Tradeoffs and synergies among ecosystem services, biodiversity conservation, and food security in coffee agroforestry

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Contribution to the Field:

Rising concern about climate change and biodiversity loss have motivated popular discourse around the need to intensify agricultural production to match global population growth. Yet opportunities in agroforestry management, such as shade coffee production, can provide simultaneous benefits to ecosystem services that mitigate the effects of climate change and biodiversity conservation while still supporting food security. Our study leverages island-wide and individual farm-level data sets from Puerto Rico to evaluate the synergies and trade-offs associated with coffee agroforestry. Using a data set of 351 coffee farms spanning the entire island of Puerto Rico, we first evaluate the claim that intensified agricultural systems are more productive than those managed under principles of agroforestry. At the farm-level, we analyze the effect of management practices, including shade, ground cover, and crop richness, on the biodiversity of ants, lizards, and birds, and on non-provisioning ecosystem services such as carbon storage and hurricane resistance and resilience. Our results suggest that agroforestry management of coffee results in many more synergies than tradeoffs with no apparent loss in yield. This study supports other findings in the literature and offer new insights on the importance of scale in evaluating the outcomes of agroforestry management.

Abstract

Concerns over the capacity of the world's existing agricultural land to provide food for the global population under climate change and continued biodiversity loss have set the stage for a prevailing narrative of inherent tradeoffs with agricultural production. However, a strict focus on increasing production can undermine attempts to build more sustainable and equitable food systems. Coffee, a major export crop of tropical countries, offers a unique opportunity to examine how management practices can drive a variety of outcomes for food security, ecosystem services, and biodiversity conservation. Our study examined this intersection to identify tradeoffs and synergies using compiled data from Puerto Rico. At the island level, we analyzed data on coffee yield and area sown under shade or sun management. At the farm level, we analyzed management variables (percent shade cover, maximum canopy height, ground cover, and crop richness), non-provisioning ecosystem service variables (total farm carbon storage, soil organic carbon storage, coffee plant carbon biomass, and hurricane resistance and resilience), and biodiversity variables (ant, bird, and lizard richness and abundance). At the island level, we found that area sown was the most significant predictor of yield, suggesting no obvious tradeoff between yield and shade in coffee farms. At the farm level, canopy cover was negatively correlated with ground cover and positively correlated with crop richness, suggesting a synergy between agroforestry and food security. We detected mostly synergies resulting from agroforestry management and no tradeoffs among ecosystem services and biodiversity. Shade canopy cover significantly increased total carbon storage, coffee plant biomass, hurricane resistance and bird species richness. Shade canopy height had a similar positive effect on total farm carbon storage while crop richness had a positive effect on farm resilience following Hurricane Maria. Ground cover was positively associated with soil carbon storage and pest-controlling lizard abundance. Tradeoffs related to agroforestry management included an inverse relationship between ground cover and hurricane resistance, and greater dominance of an invasive ant species in farms with higher shade canopies. We discuss implications of practicing agroforestry principles in this smallholder coffee system and highlight opportunities for maximizing biodiversity conservation, ecosystem services, and food security.

Key words: shade coffee, agroforestry, ecosystem services, biodiversity conservation, food security, synergies and tradeoffs, Hurricane Maria, Puerto Rico

Introduction

Home to almost 3 million inhabitants and nearly that many coffee drinkers, Puerto Rico produces specialty coffee with congenial flavor profiles that are a product of both the dedicated livelihoods of smallholder coffee farmers and the cultural significance of the drink. Though coffee has been produced locally in the mountains of Puerto Rico since its introduction by either Spanish or Cosican immigrants in 1736, the island has grown increasingly reliant on imported food and processed supermarket goods (Diaz 2016) leaving food prices and supply vulnerable to disruptions from natural disasters and top-down trade policies such as the Jones Act (García-López 2018; Rodríguez-Díaz 2018). In addition, many of the agricultural support programs in Puerto Rico cater more towards large scale, high-input farming operations (Félix and Holt-Giménez 2017; Perfecto et al. 2009) than those that are more agroecological and aligned with the principles of food sovereignty, according to farmers (Diaz and Hunsberger 2018). Compared to “sun,” or conventional coffee growing operations, agroecological, or “shade,”coffee farms are often managed as agroforestry systems with a variety of shade trees (e.g. *Inga* spp., *Andira inermis*, *Guarea* spp.), fruit trees (e.g. citrus, avocado), and food crops (e.g. plantains and a variety of tubers) grown for sale or consumption by farming households in addition to coffee (Rice 2008; Cerda et al. 2017; Perfecto et al. 2019; Stratton et al. 2020).

The conservation and ecosystem service benefits of agroforestry management in coffee production include in-farm biodiversity conservation (Philpott et al. 2006; Bos et al. 2007; Hajian-Forooshani et al. 2014; Cely-Santos and Philpott 2019), the creation of a high quality agroecological matrix that facilitates migration of wildlife between forest fragments (Perfecto et al. 2007, Jha et al. 2014; Perfecto and Vandermeer 2015; Perfecto et al. 2019), increased soil drainage and water retention (Lin 2010; Cannavo et al. 2011), mitigation of temperature and climate fluctuations (Campanha et al. 2004; Lin 2007, de Souza et al. 2012; Jha et al. 2014; Rice 2018) improved soil quality (de Souza et al. 2012; Thomazini et al. 2015), carbon storage (Denu et al., 2016; De Beenhouwer et al. 2016), and reduced incidence of coffee pests and pathogens (López-Bravo et al. 2012; Rice 2018; Vandermeer and Perfecto 2019). Previous studies have also reported co-benefits, or synergies, between ecosystem services and biodiversity conservation such as greater carbon sequestration and higher tree diversity in coffee farms under agroforestry management than in more intensively managed coffee systems (Häger 2012, De Beenhouwer et al. 2016; Cerda et al. 2017; Guillemot et al. 2018).

