto Rico.

Study Goals

Climate change, intense storms, and droughts are predicted to increase in coming years (Estrada et al., 2023; Smith et al., 2019). For this reason, it is important to study farming practices and strategies that are resilient to these kinds of climatic stressors. It is imperative to understand more about these farms to best support the decisions of farmers in the future and maintain ecosystems and biodiversity. Farming coffee with either shade or sun management practices may vary in their yield, and farm size may show potential impacts on this yield. Differences in these factors may also result in various responses to climatic changes.

In analyzing agricultural and climatic data in Puerto Rico, we can better understand coffee farming trends and practices. The Caribbean Climate Hub gathered agricultural data from farmers from 2013 to 2016 that includes farm locations, sizes, and yield. The purpose of this report is to interpret these data to inform decisions of farmers, policy-makers, and researchers who are interested in the resilience and success of sustainable coffee agriculture in Puerto Rico.
Our goals are to better understand 1) trends in farm size, cultivation methods (sun and shade-grown), climatic variables (temperature and precipitation), and how these impact yield and each other, 2) the resilience of cultivation methods to climate impacts, and 3) how shade and sun farms are distributed throughout the current climatic suitability range of Puerto Rico.

Methods

Agricultural Metrics

In this study, farm size, cultivation method (shade and sun) and yield are the primary metrics for understanding agricultural practices and productivity. Farm size is measured in hectares. The cultivation method is limited to only shade and sun-grown coffee production, which may play a role in climate resilience, and will also serves as a proxy for ecosystem/biodiversity impacts. Yield is often considered as a unit of production at the scale of the farm, or as a more spatially explicit value of unit of production per unit area. We will use total farm yield (kilograms per farm), yield per area harvested (kilograms per hectare harvested), and yield per area planted (kilograms per hectare planted). Yield per area harvested provides insight into the productivity of only the harvested plants but does not provide a measure of productivity of the scale of the entire farm operation and its spatial requirements. Yield per area planted provides insight into the productivity of the entire farm, serving as a more accurate depiction of land utilization. Further, *land use efficacy,* defined as the area harvested divided by the area planted, serves as a metric to understand trends in farming methodology and land utilization.

Data Sources & Study Area

Agricultural Census Data

Agricultural census data carried out by the United States Department of Agriculture provides information for assessing trends in coffee farm production and management.

For general trends between 1978 and 2018, data was sourced from the USDA Census of Agriculture Historical Archive. This data includes Geographic Area, Farms (number of farms), Farm Size (Cuerdas), Cultivation Method (Shade or Sun), Total Number of Trees, Nonbearing Age Trees, Bearing Age Trees, and Quantity Harvested (CWT).

For more fine-scale analysis of yield, farm size, and the ability for spatially-explicit analysis with climate data, we assessed data from the USDA Caribbean Climate Hub Agricultural Statistics. This includes a subset of farmers in Puerto Rico censused between 2013 and 2016. Data includes cultivation method (Shade or Sun), total farm harvest (kg), area harvested (ha), area planted (ha), and the GPS coordinates of each farm. According to the USDA four-year census, the number of shade and sun farms in 2012 was 1,919 and 3,104 respectively. Therefore, the 2013-2016 Caribbean Climate Hub (CCH) census is about a 30-40% subset of Puerto Rican coffee farmers. A distribution of these farms over the four-year census and their geographic location can be seen in figure 3 and 4, respectively.

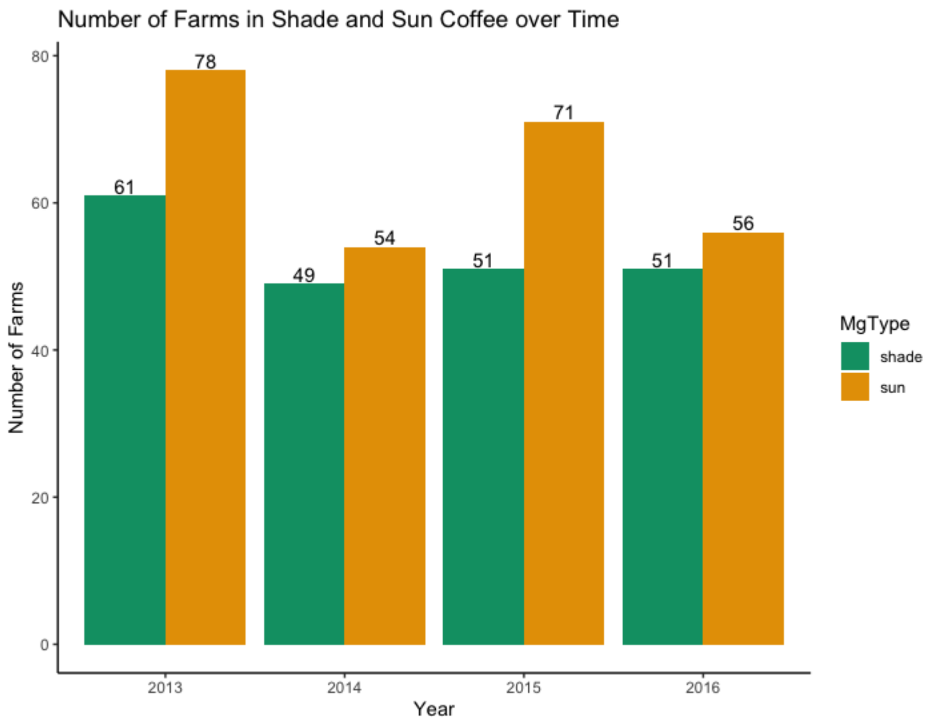

Figure 3. A year to year distribution of the number of shade and sun coffee farms from a 2013-2016 Caribbean Climate Hub Census that is 30-40% of total coffee farms in Puerto Rico

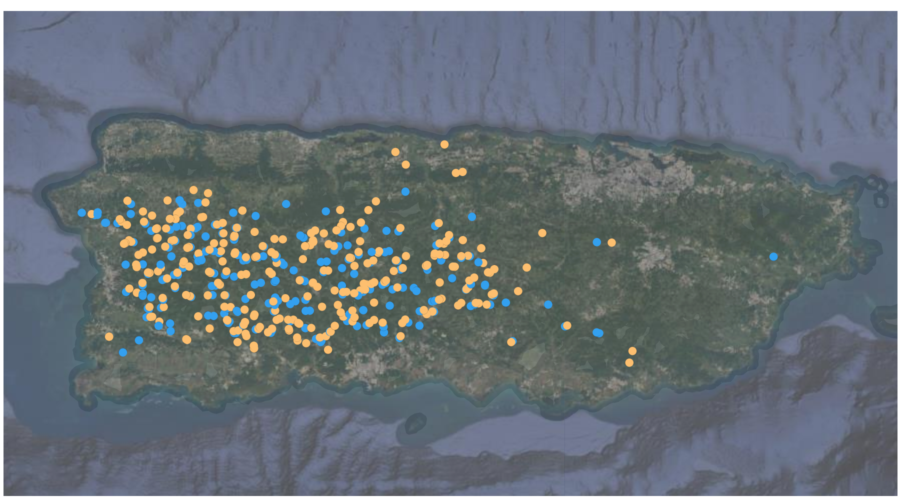

Figure 4. Study area: Puerto Rico shown with the location of sun (orange) and shade (blue) farms censused during 2013-2016 by the Caribbean Climate Hub.

Climate Data

Climate variables for total annual precipitation, average annual temperature, average minimum temperature, and average maximum temperature were sourced from the PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 4 Feb 2004.

> The PRISM (Parameter-elevation Relationships on Independent Slopes Model) interpolation method was used to develop data sets that reflected, as closely as possible, the current state of knowledge of spatial climate patterns in the United States. PRISM calculates a climate–elevation regression for each digital elevation model (DEM) grid cell, and stations entering the regression are assigned weights based primarily on the physiographic similarity of the station to the grid cell. Factors considered are location, elevation, coastal proximity, topographic facet orientation, vertical atmospheric layer, topographic position, and orographic effectiveness of the terrain. Surface stations used in the analysis numbered nearly 13 000 for precipitation and 10 000 for temperature. Station data were spatially quality controlled, and short-period-of-record averages adjusted to better reflect the 1971–2000 period. (Daly et al., 2008)

These data are at a 450m grid cell resolution and are 33-year "normals" for Puerto Rico between 1963 and 1995. These data were mapped to the CCH census data set using "sample raster values" in QGIS 3.22.11 to provide values for total annual precipitation (mm), minimum annual temperature (degrees C), maximum annual temperature (degrees C), and average annual temperature (degrees C). Average annual temperature is calculated by following standard global climate procedures – adding maximum and minimum temperatures together and dividing by two.

