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New coffee varieties as a climate adaptation strategy: Empirical evidence from Costa Rica

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ABSTRACT

Adapting to climate change in vulnerable coffee regions is crucial to maintain rural livelihoods. Among the solutions, coffee breeding strategies aim to produce coffee varieties with higher output performance than traditional varieties while reducing competition for land. This paper investigates the output performance of hybrid coffee (e.g., Starmaya and Centroamericano – H1), introgressed (e.g., Marsellesa and obatá) and traditional coffee (e.g., Caturra and Villa Sarchi) varieties. By using plot-level panel data among commercial farms in Costa Rica, we estimate the output performance of the three coffee varieties using pooled ordinary least squares and random effects models. We find that hybrid coffee varieties give 29–61% higher output than traditional coffee varieties. The results remain robust even after controlling for factor and climate inputs. Notwithstanding the larger productivity, hybrid coffee varieties demand more labor and inorganic fertilizers. While pesticide use may be reduced by hybrid's pest resistance, agroecological approaches for nutrient management are still needed to improve livelihoods and environmental outcomes. Headed towards longer-term studies, our paper presents the first evidence on the output performance of hybrid coffee varieties outside on-farm trials or experimental plots. These results suggest the potential of hybrid coffee varieties in promoting sustainable agriculture by improving the livelihood of coffee farmers, enhancing their adaptation against climate change and decreasing competition for land.

1. Introduction

Coffee production is extremely sensitive to climate change (Jaramillo et al. 2011; [9,18,21,33]). Increase in temperature and changes in precipitation are expected to reduce coffee growth, flowering and fruiting [40], increase the pressure of coffee pests ([25], 2011), and reduce coffee quality and yield in many coffee-growing regions (DaMatta et al. 2007; Jaramillo et al. 2011; [8,19,21,27]). Moreover, previous studies predict that the global land area suitable for coffee production will decrease by about 50% by the year 2050 [1,6,10,31] and in some cases as high as 88% [24]. If these scenarios unfold, the livelihood and food security of millions of smallholder farmers who directly depend on coffee are at great risk [6,42]. Similarly, the decrease in the land area suitable for coffee production implies a trade-off between coffee production and forest conservation since areas that are currently forested may be converted to coffee production [31,41].

In light of these scenarios, coffee breeding could play a great role in climate change adaptation and sustainable coffee production. The hybrids have been developed with, among others, high productivity across climate gradients, also warmer climate, as the goal. The hybridization results in heterosis or hybrid vigor, displaying better traits, including productivity, than the two parents. The improved hybrid vigor helps increase or maintain yield when climate changes. Indeed previous controlled field experiments show that hybrid coffee varieties are more productive [2,29] and pest resistance [29] than their traditional counterparts across all agro-ecological zones. Similarly, Pappo et al. [32] and Silva et al. [37] show that hybrid coffee varieties are more drought resistant than their traditional counter parts. Furthermore, coffee breading helps to sustainably increase coffee production in agroforestry systems through selecting shade adapted varieties and thus reducing coffee driven deforestation and agricultural expansion [2,12]. Until relatively recently, the main goal of Arabica coffee breeding strategies was to increase production through higher yields and increased resistance to pests and diseases, based on a limited number of traditional cultivars, genetically alike, and introgressed varieties (from C. canephora cv Robusta genetic backgrounds) derived from, for instance, Timor hybrids,

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Fig. 1. Hybrid coffee variety under shade (picture is taken from one of the plots in our data).

like Sarchimor and Catimor (van de Vossen et al. 2015). Most experiments were successful in increasing productivity, but not the bean quality. However, with more emphasis on beverage quality and the looming threat of climate change [6,28], coffee breeding now has more diverse aims than merely production, including high cup quality, pest and disease tolerance, tolerance to abiotic stress such as droughts and heat, and ability to produce satisfactorily in sun systems as well as shaded, agroforestry systems [2,12].