Along with the potential synergies between agroforestry coffee production and ecosystem services, however, tradeoffs may also exist in the form of increased disease spread (Schroth et al. 2000; Avelino et al. 2020; Durand-Bessart et al. 2020), reduced or more variable coffee yields compared to conventionally-produced coffee (Campanha et al. 2004; Vaast et al. 2016; Durand-Bessart et al. 2020), and changes in the predator-prey dynamics of pests and biological control agents that are still under study (Staver et al. 2001; Hajian-Forooshani et al. 2016; Beilhe et al. 2020). Further, one of the greatest threats to Puerto Rico’s coffee growing operations comes from climate change and associated increase in hurricane frequency and severity. Under mid-high climate warming scenarios, Fain et al. (2018) predicted an acceleration of warming and drying trends in the coffee-producing region of Puerto Rico and a 47% loss of areas with optimal temperature, precipitation, and soil conditions for growing coffee. Additionally, other climate change models predict substantial increases in the intensity and frequency of the most intense tropical cyclones in the Atlantic (Elsner et al. 2008). Following the landfall of Hurricane Maria in September of 2017 (Category 4), sustained wind speeds of 155 mph (National Weather Service, 2017) inflicted widespread damage to shade trees and surrounding forest, as expected for a hurricane of this caliber (Perfecto et al. 2019), along with significant disruption to the island's weak infrastructure and the lives of vulnerable communities (Morris et al. 2018; Kwasinski et al. 2019; Orengo-Aguayo et al. 2019; Ma and Smith 2020; Yabe et al. 2020). Interviews with farmers also revealed a devastating loss of the coffee harvest, severely damaged coffee plants, and damage to most other crops as well (Perfecto et al. 2019), including those intended for local consumption and distribution. With widespread devastation to social, economic, and ecological systems in Puerto Rico, the damage inflicted by Hurricane Maria underscores the link between biodiversity conservation, ecosystem services, and food security within the coffee agroforestry system.

In this study, we leveraged a compilation of several datasets from Puerto Rico at the island and farm level to identify tradeoffs and synergies in the agroforestry system. At the island level, we analyzed data on coffee yield and area sown under shade or sun management. At the farm level, we analyzed continuous management variables (percent shade cover, maximum canopy height, percent ground cover, and crop richness), ecosystem services variables (total farm carbon storage, soil organic carbon storage, coffee plant carbon biomass, and hurricane resistance and resilience [determined by NDVI]), and biodiversity variables (ant, bird, and lizard abundance). At the regional scale, we predicted that farms classified as sun coffee operations would produce higher coffee yields than the more shaded, agroforestry coffee systems. At the local scale, however, we predicted that more shaded, agriculturally diverse coffee farms would be more strongly associated with ecosystem service provisioning (e.g., hurricane resistance and recovery, carbon storage) and biodiversity (e.g., anole lizards, birds, and ants). We discuss the implications of producing Puerto Rican coffee with agroforestry practices and highlight opportunities for maximizing biodiversity, ecosystem services, and food security based on our findings. Additional understanding of the associated potential tradeoffs and synergies in this system generated by our study will further inform the development of agroforestry management strategies that support both ecosystem functioning and local livelihoods.

Methods

1. Study area

   Our study was conducted in Puerto Rico with regional data (from the Caribbean Climate Hub, US Department of Agriculture [https://www.climatehubs.usda.gov/hubs/caribbean]) spanning most of the island's geography and local data collection concentrated in the central coffee-producing region on the central and western part of the Cordillera Central. Average annual temperature and precipitation within the region ranges from 22 ˚C to 26 ˚C, and from 904 mm to 2,439 mm, respectively. According to the Web Soil Survey (NRCS, 2005), the soils are predominantly Ultisols with some farm soils classified as Inceptisols and Oxisols. Following the Holdridge Life Zones classification, the study area includes subtropical moist forest, subtropical wet forest, and lower montane wet forest. Coffee farms in this study included a range of management strategies from more conventional (i.e., no shade trees or low density of shade trees) to more agroecological (i.e., agroforestry with medium to high density of shade trees) and produced coffee as their primary crop (mostly *Coffea arabica* but some *Coffea canephora*). Many of the farms also produce plantain (*Musa x paradisiaca* L.), ~~and~~ orange (*Citrus sinensis* (L.) Osbeck, and a variety of tubers (e.g., Xanthosoma spp., Colocasia spp.). According to the USDA 2017 Census of Agriculture (USDA-NASS, 2020), 76 percent of the farms are family owned and are 7 ha or smaller in size.

2. Data Sources

Two data sets were used for this study. For regional-scale coffee yields (island-wide), we used the USDA Caribbean Climate Hub data set (see below). For local-scale vegetation and carbon storage metrics, we used data collected within a 100 m^2 plot (10 m × 10 m) on 68 farms throughout the coffee production region of Puerto Rico. From those 68 farms, we selected 25 farms (effectively from the municipality of Orocovis in the center to Las Marias in the west). These 25 farms were selected as representative of the management types, based on shade cover and geographic position, and sampled for biodiversity of ants and anole lizards. Bird data was obtained from a separate data set of bird surveys conducted on 67 farms in the same region from which the 68 farms were sampled, though not necessarily on all those same farms. We matched the first and last names of the farmers from the bird data set to unique regional codes recorded in the vegetation and carbon estimate data which allowed us to merge bird survey data for 46 farms to a compiled data set that included all of our other variables.

3. Regional Data

Island-wide coffee production data (n= 351) was obtained from the USDA Caribbean Climate Hub (2016) based on surveys with farmers and included: municipality, scientific name (*Coffea spp*.), management type (a binary classification: shade or sun grown), production (kg), area sown (ha), harvested area (ha), and geographic point locations for the most recent year available (2016)(Figure 1). Yield was calculated by dividing coffee production (kg) by area harvested (ha).