Analysis Procedures

Statistical analysis was performed in R version 4.2.2. Climatic variables and Caribbean Climate Hub Agricultural Statistics were bound by gps coordinates in QGIS 3.22.11 with "sample raster values." The maps for average annual precipitation and average annual temperature for Puerto Rico were made using QGIS 3.22.11 and Adobe Illustrator. For some analyses comparing shade and sun coffee, only farms 65 hectares and under were assessed because shade farms were not larger than 65 hectares and there were limited data for large sun farms.

Shade and sun farm size, yield per area planted, and land use efficacy were compared using a Wilcoxon t-test. Outliers were removed that were above 3 standard deviations from the mean yield. The relationship between Total Farm Harvest and Farm size, with management type (shade or sun) as an interaction effect, was determined with a polynomial regression. To visually explore how yield responds to farm size and cultivation method (sun or shade), we used a locally estimated scatter plot (LOESS), or locally weighted regression. This had the formula *yield per area planted ~ farm size * cultivation method*. To determine the statistical strength of the response of yield to farm size and cultivation method, a generalized linear model was performed with the following equation *yield per area planted ~ farm size * cultivation method*. A polynomial factor was included to increase the model fit to the data, and a gamma log-linked generalized model was chosen to accommodate the left-skewed continuous data. *glm(yield per area planted ~ poly(area planted, 2)* cultivation method, data=datasizesubset, family = Gamma(link = "log"))*

In assessing how the climate variables average total precipitation (1963-1995) and average annual temperature (1963-1995) influenced yield, gamma log-linked generalized linear models were used.

Yield per area planted ~ average total precipitation (1963-1995).

Yield per area planted ~ average annual temperature (1963-1995)

To determine if cultivation method influenced the impact of precipitation or temperature on yield per area planted, a gamma log-linked generalized linear model was used with cultivation method added as an interaction effect.

*yield per area planted ~ average total precipitation (1963-1995) * cultivation method*

*yield per area planted ~ average annual temperature (1963-1995) * cultivation method*

To determine if the impacts of temperature and precipitation had different effects on yield when both considered in the model, a log-linked gamma generalized linear model was used with formula *yield ~ average annual temperature + total annual precipitation.*

To calculate the number of farms and number of hectares in different cultivation types that were in the suitable range of coffee for temperature and precipitation, values were selected for within the precipitation range of 1905mm – 2540mm, minimum precipitation of 1000m, 18 degrees C – 21 degrees C for *Coffee. arabica* and 22 degrees C – 26 degrees C for *Coffee robusta* (DaMatta et al., 2007; Muñiz et al., 2018)

Results

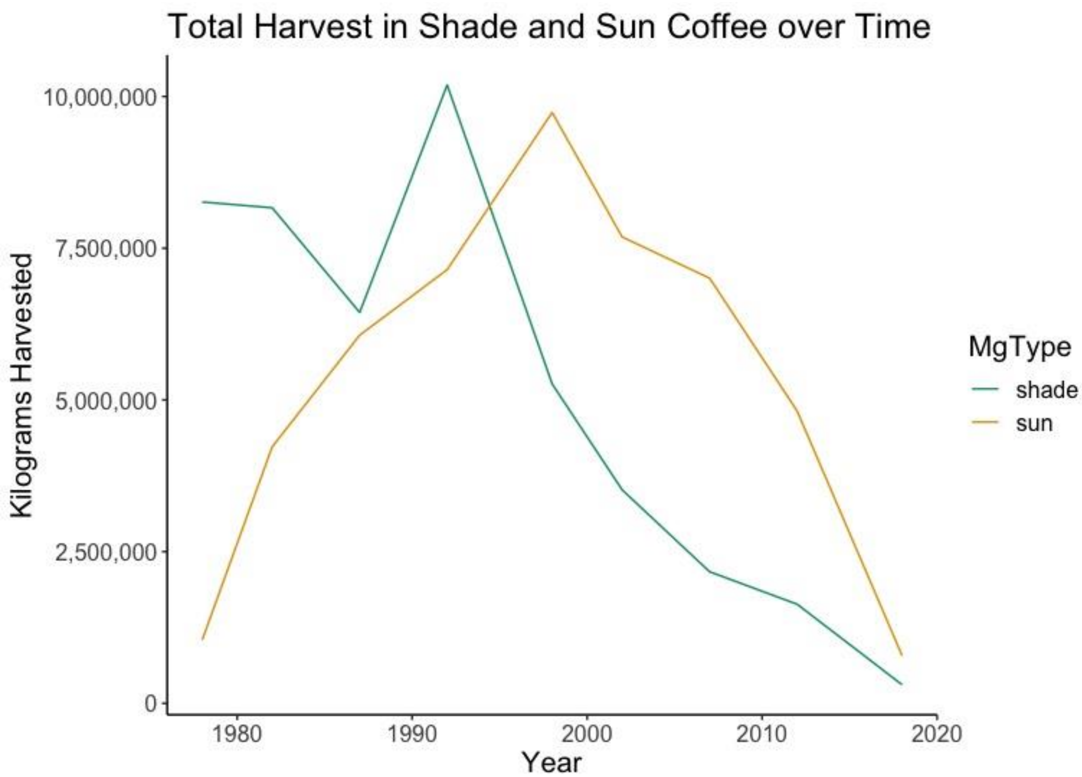

Figure 5. The total annual coffee harvest in kilograms of shade and sun coffee in Puerto Rico from 1978 to 2018. Shade coffee has seen a downward trend since the late 1970's. Sun coffee had a steep rise in total harvest from the 1970's, peaking in 1998, then decreasing in total harvest until 2018. Source: 2019 USDA Census of Agriculture

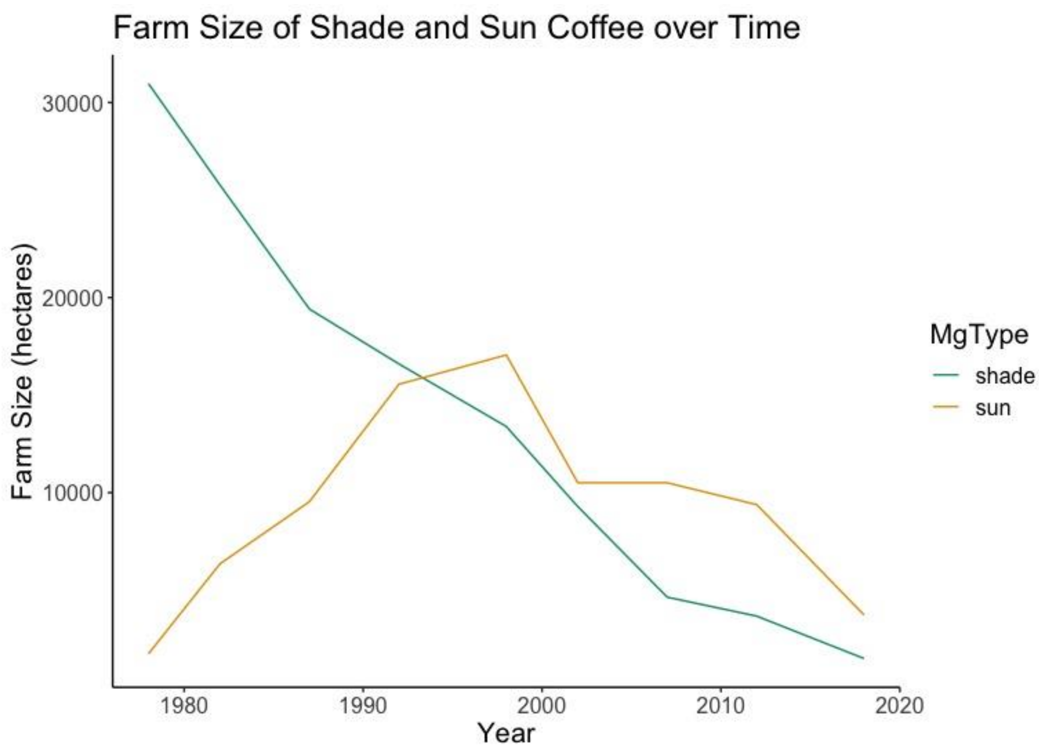

Figure 6. Total annual area of coffee farms censused every 5 years from 1978 to 2018 in Puerto Rico. The total area of shade farms decreased from 1978 to 2018. Sun farms increased from 1972 to 1998, peaking at 9,736,768.8 kilograms before decreasing to 785,708.4 kilograms in 2018. Data Source: 2019 USDA Census of Agriculture Historical Archive