Currently, there are several crossbreeding initiatives across the world, which involves private companies, national coffee organizations and research institutions [4,30]. The evaluation of first generation (F1) Arabica hybrids available to farmers have so far been conducted in experimental plots or small scale on-farm trials under controlled management [2,3,29]. While there seems to be consensus on the superiority of F1 hybrids over traditional pure line cultivars, we know less about the agronomic performance of F1 hybrids among commercial farmers, whether large or smallholders. We believe that it is important to investigate the performance of F1 hybrids using real world field data among coffee producers for at least two reasons. First, analysis based on farmer-level field data considers differences in plot-level and farmer-level characteristics, climate adaptation and farm management practices, production and harvesting techniques. Second, such analysis shades light on key socioeconomic and institutional challenges in the adoption of F1 hybrids among farmers and provides key policy insights. So far, no study has documented the performance of the new Arabica hybrids (shown in Fig. 1) in comparison with traditional varieties in commercial cultivations when cultivated outside experiments or controlled trials aimed/focusing in priority at research purposes. Changing to climate change-resilient coffee varieties is one of the most commonly used climate adaptation strategy among farmers in developing countries and has been found to increase productivity and food security [5,11,22,36]. While the importance of new coffee varieties is being recognized and adopted, albeit slowly, among coffee farmers [15,23,34], we know very little about the performance of these varieties.

In this paper, we aim to offer the first insight into the productivity of F1 Arabica hybrids compared with American pure line varieties in commercial farms. We do this by investigating the production of pure line traditional, introgressed and hybrid varieties[1] using unique plot-level panel data on coffee output, type of coffee variety and factor inputs as well as farm-level temperature and precipitation variables among large scale commercial farms across coffee growing regions in Costa Rica.

2. Hybrid coffee and production

When the goat herder Kaldi according to the folklore first discovered the energizing properties of the Arabica coffee plant in the forested mountain areas of Ethiopia, he could not have imagined the magnitude of importance the gene pool of the local coffee trees would have many centuries later. Today, in the search for multiple beneficial traits, including high cup quality, pest and disease resistance, high yields and a compact growth, shade adaptation, low caffeine content, coffee breeders often go to the origin of the *Coffea arabica* L. plant to explore the wild coffee landraces growing in the Ethiopian forests. The aim to introgress multiple traits in one genotype often involves crossbreeding of a commercial variety with wild landraces from the coffee forests in Ethiopia and Sudan, leading to first generation (F1) hybrids with high heterosis compared to traditional pure line varieties [2]. The higher vigor observed in the F1 hybrids means that, in theory, they are more adaptable to various environments (homeostasis) and some of them have been

[1] We refer to the three categories of varieties: hybrid varieties, introgressed varieties and traditional varieties. When we refer to varieties, without prefix, we refer to all categories.

found to exhibit a wide range of beneficial traits, such as high yield, pest tolerance/resistance, and higher cup quality [2,3,29,38].

The first Coffee Arabica intraspecific F1 hybrid was created by crossing Latin America traditional varieties with wild coffee originating from Ethiopia and Kenya as part of a collaborative breeding and selection program initiated at the beginning of 1990s by the French Agricultural Research center for International Development (CIRAD) and Central American research networks, PROMECAFE and CATIE. The resulting hybrids proved to be extremely promising as they displayed an unexpected high level of heterosis (despite the narrow genetic base of the Arabica species), producing on average 40% more than the best cultivated varieties, with some of them producing coffee exhibiting better sensory qualities than those of the reference varieties such as the famous Caturra cv. [2,3]. Thirty years later, Marie et al. [29] compared nine different F1 hybrids (coming from CIRAD/PROMECAFE/CATIE and CIRAD/ECOM breeding programs), with the traditional variety Caturra and the improved pure line introgressed variety Marsellesa®, using on-farm trials established in commercial plantations in seven different agro-ecological environments in Nicaragua. The two F1 hybrids named Centroamericano (H1) and Mundo Maya® (EC-16) were superior in yield and yield stability across environments, while Centroamericano and Starmaya (the only F1 hybrid propagated through seeds, the others must be clonally propagated through somatic embryogenesis and rooted mini-cuttings vegetative propagation methods), had superior cup quality [29].

Despite the availability of F1 hybrids, especially in Central America, which has seen the bulk of F1 breeding projects, a relatively small share of farmers have replaced their traditional varieties with F1 hybrids. In unpublished material, Fazenda (2017) documented that the most prevalent F1 hybrid, the H1-Centroamericano, which has been on the market in Central America since 2001, has had a rather modest expansion, with just around 4000 ha planted since 2008, out of the total of 1.7 million ha of coffee in the region according to FAOSTAT. With the development of Starmaya, propagated by seed rather than clonal propagation then facilitating its large-scale dissemination and low cost production, the accessibility and adoption of F1 hybrid by farmers is expected to increase [17].