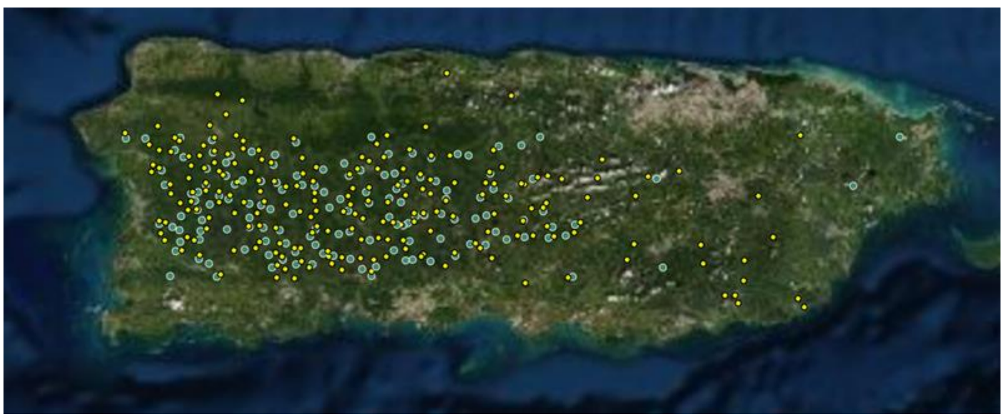

Figure 1: Spatial distribution of shaded (green circles) and unshaded (yellow circles) coffee farms in Puerto Rico from the Carribean Climate Hub (n = 351).

Regional Data Statistical Analysis

Island-level yield data was analyzed in R version 1.3.1093 (R Core Team 2020). Instances of 0 kg harvest on a non-zero harvested area (N = 58) were omitted as well as the top 3 yield outliers of the square-root transformed normally distributed dataset (z-score > 3). Two-sample t-test assumptions were verified using the *car* package version 3.0-10 (Fox and Weisberg 2019) to confirm the normality of transformed yield distributions with the Shapiro-Wilk Test (p = 0.05746, sun grown coffee; p = 0.5943, shade grown coffee) and equal. We then ran a linear mixed model analysis using the *lme4* package version 1.1-26 (Bates et al. 2015) including coffee yield as the dependent variable and added fixed effects of area sown and sun or shade management. We included the region in which farms were located as a random effect. The model specification was as follows: *Yield (ha) ~ Area Sown (ha) + Management Type (sun or shade) + (1|Farm Region)*. Significance was calculated using the *lmerTest* package (Kunzetsova et al. 2017), which applies Satterthwaite's 1946 method to estimate degrees of freedom and generate p-values for mixed models (.

4. Local Data

Ant Sampling

Ant sampling was conducted in the 25 farms selected for this study. During the months of December 2018 and January 2019, we visited each of the farms and placed five tuna fish baits directly on the stem (or stems) of each of 20 coffee plants selected randomly from the 10 x 10 m plot, which was chosen to reflect the basic management style of the farm. Thus, we placed a total of 100 arboreal baits in a representative area of 100 m^2 on each of 25 farms, waited for 40 minutes and then checked each bait for ants, recording the species present at each bait (no counts of numbers of foragers). For further ant sampling details, see Perfecto and Vandermeer (2020).

Lizard Sampling

Lizards were sampled in the same 25 farms and the same 20 randomly selected plants where the ants were sampled. Sampling took place monthly from May 2019 to July 2019. Two observers visited each coffee plant, slowly approaching the bush from opposite sides, and spent two minutes carefully searching all branches for lizards. Numbers and identity of the lizards observed were recorded for each plant.

Bird Surveys

From the original 68 farms used to conduct the vegetation survey to estimate carbon storage (see below), 58 farms were selected as representative of the habitat types, based on shade cover and geographic position. Three avian surveys were conducted at each of the 58 farms between March and June 2018. This period encompassed the breeding season of avian resident species in Puerto Rico (Gleffe et al. 2006), thereby minimizing changes in detectability throughout the season (Thompson 2002). Birds were surveyed using fixed-radius point counts in which two observers recorded all bird species detected visually or by sound, within 50 meters of the center of the station for 10 minutes (for a more detailed methodology see Irrizarry et al. 2021). Though the survey points were not conducted within the exact 100 m^2 plots used for the rest of the data collection, first and last names of farmers were used to match survey locations to farm sites representing the same general area. All surveys were conducted between 0600 and 1000 hrs under favorable weather conditions.

Vegetation Data and Farm Management

Vegetation data was obtained for the same 25 farms and 100 m^2 plots used for the ant and lizard sampling. Farm vegetation was assessed between February and August 2018: about five months after Category 4 hurricanes Irma and Maria made landfall in September 2017. The 100 m^2 plots were established to avoid lot-edges and ensure representation of the general farm management. Respective GPS coordinates were recorded at the center of each plot. All trees, coffee shrubs and *Musa* plants with a diameter at breast height (*DBH*, measured 1.3 m above the ground) > 3 cm were measured and identified. When trees could not be identified in the field, samples were taken for identification in the laboratory.

Percent canopy cover was measured using the application Canopy App (University of Connecticut) and averaging five measurements: one at the center of the plot and at each of the four plot corners. Given that sites were selected to be characteristic of overall farm management, we used the average shade across the plot to be representative of the shade from tree canopies (excluding coffee plants) in the farm overall. Maximum canopy height was recorded in each plot and ground cover was estimated for the farm by randomly placing a 1 x 1 m square at five different locations (center and 4 corners) in the 100 m^2 plot and recording the percentage of bare ground. Crop richness was also surveyed within each 100 m^2 plot based on the number of crops, including coffee and fruit trees, that were recorded from each plot.

Hurricane Damage and Recovery Rate

To quantify the impact of the hurricanes and the recovery from them at the farm scale, we used the NDVI pre and post-hurricane to create a variety of metrics (Figure 2a). Post-hurricane NDVI was calculated in Google Earth Engine (Gorelick et al. 2017) from the USGS Landsat 8 Surface Reflectance Image Collection by first applying a 1km buffer around the center point of the 100 m^2 plots within the 25 representative farms for which vegetation, ant, and lizard surveys were conducted. A cloud mask was applied to the images by searching through the points where the "*Pixel_qa*" band (a pixel quality assessment band provided by the Surface Reflectance image collection) in landsat had a corresponding value of 322, which indicated clear terrain and low confidence cloud and cirrus interference.