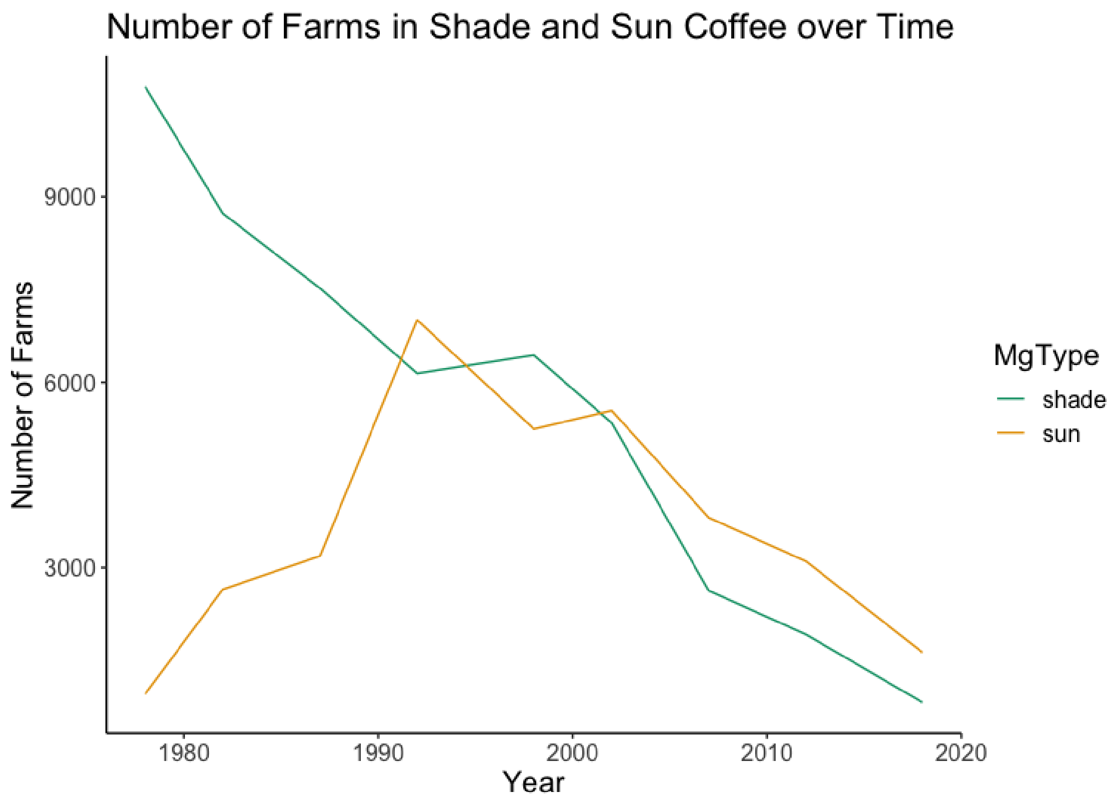

Figure 7. The annual number of coffee farms censused every 5 years from 1978 to 2018 in Puerto Rico. The total number of shade farms decreased from 1978 to 2018. Sun farms increased from 1972 to 1992, peaking at 7007 farms before decreasing to 1627 farms in 2018. Data Source: 2019 USDA Census of Agriculture Historical Archive

From the 2013-2016 Caribbean Climate Hub census, shade farms ranged in size between 0.22 and 66.420 hectares in size, with an average farm size of 7.559 hectares (figure 8a). Sun farms ranged in size between 0.39 and 243.58 hectares in size, with an average farm size of 26.38 hectares. Between 2013 and 2016, Puerto Rican shade coffee farms were, on average, are smaller than sun farms (p-value = 2.3e-14, figure 8a).

Shade farms have an average yield per area planted of 359.5 kg/hectare, and sun an average yield per area planted of 392.6 kg/hectare, which did not demonstrate a statistically significant (p-value = 0.051, figure 8b). Yield per area harvested, however, did show a significant difference, with shade farms harvesting 403.1 kg/hectare, and sun farms harvesting 457.4 kg/hectare (p-value = 0.0011, figure 8d). Shade farms harvest a higher proportion of their land that is planted with coffee (p-value = 2.7e-09, figure 8c), thus showing a higher land use efficacy.

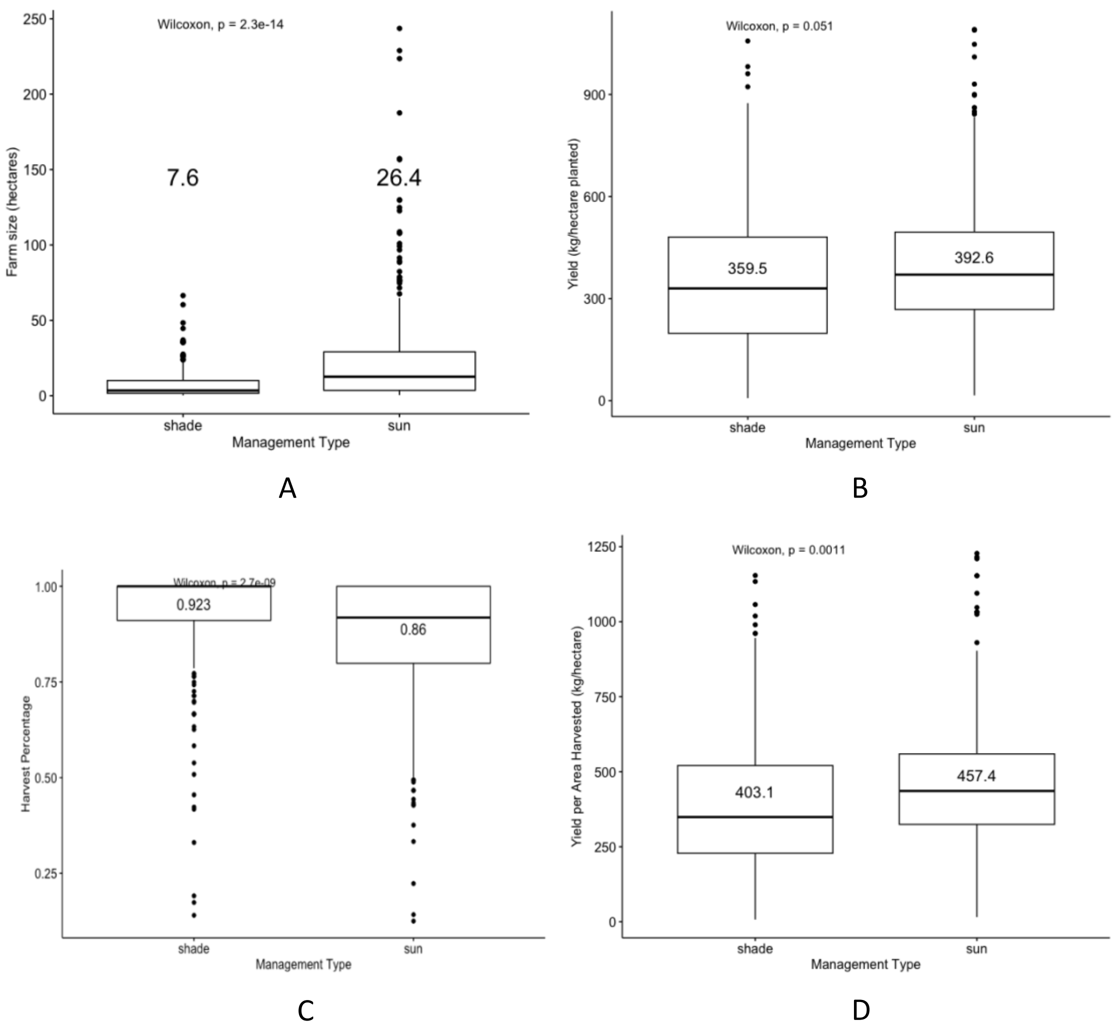

Figure 8. Wilcoxon T-Test of shade and sun farms in Puerto Rico censused by the USDA Caribbean Climate Hub between 2013 and 2016. (A) Boxplot of farm size (ha). (B) Boxplot of yield per area planted (kg/ha). (C) Boxplot of Harvest Percentage (Land Use Efficacy). (D) Boxplot of yield per area harvested (kg/ha).

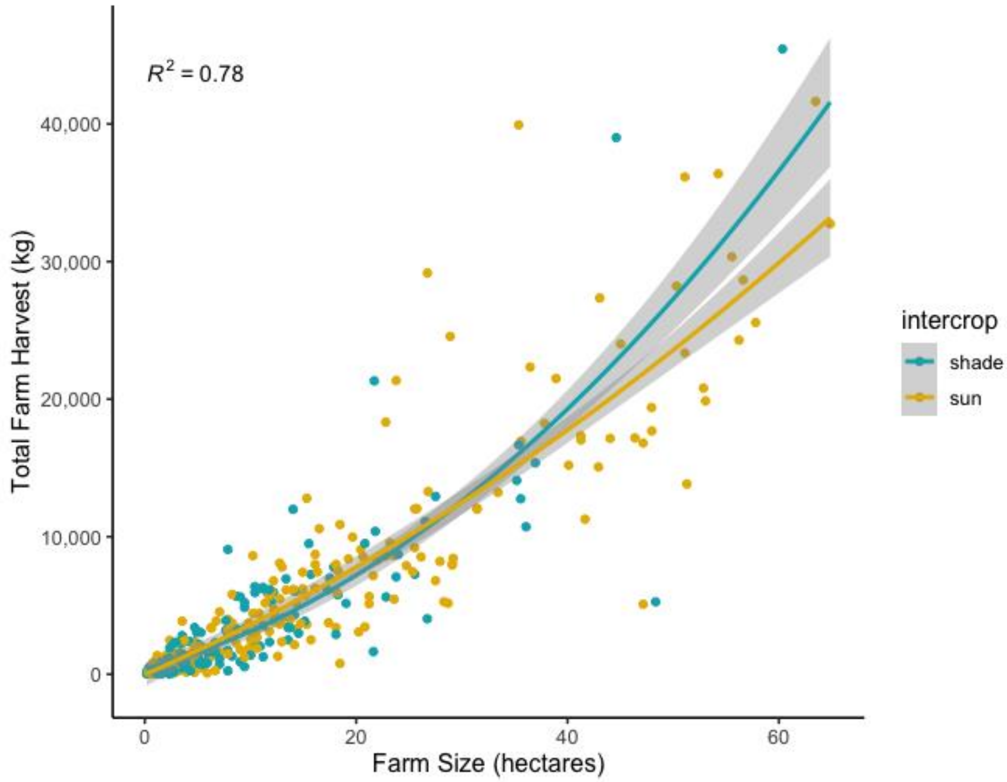

Figure 9. A polynomial Regression of the response of total farm harvest (kg) to farm size (ha) with cultivation method (shade and sun) as an interaction effect (R2 = 0.78). This data is subset to 65 ha due to limited data points above this value. Both shade and sun demonstrate a non-linear relationship between farm size and total farm harvest, with cultivation method expressing a slight but not significant interaction effect.

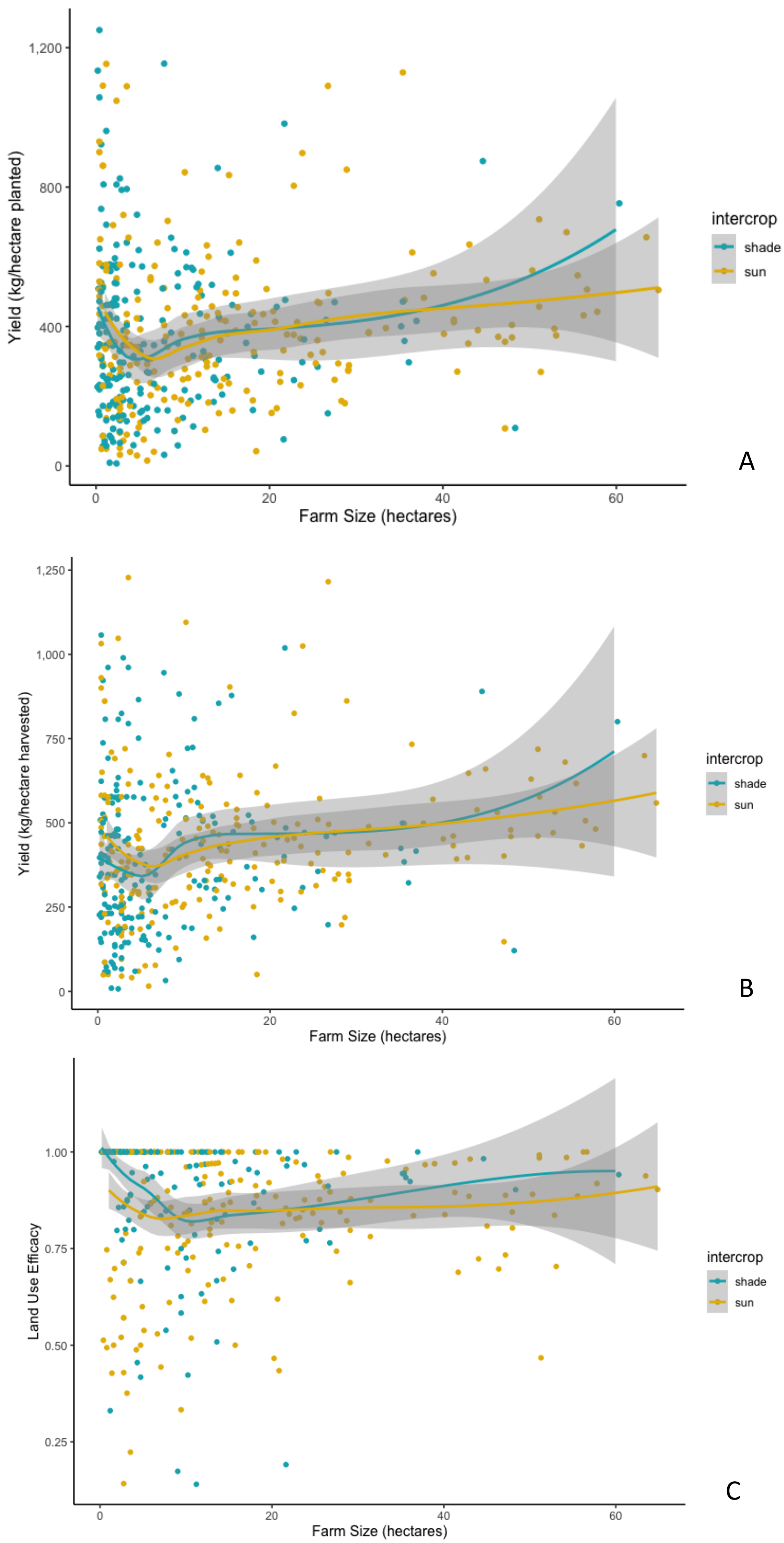
1,200
800
400
0
Yield (kg/hectare planted)
0
20
40
60
Farm Size (hectares)
intercrop
shade
sun
A
1,250
1,000
750
500
250
0
Yield (kg/hectare harvested)
0
20
40
60
Farm Size (hectares)
intercrop
shade
sun
B
1.00
0.75
0.50
0.25
Land Use Efficacy
0
20
40
60
Farm Size (hectares)
intercrop
shade
sun
C

Figure 10

Figure 10. Locally Estimated Scatterplot Smoothing / Local Regression of (A) yield per area planted (kg/ha), (B) yield per area harvested (kg/ha), (C) land use efficacy as a function of farm size (ha) with cultivation method (shade and sun) as an interaction effect. This data is subset to 65 ha due to limited data points above this value. Shade and sun farms show similar trends in the relationship between yield and farm size. Yields tend to be higher at very small farm sizes, decreasing as farms increase in size at around 5 hectares, then show a positive relationship with yield increasing as farm size increases. However, the yield does not surpass the yield of the very small farms until the farm size is above 40 hectares. Shade farms below 5 ha show a greater land use efficacy than sun farms of the same sizes, then both farms follow the same trends, decreasing in LUE until 10 ha, then remaining consistent as farm sizes increase.