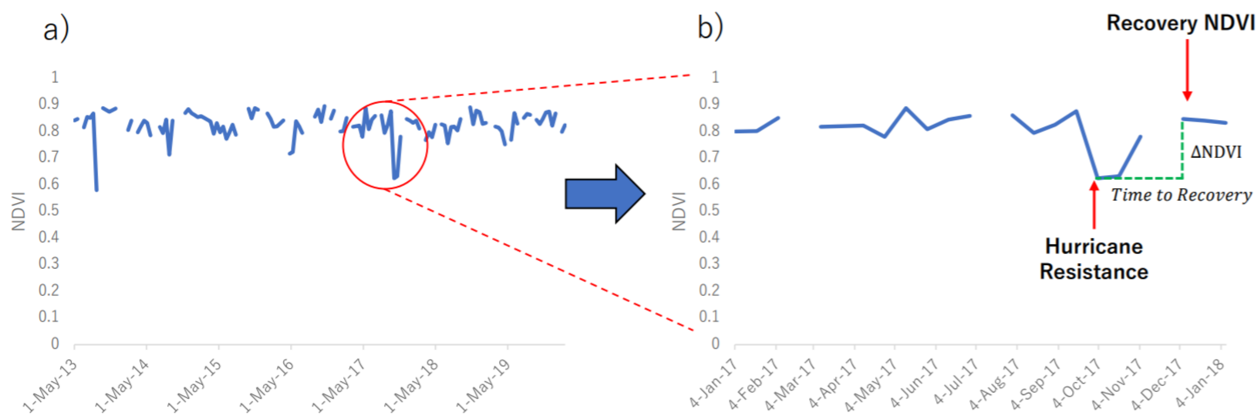

Figure 2: a) Mean NDVI time series from 25 farms in Puerto Rico from 2013 to 2019 b) Mean NDVI time series in the year that Hurricane Maria hit the island, showing the drop in NDVI.

For the hurricane impact analysis, we defined five variables: Hurricane Resistance, Recovery NDVI, Recovery Time, Recovery Velocity and ΔNDVI (Figure 2b). The lowest NDVI value after Hurricane Maria made landfall in Puerto Rico between September and October 2017 was selected as the "Hurricane Resistance" variable. In the NDVI time series chart, we observed that the NDVI dropped immediately following the hurricane, then gradually increased back up to a higher value before resuming seasonal fluctuation patterns. This highest point was selected as the "Recovery NDVI". The recovery time was defined as the period between the measured lowest peak and the Recovery NDVI. Because the Landsat 8 satellite has a visiting frequency of 16 days, recovery time values were discretized to 48, 64 and 80 days. ΔNDVI was defined as the difference between Recovery NDVI and the lowest NDVI value. Recovery velocity was defined as $30\Delta NDVI/recovery\ time$. The multiplication factor of 30 was included to convert the units from (NDVI)/day to (NDVI)/month. See Vargas de Mendonça (2021) for a repository of the code and data used in the NDVI analysis.

$$\Delta \mathrm{NDVI} = Recovery_{NDVI} - Resistance$$

$$Rec_{velocity} = \frac{\Delta \mathrm{NDVI}}{Recovery\ days} * 30$$

Carbon Storage

Carbon storage data was obtained between February and August 2018 (following Hurricane Maria) from the same study of 68 coffee farms in the central rural region of Puerto Rico (Lugo et al., in review). Above and below ground carbon stocks were estimated for all citrus trees, shade trees, coffee shrubs, and banana plants within the 100 m^2 plots. For trees and shrubs with a main stem that forked below 1.3 m DBH (naturally or by pruning), all secondary stems were measured. Secondary stem basal areas were added to calculate individual basal area (BA). Soil organic carbon content was estimated from soil core samples taken from the same plots and added to the total above and below ground plant carbon stock estimates to calculate the total farm carbon storage. Allometric equations were used to estimate aboveground biomass (AGB) and coarse root biomass (CRB). For AGB of shade trees, citrus trees, and bananas and plantains (*Musa* x *paradisiaca*), peer-reviewed models from the literature were applied (for details see Lugo et al, in review). To estimate AGB of coffee shrubs, an allometric model based on BA was developed using destructive sampling of 29 coffee shrubs (for details see Lugo et al, in review). The coarse root biomass density (CRB) for shade trees, citrus trees, and coffee shrubs was estimated using a model developed by Cairns et al. (1997). To convert AGB and CRB into C biomass (AGCB and CRCB, respectively), the carbon present in the living biomass was assumed to be 50% for woody plants (Brown, 1997) and 46% for *Musa* plants (Danarto and Hapsari, 2016). All C stocks were expressed in Mg C ha^{-1}.

Local Data Statistical Analysis

Because we did not have access to yield data for the same farms from which we collected ecosystem service and biodiversity data, we examined relationships with management variables (i.e., percent canopy cover, maximum canopy height, ground cover, and crop richness) to look for potential tradeoffs and synergies. Specifically, we divided our analyses into 3 conceptual groups: (1) *relationships among management variables*, (2) *management effects on ecosystem services and biodiversity*, and (3) *relationships among ecosystem services and biodiversity*. Management effects on ecosystem services and biodiversity were analyzed through a series of linear regressions with management variables as the independent variable. We explored interactions among an informed selection of the ecosystem service and biodiversity variables through a correlation analysis that could capture significant nonlinear relationships and used non-parametric Spearman rank correlations because many of our variables were not normally distributed (see supplementary information for a table of results). Given that this study synthesized data from multiple data sets, using a generalized linear mixed model approach was not feasible due to the low overlap in farm data for the explanatory variables of interest, hence our use of correlations.