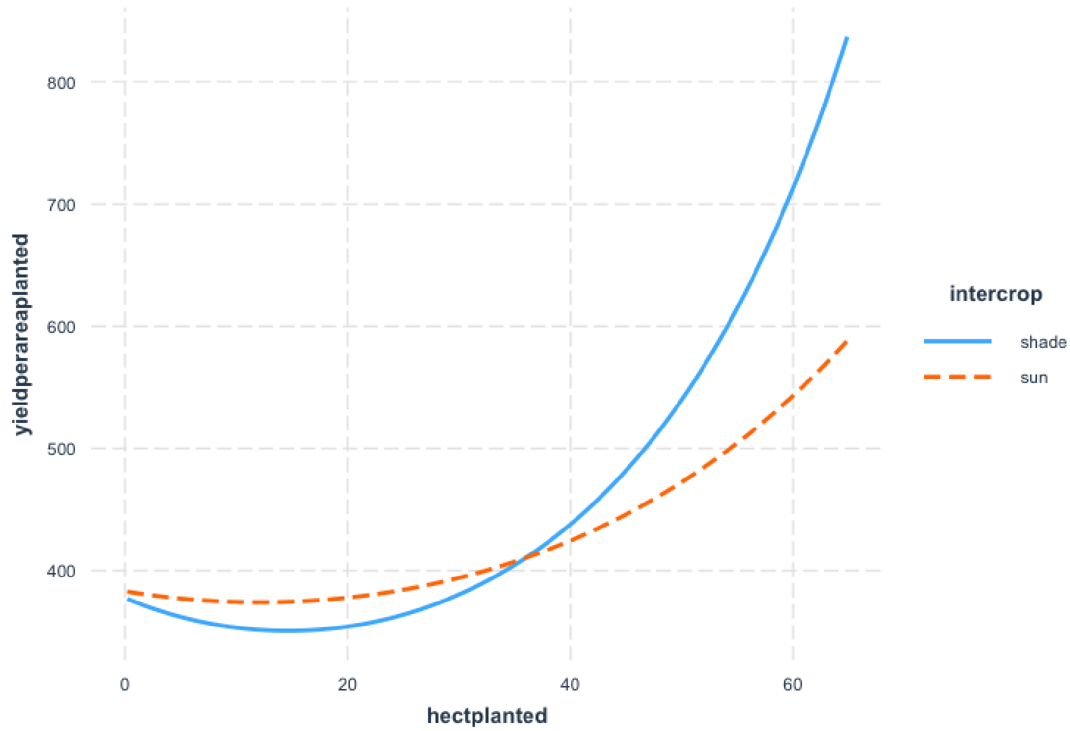

Figure 11. A generalized polynomial model with gamma log-linked distribution showing yield per area planted (kg/ha) as a function of farm size (ha) with cultivation method (shade and sun) as an interaction effect. Farm size has a significant relationship with yield per area planted, but there not a significant interaction effect of management type on the relationship between farm size and yield. In other words, shade and sun farms did not significantly differ in yield, and the size of the farm had a larger impact on yield than management type. The relationship between farm size and yield follows a positive parametric shape. Model output in appendix.

Precipitation

A farm's suitability for coffee is in part determined by precipitation patterns. An area's total annual precipitation is a primary metric. While the impact of precipitation is modified by the water retention of the soil, atmospheric humidity, and farming practices, the optimal conditions for coffee in Puerto Rico are between 1905mm and 2540mm a year, with the minimum for viable plants around 1000mm (Fain et al., 2018; Muñiz et al., 2018; Teketay, 1999). A map of the total annual precipitation for Puerto Rico, averaged between the years of 1963 and 1995, is in the discussion as figure 14. This is what was used for calculating each farm's annual average precipitation.

53.92% of all farms sampled in the climate hub between 2013 and 2016 were in the optimal precipitation range. When considering respective total farm size differences, shade and sun farms were equally represented in this distribution. 59.74% of shade acreage and 57.38% of sun acreage were in the optimal precipitation conditions. All farms were above the minimum required annual precipitation of 1000mm.

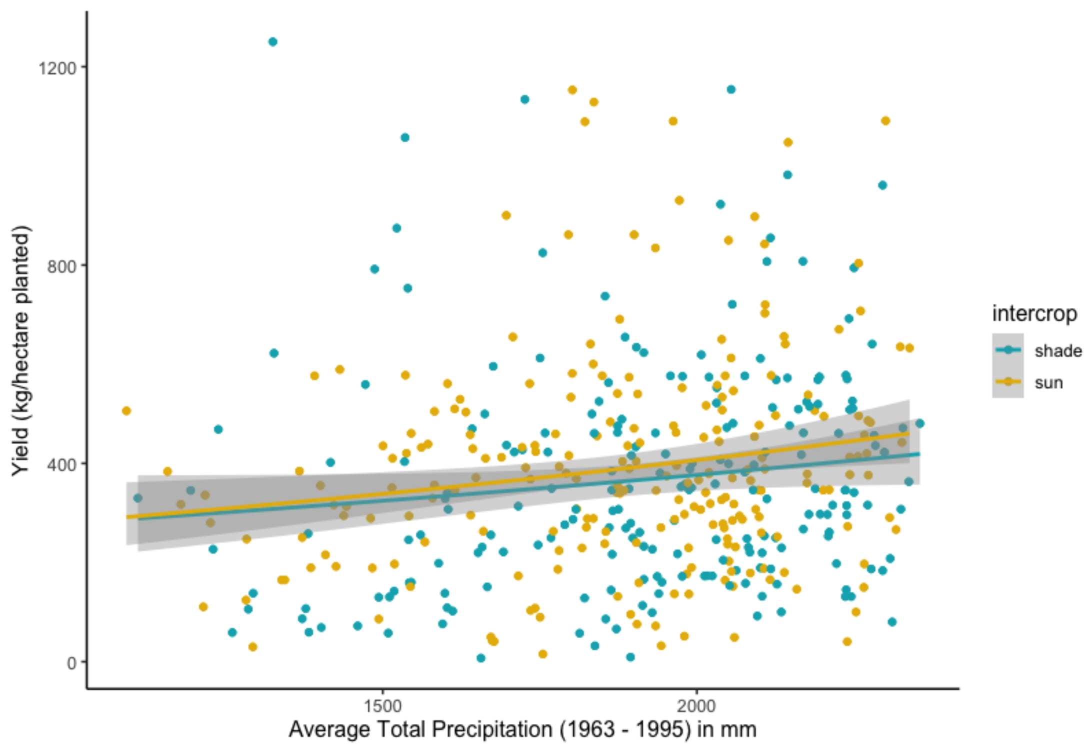

Figure 12. A generalized polynomial model using a log-linked gamma distribution of yield per area planted (kg/ha) as a function of average annual total precipitation (mm) (1963-1995) with cultivation method (shade and sun) as an interaction effect. There is a significant positive relationship between total annual precipitation and yield for the farms sampled in the climate hub census (p-value = 0.0015). There does not appear to be an interaction effect of intercropping management on precipitation's relationship with yield.

Temperature

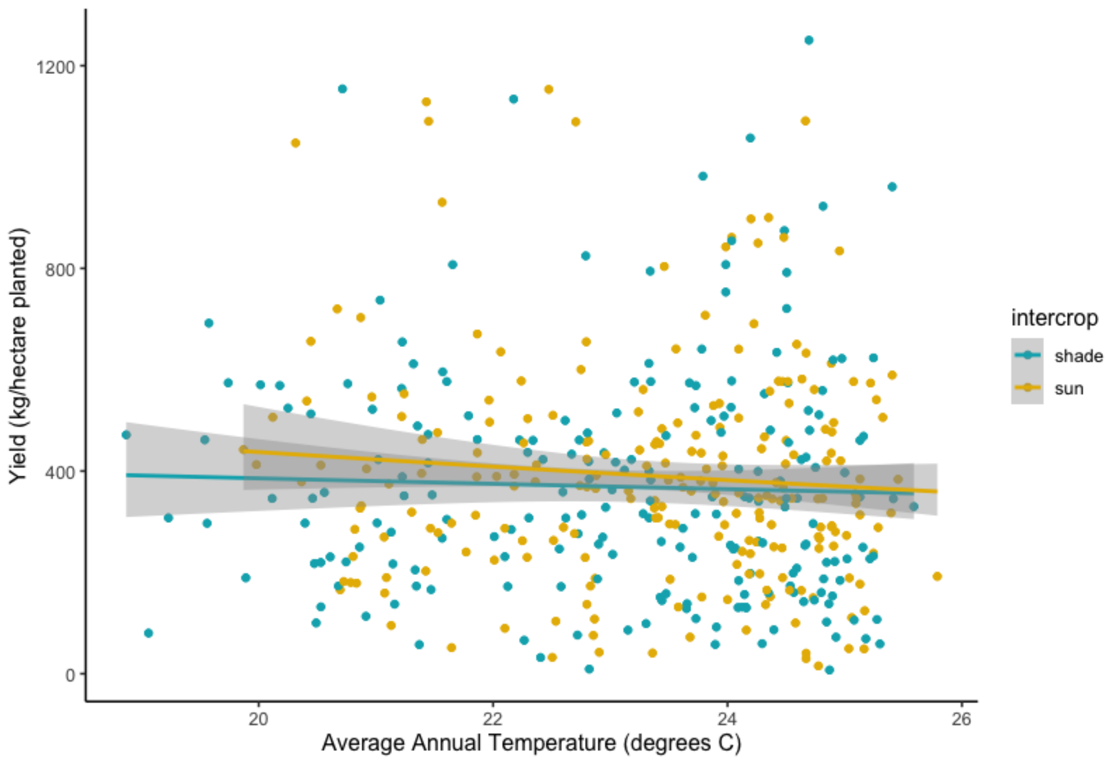

Figure 13. A generalized polynomial model using a log-linked gamma distribution of yield per area planted (kg/ha) as a function of average annual temperature (degrees C) (1963-1995) with cultivation method (shade and sun) as an interaction effect. There is not a significant relationship between average annual temperature and yield for the farms sampled in the climate hub census.

According to the data analyzed, there does not appear to be a strong relationship between annual temperature and yield (fig. 13) When assessing how the yield of all farms responds to annual temperature, there appears to be a slight negative relationship, but this is not statistically significant. There does not appear to be an interaction effect of cultivation method, although sun coffee does show a more negative decline in yield with increasing temperature than shade, but this is not statistically significant (fig. 13). Similar analyses were run for maximum and minimum temperatures and no apparent relationships were found.

Modeling Temperature and Precipitation Together

A log-linked gamma GLM with formula yield ~ average annual temperature + total annual precipitation indicated that annual precipitation had a significant positive relationship on yield (p-value = 0.0035), while average annual temperature had an insignificant negative relationship on yield (p-value = 0.8377). These results affirm the previous analyses and show how precipitation is a stronger predictor of yield than temperature. Output for this analysis is in the appendix.

Discussion

In collaboration with farmers and scientists of Puerto Rico, we sought more understanding of diversified and ecologically symbiotic agricultural methods to support the people and environments of the region. Researchers and agricultural scientist in Puerto Rico at the USDA Caribbean Climate Hub collected census data from farmers between the years 2013 and 2016, in addition to more general agricultural census data collected between 1978 and 2018. We assessed this data, in conjunction with global climate data, to provide summaries and trends that can inform farmers, policymakers, and researchers on stewardship decisions that can provide for people and the environment, especially in changing climatic conditions. We focused on two different methods of growing coffee, shade and sun-grown, farm size trends, various metrics of yield, and responses of yield to precipitation and temperature.

Trends in Farm Size and Cultivation Methods

Between 2012 and 2018, the total number of all types of farms in Puerto Rico and the total land area of farms decreased, while the average size of farms increased (USDA 2017). Coffee farms are not an exception to this trend. From 1978 to 2018, the number of coffee farms, the total land of coffee farms, and the total production of coffee has greatly decreased (fig. 5, 6, 7). The total number of farms in 1978 was 11,736. Now there are fewer than 2,500.

As the number, total land, and total production of shade and sun-farms has been decreasing over the past 40 years, the average size of farms has been increasing. These larger farms are often sun-farms. According to our analysis, shade-farms and sun-farms between 2012 and 2016 are statistically different in size (p-value = 2.7e-09). On average, shade farms are 18.8 hectares smaller than sun-farms. Sun-farms also show a much greater range of farm sizes, with the largest farm censused being 243.58 hectares compared to shade-farm's largest being 66.42 hectares. In the mid-1990's, sun-coffee overtook shade-coffee in its contribution to the total amount of coffee harvested, and the total amount of land in coffee cultivation (figure 5 and 6). This signifies a paradigm shift in agriculture towards more industrial methods of cultivation – larger farms that cultivate sun-grown monoculture fields of coffee. Additionally, the economic policies of Operation Bootstrap in the 1980's, which promoted industrialization, US-like development, and discouraged agricultural careers, left a hole in the landscape previously held by small-scale shade-grown coffee farmers. This empty space was filled by high-capital corporations that could operate larger coarse-scale industrial sun-grown farms with less labor than the fine-scale management of smaller shade-farms. These changes in coffee cultivation over time: the increased prevalence of sun-grown coffee, the decrease in the total number of farms with an increasing size of farms, has important repercussions for people and the environment. Monocultural coffee farms reduce landscape connectivity (Grass et al., 2019), which is vital for the maintenance of viable populations of wildlife that support the biodiversity necessary for functional ecosystems (Cardinale et al., 2012; Grass et al., 2019)

Some have argued that these negative ecological impacts are justified because the sun-grown cultivation method has high yields, allowing for less land to be needed for agriculture and more can be spared for conservation (Green et al., 2005; Phalan, Onial, et al., 2011). While this perspective has been heavily rebutted by discussions on landscape connectivity, meta-population dynamics and wildlife migration (Perfecto & Vandermeer, 2008, 2010; Perfecto et al., 2009), it stands that more understanding on the nature of the land use of shade and sun cultivation and their apparent yields can further inform cultivation decisions and trends in farming practices over time. The production of coffee on these farms, their yield, is an important metric when considering how coffee cultivation supports the livelihoods of those who choose to grow coffee. It is important to note, however, that a heavy focus on high yield is not always the case for agriculturalists. Certain peasant movements and ecologically focused farmers oppose placing priority on high yields, instead emphasizing practices that promote ecological health, self-sufficiency, and community (van der Ploeg, 2008). Further, the "productionists trap" created by the *Borlaug Hypothesis* warns of the consequences of a yield focused perspective on agriculture (Fouilleux et al., 2017). Nonetheless, yield remains important for farmers who must consider their production in supporting their livelihoods.

Impact of Farm Size and Cultivation Method on Yields

According to our analyses, shade and sun-farms do not show evidence of strong differences in yield overall but do have differences in their land use efficacy. More specifically, the yield per area planted (kg/hectare planted), a yield metric that accounts for not only the harvested areas of a farm but the entire productivity of the farm, was not significantly different between shade and sun (p-value = 0.051). When only considering harvested areas, sun-farms yielded more, on average (p-value = 0.001). However, to account for the correlation between farm size and cultivation method (shade and sun), both were included in regression models. When both farm size and cultivation method (shade and sun) are considered in the same model (glm and loess), cultivation method does not show a significant influence on yield (fig. 10a, 10b, 11).

When modeling total farm harvest as a function of farm size, the relationship fit a positive polynomial regression (R2 = 0.78). In other words, the relationship between yield and farm size does not increase linearly, instead having higher yields at either end of the farm size spectrum. Since shade and sun farms are, on average, different in size, it was not clear if the farm size or the cultivation method was impacting the yield. According to a generalized linear model with yield per areas planted as a response to farm size with cultivation method as an interaction effect, farm size shows a statistically significant positive polynomial relationship with yield per area planted, but cultivation method does not appear to have a strong influence on this. In other words, farm size, and not shade or sun cultivation, influences yield.

The nature of this relationship is more descriptively showcased in figure 10. Here, a series of LOESS illustrates how as farm sizes increase, yield decreases and then eventually starts to increase again, following a rough u-shape. Again, shade and sun both appear to follow the same relationship, and don't statistically differ in their overall yield or impact on the relationship between farm size and yield. This complicates early inverse-farm-size-relationship theories, instead depicting a continuum of yield and farm size dynamics. While we don't have data to insinuate causality, it could be due to a range of causes. Basic economies of scale may result in this dynamic, where the labor and capital required to manage a farm can be stretched and strained as the total area of a farm increases until a point in which more labor, equipment, and inputs must be attained to continue managing the farm for high yields. A farm must be large enough to justify and support these added expenses, creating a valley between these jumps in investment. This is further complicated by increased organization and management of labor, resources, and landscape as farms increase in size.

The proportion of land in cultivation that is harvested also differed based on cultivation method and farm. Shade-farms harvest a greater proportion of their land, at 92.3% compared to 86% for sun-farms (p-value < 0.5). This indicates that sun-farms occasionally have higher yield per area harvested than shade-farms but have a greater proportion of their land that goes unharvested. There are many reasons why this may be. For instance, this could be due to a lack of labor force, a fallow/rest period, or failed crop production due to pests, disease, or poor resilience to climatic events. Newly planted coffee trees also take 2 to 5 years to reach maturity, in which case these "planted" hectares would not be harvestable. Therefore, it is difficult to draw larger conclusions on land use here other than that shade-farms, on average, harvest a greater proportion of their land than sun-farms.

Farm size was related to land use efficacy (LUE), as well, with smaller farms (~5 hectares) harvesting a greater proportion of land in cultivation than larger farms (fig. 10c). As farms increased in size, they had the lowest LUE around 10 ha, then slowly increase and plateau in LUE as farm size increases. Differences between shade and sun farms do not appear significant in farm sized over 10 ha.

To visually see a comparison between these dynamics, figure 14 illustrates an example of a sun-farm and shade-farm with the same area planted, total farm yield, yield per area planted, but different land use efficacies, yield per area harvested, and ecosystem/biodiversity impacts. Even with a greater amount of the land being harvested, intercropped and shade-grown coffee provides more support for ecosystem functioning and biodiversity with similar total yield and "productivity". We get closer to understanding the true nature of farming systems by assessing a farm's yield per area planted, land use efficacy, and ecosystem impacts.