Results

1. Yield and Shade Management at the Regional Level

Mean yields between sun and shade grown coffee (as reported by farmers) in the two-sample t-test were significantly different ($p = 0.017$, df = 238), though the variances were not according to a Levene's Test ($p = 0.1615$, df = 238), with mean sun coffee yield (441 kg/ha) being 62 kg/ha higher than the mean shade coffee yield (379 kg/ha). In the linear mixed model that incorporated area sown, however, management type did not have a significant effect on coffee yields ($p = 0.165$, df = 237) while area sown was a significant predictor of yield ($p = 0.094$, df = 234) suggesting that there was no clear relationship between farmer-reported yield and management type after accounting for regional variation and farm size.

2. Management Variables, Ecosystem Services and Biodiversity at the Local Level

Relationships among management variables

Among the four management variables we analyzed (percent canopy cover, maximum canopy height, ground cover, and crop richness), two significant associations arose (Figure 3). Percent canopy cover from shade trees was positively associated with crop richness (r = 0.289, p = 0.015), including bananas, tubers, citrus, peppers, plantains, pumpkin, legumes, and sweet potatoes in addition to coffee, indicating a possible synergy between agroforestry management and food security. Percent canopy cover was negatively associated with percent ground cover (r = -0.235, p = 0.025). However, ground cover was a problematic variable given that it could be driven by direct management practices (i.e., weeding, herbicide application) or an associated effect of management (i.e. a very dense canopy cover).

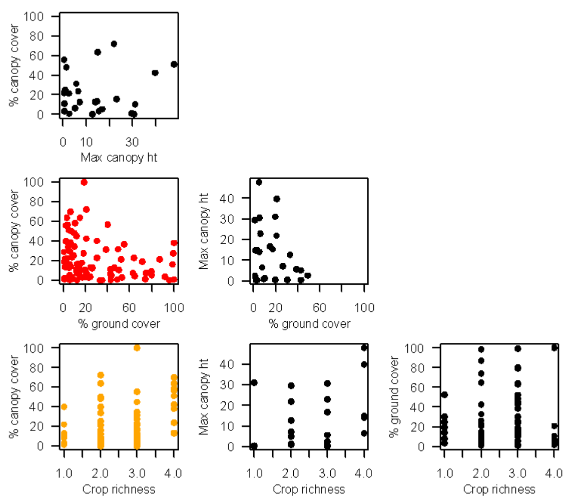

Figure 3: Spearman Rank correlations for management variables considered in the coffee system studied. Black data points indicate non-significant relationships, yellow data points indicate a positive significant relationship, and red data points indicate a significant negative relationship ($p < 0.05$).

Management effects on ecosystem services and biodiversity

Our results suggest that agroforestry management variables (i.e., percent canopy cover, maximum canopy height, ground cover and crop richness) had mostly positive effects on ecosystem services (summarized in Figures 4 and 5). Higher percent canopy cover was associated with higher total coffee plant carbon storage ($R^2 = 0.138$, p = 0.001), total farm carbon storage ($R^2 = 0.140$, p = 0.001), and hurricane resistance ($R^2 = 0.201$, p = 0.021). Higher maximum canopy height was also positively associated with total farm carbon storage ($R^2 = 0.250$, p = 0.009). While more ground cover provided soil carbon storage benefits ($R^2 = 0.104$, p = 0.006), it was negatively associated with hurricane resistance ($R^2 = 0.194$, p = 0.024), though this could be partially explained by the negative relationship between shade and ground cover. Finally, crop richness was positively associated with higher hurricane resilience (quicker recovery to pre-hurricane NDVI values) ($R^2 = 0.243$, p = 0.016).

Agroforestry management practices including percent shade canopy cover, maximum canopy height and percent ground cover had positive effects on some biodiversity variables with only one potential tradeoff. Bird species richness tended to be higher in farms with higher percent shade cover (R^2 =

0.094, p = 0.035) and anole abundance tended to be higher on farms with more ground cover (R^2 = 0.177, p = 0.031). Ant species richness observed on coffee plants decreased with higher shade canopies (R^2 = 0.165, p = 0.039) which could be considered a tradeoff, but the effect on individual species of invasive ants (i.e. Wasmannia auropunctata, Solenopsis invicta, Monomorium floricola, and Tapinoma melanocephalum) was mixed.

Management	Synergies	Tradeoffs
Percent Canopy Cover of Shade Trees	***ecosystem services***	
	Coffee Plant Carbon Biomass	
	Total Farm Carbon Storage	
	Hurricane Resistance	
	biodiversity conservation	
	Bird Species Richness	
Max Canopy Height	***ecosystem services***	
	Total Farm Carbon Storage	
	biodiversity conservation	
		Ant Species Richness
Percent Ground Cover	***ecosystem services***	
	Soil Organic Carbon Storage	Hurricane Resistance
	biodiversity conservation	
	Lizard Abundance on Coffee Plants	
Crop Richness	***ecosystem services***	
	Hurricane Resilience	

Figure 4: Summary table of the effects of the four agroforestry management practices on ecosystem services and biodiversity outcomes. Red indicates a positive relationship and blue indicates a negative relationship.