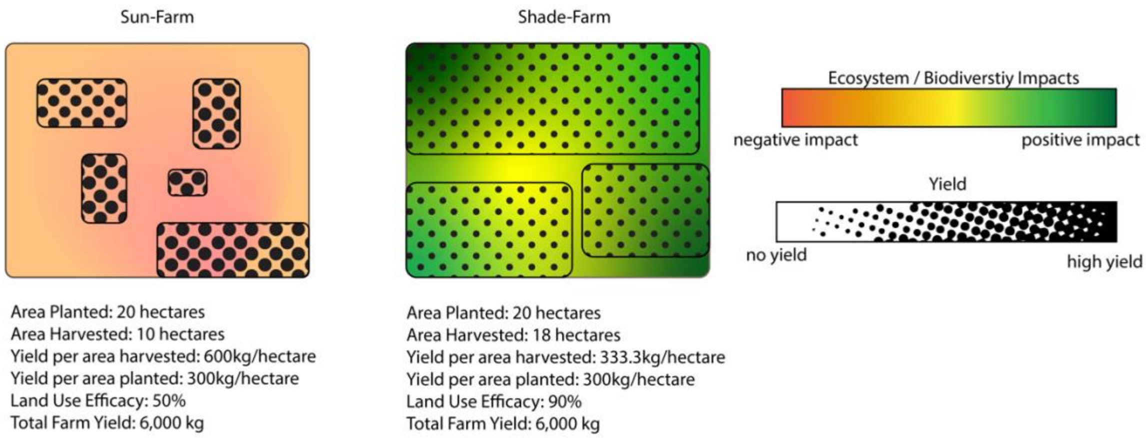

Figure 14. Example of sun-farm and shade-farm that overlays ecosystem/biodiversity impacts with different spatial yield dynamics, illustrating how different practices can use space differently while still producing the same total farm yield, and that these can be associating with different ecosystem/biodiversity impacts.

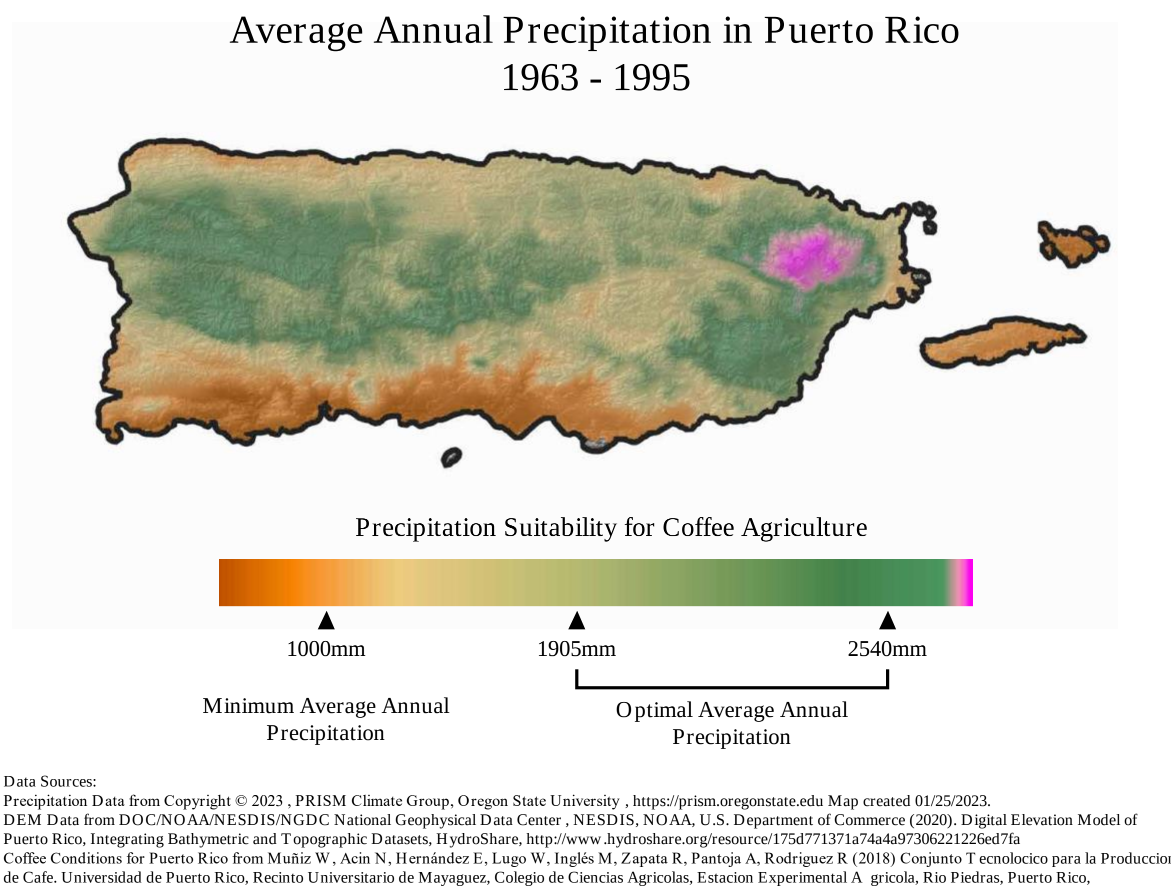

Figure 15. Map of average annual precipitation in Puerto Rico between 1963 and 1995 indicating precipitation suitability for coffee agriculture.

The yield of sun and shade farms did not respond differently to total annual precipitation. This may be due to variability in irrigation, pesticide use, and fertilizer use since those can moderate the impacts of precipitation. While around 50% of coffee farms censused were in the optimal range, this is expected to decline in future climate scenarios (Fain et al., 2018), however, the current primary growing regions in Puerto Rico should remain above the minimum requirements for arabica coffee (Fain et al., 2018). Other patterns in precipitation are important to consider, such as periods of dry conditions during the dry season which are important for synchronizing fruiting, and periods of heavy rainfall during fruiting season which can possibly lead to higher rates of rotting and fungal infection.

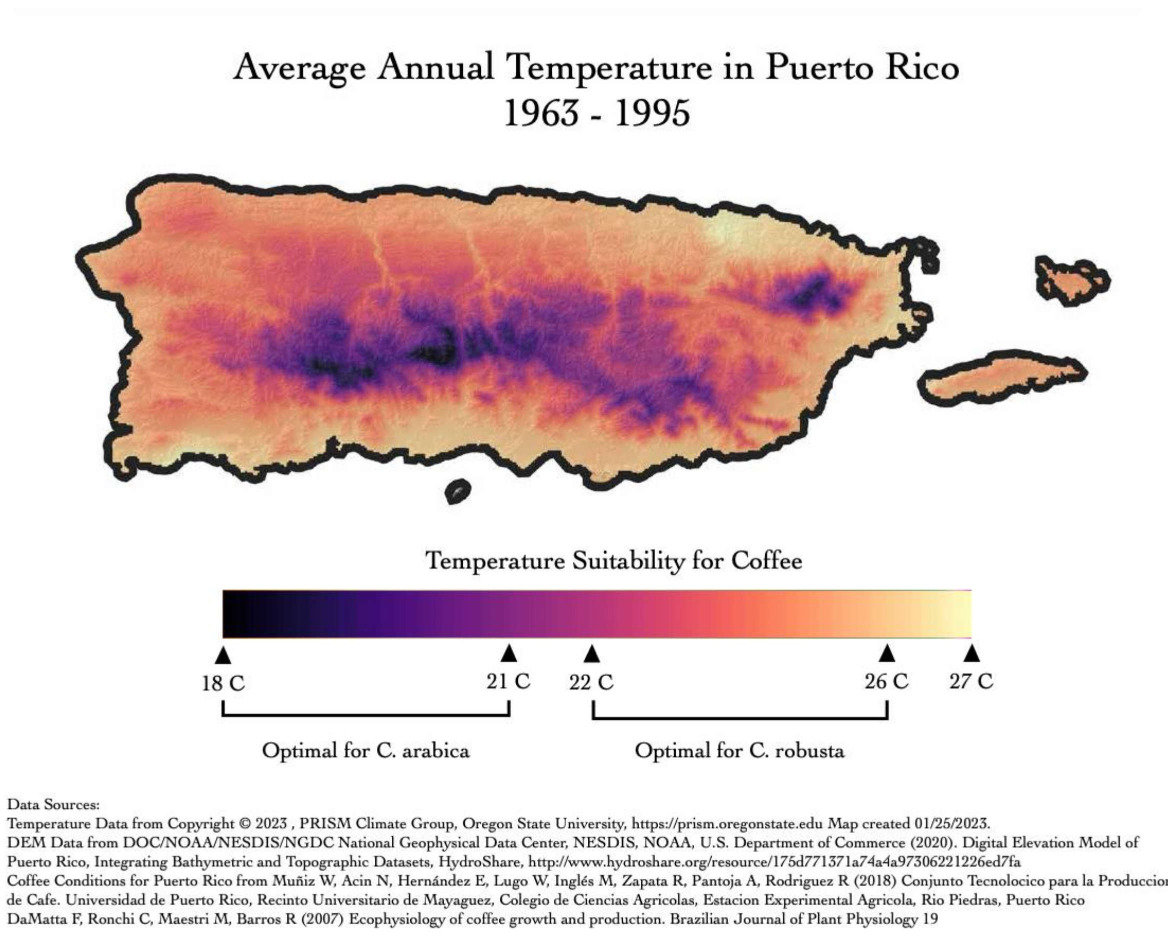

Figure 16. Map of average annual temperature in Puerto Rico from 1963 to 1995, indicating the optimal temperature ranges for *Coffee arabica* (18-21° C) and *Coffee robusta* (22-26° C).