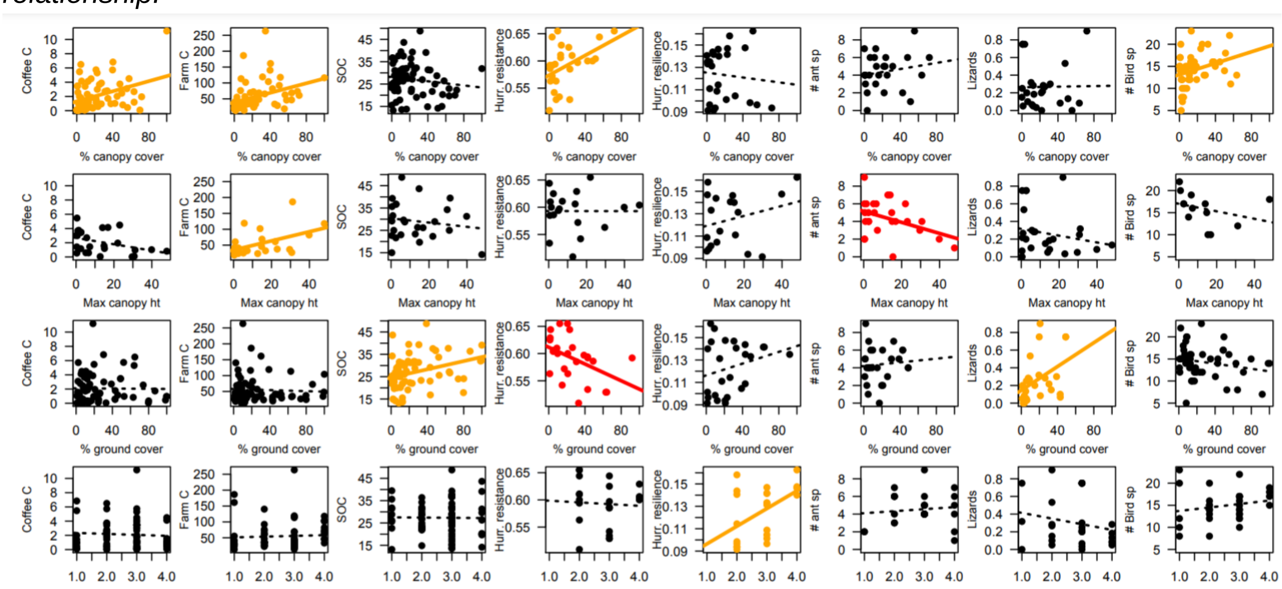

Figure 5: Scatter plots for all of the management effects on ecosystem service and biodiversity conservation studied. Black indicates a non-significant relationship, red indicates a negative significant relationship, and yellow indicates a positive significant relationship (p < 0.05).

Relationships among ecosystem services and biodiversity conservation

Among the ecosystem service and biodiversity variables we analyzed, several statistically significant synergies arose with no evidence of tradeoffs (Figure 6). Total farm carbon storage was positively related to both soil organic carbon storage ($r = 0.341$, $p = 0.003$) and total coffee plant carbon storage ($r = 0.330$, $p = 0.004$) which was not surprising given the contribution of soil carbon and coffee plant carbon to the calculation of overall farm-level carbon storage. Conversely, the positive association between SOC and coffee plant carbon biomass ($r = 0.239$, $p = 0.04425$), two distinct metrics, is ecologically meaningful and suggest a synergy between ecosystem services and crop production. Interestingly, preliminary data exploration did not indicate a negative relationship between coffee plant carbon biomass and shade tree carbon biomass which could imply a lack of competition. Total farm carbon storage was also positively associated with hurricane resilience ($r = 0.435$, $p = 0.037$), suggesting that farms with more woody vegetation tended to re-establish more quickly following Hurricane Maria. Evidence of a crossover synergy between ecosystem services and biodiversity was supported by the positive association of soil organic carbon and lizard abundance on individual coffee plants ($r = 0.443$, $p = 0.018$).