Average annual temperature varies greatly across Puerto Rico (fig. 16) and has been an important predictor of coffee yields in Puerto Rico and elsewhere (DaMatta et al., 2007; Fain et al., 2018; Muñiz et al., 2018). High temperature can cause heat stress, especially during flowering and fruiting season when extreme high temperatures can lead to coffee plants aborting their fruit. Coffee varieties differ in their optimal temperature ranges. The two principal varieties are *Coffee arabica* (Arabica) and *Coffee canephora var robusta* (Robusta), with *C. arabica* being the primary species in Puerto Rico. Arabica coffee's optimal annual temperature range falls between 18 – 21 ° C (Alègre, 1959), however certain cultivars and with intensive management, Arabica coffee has yielded well up to 25° C (DaMatta & Ramalho, 2006). On the other hand, robusta coffee has a higher optimal average annual temperature range, between 22° C and 26 ° C (Matiello, 1998), and possibly up to 27 ° C (Bunn et al., 2014). Annual maximum and minimum temperatures can provide a proxy for extreme temperature events that can cause stress to coffee plants.

When assessing how the yield of all farms responds to annual temperature, there appears to be a negative relationship, but this is not statistically significant. To further understand if shade or sun farms differed in the response of yield to temperature, management type was added as an interaction. There does not appear to be an interaction effect, although sun coffee does show a more negative decline in yield with increasing temperature than shade, but this is not statistically significant. Similar analyses were run for maximum and minimum temperatures and no apparent relationships were found.

These results can be expected, as all farms analyzed fell within the range of conditions in which coffee produces viable yields. Both irrigation and shade management have evidence of mitigating the consequences of high temperature (DaMatta & Ramalho, 2006; Jassogne et al., 2013), both practices which are common in Puerto Rico. However, we can expect this to change in the future with climate change. Estimates for future temperature change in Puerto Rico predict a large loss of suitable land for coffee production, under all possible scenarios (Fain et al., 2018). According to Fain et al's predictive models, under "business-as-usual" GHG emissions, by 2100, there will be no suitable land within the temperature range for either arabica or robusta coffee. These models, however, do not account for the increased photosynthetic functioning of plants under elevated CO_2 levels, which has been shown to mitigate the impact of above-optimal temperatures in arabica and rustica coffee (Rodrigues et al., 2016). Further, adaptive strategies including plant breeding and diversified shade coffee management can increase resilience to a changing climate.

Conclusion

Farming practices are changing in Puerto Rico, and this is likely the result of socio-economic changes and policies that promote industrial forms of agriculture. Additionally, extreme weather events have influenced coffee agriculture, such as Hurricanes Georges, Maria, and Fiona, each of which caused crop damage and negative economic impacts. We found that sun-farms are generally larger than shade-farms and make up a greater proportion of farmland, and that yields are more influenced by farm size and precipitation than cultivation method.

This study was limited to the agricultural metrics and variables included in the census data. Future studies would benefit from observations on the use of pesticides, fertilizers, and irrigation, and how these may contribute to the degree of biodiversity and climate resilience of farming operations. Further, with the observed trends in land use efficacy, determining the causes of some farms harvesting smaller proportions of their cultivated land than others can shed light on economic and climatic resilience. While shade coffee and sun coffee did not exhibit strong differences in yield metrics, our understanding of farm resilience and food security would be supported by studies on the non-coffee crops and timber production of shade-grown farms.

Supplemental materials

Total Farm Harvest ~ Farm Size * Cultivation Method

```
lm(formula = Harvest ~ poly(Farmsize, 2) * intercrop, data = datasizesubset)

Residuals:
    Min      1Q  Median      3Q     Max
-20602.5   -820.9   -173.6    454.6  24663.4

Coefficients:
                      Estimate Std. Error t value Pr(>|t|)
(Intercept)                   4789.5      243.6  19.662  < 2e-16 ***
poly(Farmsize, 2)1            146531.1     7561.9  19.378  < 2e-16 ***
poly(Farmsize, 2)2             31393.4     6616.5   4.745 2.84e-06 ***
intercropsun                   -148.4      329.1  -0.451   0.6522
poly(Farmsize, 2)1:intercropsun -15499.3    8549.6  -1.813   0.0705 .
poly(Farmsize, 2)2:intercropsun -18387.1    7716.4  -2.383   0.0176 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 3230 on 434 degrees of freedom
Multiple R-squared:  0.7979,	Adjusted R-squared:  0.7956
F-statistic: 342.6 on 5 and 434 DF,  p-value: < 2.2e-16
```

Figure 17. Regression output for total farm harvest as a function of farm size with cultivation method as an interaction effect.

GLM with yield per area planted function of farm size and shade

```
glm(yieldperareaplanted ~ poly(hectplanted, 2)*intercrop, data=datasizesubset, family = Gamma(link =
"log"))
```

	Dependent variable:
	yieldperareaplanted
poly(hectplanted, 2)1	1.712
	(1.382)
poly(hectplanted, 2)2	1.656
	(1.209)
intercropsun	0.028
	(0.060)
poly(hectplanted, 2)1:intercropsun	-0.672
	(1.563)
poly(hectplanted, 2)2:intercropsun	-0.875
	(1.411)
Constant	5.926***
	(0.045)
Observations	440
Log Likelihood	-2,964.645
Akaike Inf. Crit.	5,941.291
Note:	*p<0.1; **p<0.05; ***p<0.01

Figure 18. Generalized linear model of yield per area planted as a function of farm size and cultivation method as an interaction effect.

```
Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       5.307e+00  2.854e-01  18.597   <2e-16 ***
annP             3.006e-04  1.470e-04   2.045   0.0415 *
intercropsun     -7.628e-03  3.961e-01  -0.019   0.9846
Farmsize         3.121e-03  2.243e-03   1.392   0.1648
annP:intercropsun  2.689e-05  2.073e-04   0.130   0.8968
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Gamma family taken to be 0.3573761)

    Null deviance: 180.67  on 439  degrees of freedom
Residual deviance: 175.88  on 435  degrees of freedom
AIC: 5933.9
Number of Fisher Scoring iterations: 6
```

Figure 19. Generalized linear model output of yield per area planted as a function of farm size and cultivation method as an interaction effect. Average annual precipitation shows a positive relationship with yield per area planted (p-value <2e-16).

(Dispersion parameter for Gamma family taken to be 0.3471065)

Null deviance: 180.67 on 439 degrees of freedom

Residual deviance: 179.67 on 436 degrees of freedom

AIC: 5941.9

```
                          Estimate Std. Error t value Pr(>|t|)
(Intercept)   6.23902    0.58217  10.717   <2e-16 ***
TaveragePrism_1  -0.01421    0.02513  -0.565    0.572
intercropsun    0.51861    0.86703   0.598    0.550
TaveragePrism_1:intercropsun -0.01963    0.03721  -0.528    0.598
```

Figure 20. Generalized linear model output of yield per area planted as a function of average annual temperature with cultivation method as an interaction effect.

```
Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept)          5.429516  0.562468  9.653  <2e-16 ***
TaveragePrism_1 -0.004040  0.019715 -0.205  0.8377
annP                 0.000317  0.000108  2.936  0.0035 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Gamma family taken to be
0.3502729)

   Null deviance: 180.67  on 439  degrees of freedom
Residual deviance: 177.19  on 437  degrees of freedom
AIC: 5933.4
```

Figure 21. Log-linked gamma generalized linear model output for yield per area planted as a response to average annual temperature (1963-1995) and total annual precipitation (1963-1995) where precipitation is a significant predictor of yield.

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