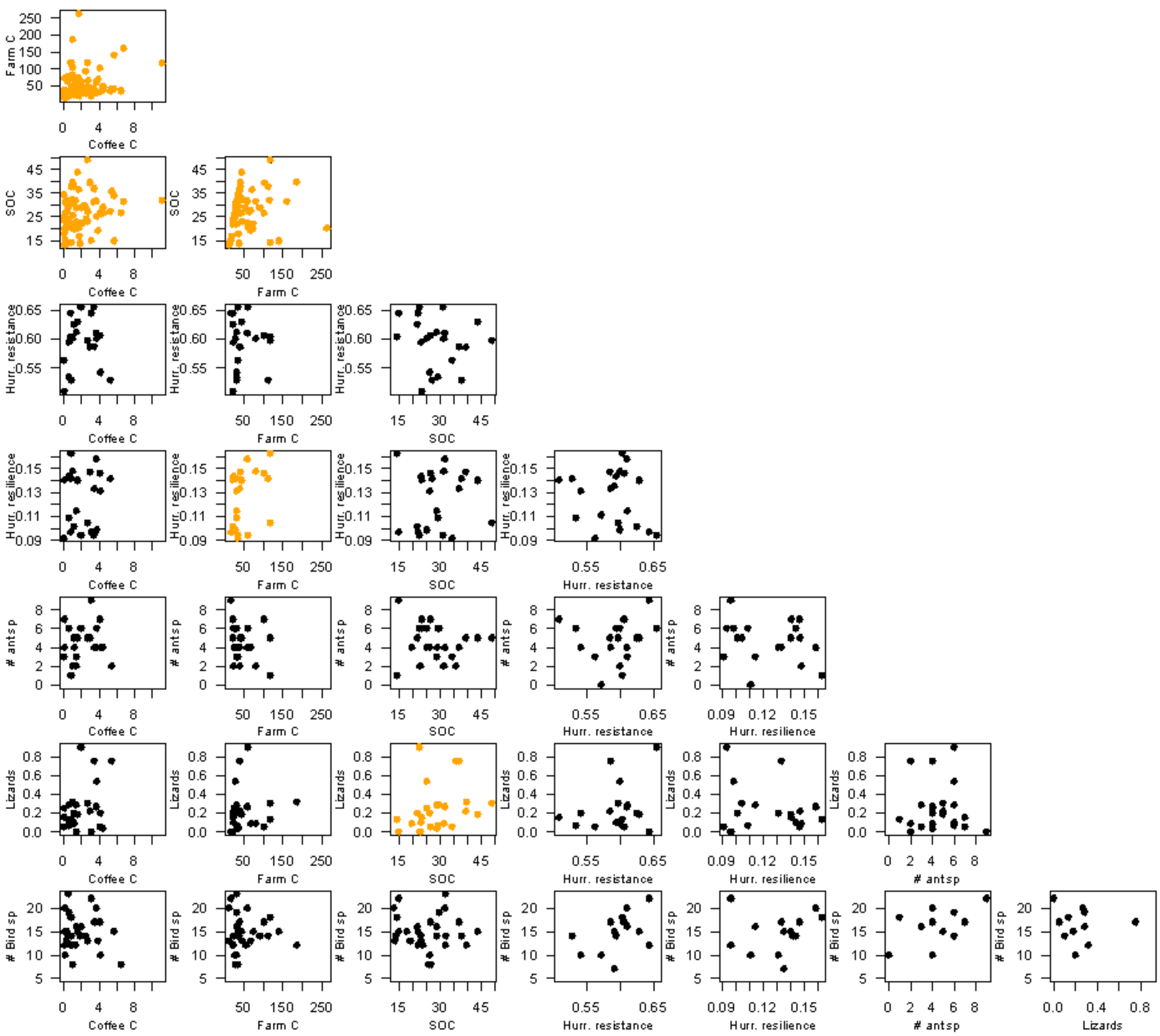

Figure 6: Scatter plots for all of the ecosystem service and biodiversity conservation variables in the coffee system studied. Black data points indicate non-significant relationships and yellow data points indicate a positive significant relationship (p < 0.05).

Discussion:

Relationship between Coffee Yield and Shade Management at the Regional Level

The results of our analyses provide support for those who advocate for agroforestry management in tropical coffee systems. We found evidence of synergistic benefits among coffee production, biodiversity conservation, and ecosystem service provisioning within the food security landscape of Puerto Rico. At the regional scale, there was no obvious tradeoff between shaded and sun coffee production and no difference in the variability of yields between the two groups. Once farm size and regional variation were accounted for, there was no significant difference between the yields for sun and shade coffee. This is in contrast to previous studies which report losses in yields (Jezeer et al. 2018; Schnabel et al. 2018) with agroforestry management. Though we could not detect trends between shade level and yield per hectare since our measure of shade was categorical, it is possible that there may be a positive effect on yield at intermediate levels of shade as other studies have found (Elevitch et al. 2009; Piato et al. 2020) or that some of the variation may be driven by other factors such as coffee plant density. In addition to the lack of a clear yield tradeoff at the regional scale, our results also provide evidence of benefits to biodiversity conservation and ecosystem services associated with higher shade cover at more local scales.

Local Synergies Between Management, Ecosystem Services & Biodiversity Conservation

At the farm scale, we found synergies between shade cover and ecosystem service and biodiversity variables such as bird species richness, carbon storage, and resistance to hurricane damage, with no evidence of tradeoffs among ecosystem service and biodiversity conservation measures. At the local scale, we found that farms with more shade cover and higher shade tree canopies (continuous measures of agroforestry management), were associated with more biodiversity and ecosystem service provisioning. Coffee bushes under more dense shade tree canopies tended to have greater biomass both above and below ground, similar to findings by Campanha et al. (2004), suggesting no obvious tradeoff with coffee plant growth and perhaps even yield with certain shade tree intercropping (Boreux et al. 2016). This result is consistent with Soto-Pinto et al. (2000) who reported an increase in coffee yield with shade cover up to 38% and no effect of shade on yield up to 50% shade. Our study also identified a synergy between soil organic carbon storage and coffee plant carbon storage that could be driven by a combination of higher microbial activity, greater nutrient mineralization in the soil, or greater water infiltration contributing to higher soil quality, as de Souza et al. (2012) and Cannavo et al. (2011) reported for coffee agroforestry systems in Brazil and Costa Rica. More fertile soils could enable coffee plants to grow and potentially contribute to higher yields or different flavor profiles, though the relationship between coffee plant size, bean quality, and yield depends on how resources are allocated within the plant (Steiman et al. 2011; Bote and Jan 2016).

Though our island-wide data showed no relationship between management type and yield, a relationship between yield and shade may have been detected with a continuous measure of shade or an alternative measure of productivity such as yield per coffee plant. The synergy between agroforestry management and biodiversity conservation was most apparent for birds in our study, with more shade cover being associated with higher bird species richness as other studies have reported (Philpott and Bichier 2012; Buechley et al. 2015), though we did not examine community composition. Notably, many of the tropical bird species observed in the farms were species endemic to Puerto Rico including the Puerto Rican Emerald, Puerto Rican Flycatcher, Puerto Rican Lizard-Cuckoo, Puerto Rican Oriole, Puerto Rican Spindalis, Puerto Rican Tody, Puerto Rican Tanager, Puerto Rican Vireo, Puerto Rican Woodpecker, and the Puerto Rican Bullfinch. Our study also detected a positive relationship between percent ground cover and lizard abundance which could be the result of lizards using herbaceous vegetation in the coffee farms for cover from predators. In another study conducted in Puerto Rico, Monagan et al. (2017) reported a negative relationship between coffee intensification and lizard abundance, with higher lizard abundance in shade coffee farms compared to sun coffee farms. We did not find such a relationship. On the contrary, our study found more lizards in farms with more ground cover, which was correlated with lower shade cover. It is possible, however, that increased ground cover from low-lying vegetation found in the less shaded farms facilitated lizard movement between coffee plants thereby increasing their detected abundance.

The synergies we report among shade, ground cover, and carbon storage, highlight the potential for agroforestry management to play a key role in carbon sequestration and, by extension, climate change mitigation efforts. Additional synergies may also be realized by policies that prioritize land with high biodiversity value, such as the more shaded farms, which offer higher carbon storage benefits than conventional systems (Reside et al. 2017; Middendorp et al. 2018). Agroforestry management of coffee farms, therefore, could support climate change resistance in coffee production both at a microclimatic scale by moderating temperatures (Lin 2007; de Souza et al. 2012; Rice 2018) and at a global scale by sequestering carbon in plant biomass and soil. The benefits of agroforestry management to long-term coffee production and farmer livelihoods are further compounded by the synergies between shade cover and resistance to hurricane damage and that of crop richness and hurricane resilience. Regional studies have identified land cover type, terrain, slope orientation, and vegetation complexity as significant determinants of hurricane damage severity that could be mediated by agroforestry management practices such as planting shade trees to slow hurricane winds and protect lower strata coffee bushes (Hu and Smith 2018; Mariño et al. 2018; Philpott et al. 2008). Our analysis suggests that farms with more shade suffered less damage from Hurricane Maria's impact, and farms growing a variety of crops recovered faster. Considering the contribution of percent canopy cover to lower annual soil erosion rates in other systems (Zuazo and Pleguezuelo 2009), agroforestry presents dual benefits for coffee farming in Puerto Rico, including higher resistance to hurricanes and lower damage due to erosion. Factors such as tree size, root depth and cohesion, and mean tensile root strength supported by management decisions to include shade trees or additional crops may offer opportunities for maximizing soil conservation and protection against hurricanes (De Baets et al. 2008; Ali 2010; Hwang et al. 2015).

Local Tradeoffs Between Management, Ecosystem Services & Biodiversity Conservation

Our analysis identified only three negative relationships: between percent canopy cover and percent ground cover; percent ground cover and hurricane resistance; and maximum canopy height and ant richness. The negative relationship between percent canopy cover and ground cover is not surprising since heavier shade can help regulate the herbaceous vegetation in the understory. Indeed, weed control is frequently cited as one of the benefits of shade cover in coffee agroforestry systems (Staver et al 2001, 2020; Soto-Pinto et al. 2002). In this study, we included ground cover as a management variable that indirectly measures the control of weeds by either chemical or mechanical methods because of the heavy use of herbicides among Puerto Rican coffee farmers (informal conversations with farmers). In spite of that, we detected a negative relationship between percent canopy cover and percent ground cover, suggesting that ground cover is a result of the shade level rather than an indirect measurement of weed management. We also found that hurricane resistance decreased with ground cover, however, this could simply be a reflection of the negative relationship between shade and ground cover. Since farms that had higher shade levels also had higher hurricane resistance and lower ground cover, it follows that we would detect a negative relationship between ground cover and hurricane resistance.

The decrease in ant richness with taller shade canopies could also be a considered an ecosystem service tradeoff partially explained by the dominance of the invasive "fire ant" *Wasmannia auropunctata*, which disrupts farmworkers with their painful bite and are commonly observed on citrus trees intercropped with coffee plants. Though *Wasmannia* are a known biocontrol agent of the coffee berry borer and the coffee leaf miner, both prolific pests in Puerto Rico, they have also been found to deter Anole lizards, another generalist pest predator, with their bite (Perfecto and Vandermeer 2020; Perfecto et al. 2021). It is not fully understood how *Wasmannia* interacts with other species in the ant community, such as *Solenopsis invicta*, and how those interactions are mediated by management practices such as agroforestry (Perfecto and Vandermeer 2020), but our results indicated that less shaded farms with more groundcover had more Anoles. Therefore, though our findings suggest a tradeoff between ant species richness and shade, future research on the interactions between biocontrol agents and coffee pests in Puerto Rico could inform low-input management strategies that minimize the effect of the coffee berry borer and leaf miner while supporting biodiversity. Due to the lack of yield data for the farms we surveyed for ants, lizards, birds, and vegetation, we were not able to examine direct relationships between yield and our biodiversity and ecosystem service measures. Future studies could collect this data through relatively simple questionnaires that could be combined with other tools such as the Household Dietary Diversity Survey (Swindale and Bilinsky 2006) to explore further linkages between management, yield, and food security (see supplementary information for a sample survey).

Food Security & Agroforestry

Our study also illustrated relationships that may indicate potential synergies between agroforestry management and food security in Puerto Rico. We found higher crop richness, including bananas, tubers, citrus, peppers, plantains, pumpkin, and legumes in coffee farms with more shade cover suggesting that agroforestry management may also be a means to provide households with local food resources while supporting local biodiversity. This idea is consistent with Frison et al. (2011) and Jha et al. (2014) who argue that agrobiodiversity resulting from management strategies such as agroforestry, can provide sustainable social, political, and economic benefits to food security while delivering "agricultural intensification without simplification." Surveys of walking trails within farms (data not included in this article) revealed a great diversity of fruit trees and food crops such as guava, breadfruit, coconut, mango, loquat, soursop, avocado, and star apple which may supplement the diets of farmers and their families, though further research is needed to quantify the nutritional value of local production and understand its role in household consumption as some studies have already done in other farming communities (Remans et al. 2011; Blesh et al. 2015; Valencia et al. 2019; Stratton et al. 2020). In addition, it is important to consider that fruits and tubers comprise much of the non-coffee crops grown on the farms in this study, so additional subsistence would need to be purchased or planted in order to approach the micro- and macronutrient needs of a complete diet. Nevertheless, our results support the idea that coffee farms under agroforestry management do have the potential to reduce some level of food insecurity in farming households and provide fresh, potentially organic produce at a low cost. Given that some farms in our study produced up to 12 food crops in addition to coffee, opportunities also exist to leverage the spatial analysis power of Geographic Information Systems (GIS) software to map out potential distribution pathways for small scale production of food crops on the island. This, combined with qualitative interviews with farmers, could build on the literature connecting agroforestry farming practices to food sovereignty in agricultural communities.

Conclusion

In sum, our analyses present evidence-based insights into the synergies and tradeoffs between agroforestry management, biodiversity conservation, and ecosystem services at regional and local scales of coffee production in Puerto Rico. We found few tradeoffs and several synergies resulting from shaded coffee production, including benefits to carbon storage, resistance and resilience to hurricane damage, and bird and lizard conservation. At the island level, we found no evidence of a significant tradeoff in yield between shade and sun-managed coffee farms after isolating the effects of area sown and region. Among ecosystem services and biodiversity conservation, we identified synergies among carbon storage sinks, between total farm carbon storage and hurricane resilience, and between pest-controlling lizard abundance and soil organic carbon storage with no evidence of tradeoffs. Finally, we discussed the advantages of agroforestry management to household and regional food security and highlighted opportunities and the need for future research in supporting areas such as food sovereignty.

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