3. Materials and methods

3.1. Data source and description

Our data come from 14 large commercial farms in Costa Rica, collected from ECOM Agroindustrial Corp. Ltd. data records. The farms are situated in an altitude range of 950–1600 m.a.s.l. (see Fig. 2). Overall, plot-level data on coffee output, type of Arabica coffee variety, number of varieties and inputs were collected from 113 plots, of which 98 are specialized in one coffee variety.

These data include name of the farm, coffee growing region, elevation range, latitude and longitude, farm code (individual number that identifies each farm). The name and code of each plot in a farm, its state in 2017 and 2019 (investment, development, production), the year of plot establishment, names of all coffee varieties in a plot, total area of the plot (ha), and the area of each individual variety in the plot (ha) were documented. When a plot is renovated partly, the new "subplot" takes the name of the original plot plus year of renovation. The coffee varieties were grouped into 3 categories: Traditional pure line varieties (Catuaí, Caturra, Venecia and Villa Sarchí) which originate from Typica or Bourbon mutations; (ii) Introgressed varieties (CR-95, Marsellesa® and Obatà) which derive from crosses between Caturra and the Timor Hybrid CIFC 832/2; and (iii) F1 Hybrid varieties [H1, grafted-H1 (grafted on Robusta Nemaya root stock), H3, EC-15, EC-16, EC-17, EC-18, and Starmaya] derived from the cross between traditional American varieties or introgressed varieties and Ethiopian landraces. According to the World Coffee Research, the optimal altitude, which is arguably a good proxy for optimal climate, for most traditional, introgressed and hybrid coffee varieties is >1300 m, 700–1300 m and >700 m respectively (see https://varieties.worldcoffeeresearch.org/varieties for detail characteristics of each coffee varieties).

All inputs applied in each plot were recorded. A yearly report of the products used, type of product (e.g. fertilizer, herbicide) and subtype of these products (e.g. foliar fertilizer, herbicides) were collected. The activities linked to each input were recorded, for example, fertilization, foliar spray, herbicide spray, or irrigation. The amount of a product applied, the measuring unit, cost of unit, and total costs in USD were documented. labor was documented at plot level for each year. Information on employees and activities carried out (e.g. harvesting, applying fertilizer, supervising) were detailed. The amount of worked hours divided into light/heavy/extra heavy work were recorded, together with their cost per hour and total cost in USD.

Harvest data at farm level included the yearly number of *cajuelas*, a Costa Rican measurement of coffee harvest. A *cajuela* is a 20 liter of container which corresponds to an average of 12.9 kg of harvested fresh coffee cherries. Twenty cajuelas equals one *fanega*, which corresponds to an average of 258 kg of coffee cherries and the equivalent of one quintal (i.e. 46.2 kg) of transformed green coffee cherries. In Costa Rica, coffee harvesters are paid per cajuela, while coffee production and sales is often recorded in fanegas. Harvest data at plot level were divided into amount of fanegas produced per year.

Using each farm's latitude and longitude coordinates, we extracted monthly farm-level precipitation, minimum and maximum temperature data from WorldClim for the period up to 2018, the latest available data [14,20]. These data have a 2.5 min (~21 km2) spatial resolution. The monthly data were aggregated corresponding to the dry and wet seasons, running from November to April and from May to October, respectively.

While the use of fertilizer, other inputs and labor days are often recorded per plot, harvest data are usually not. It would be practically very difficult to record coffee collectors' harvest per variety and/or per plot. Groups of collectors move around multiple plots at any one time and deliver their harvest to waiting trucks. Each collector's amount of cajuelas are recorded for payment, but not from which particular plot the harvest comes from. Once a truck is full, the coffee cherries are transported to the processing plant, where the total amount is weighted. However, the coffee farms keep record of plot-level harvest data for a limited number of plots serving the coffee trading company to keep track of the productivity of certain varieties as well as the nutritional needs of these varieties. In this regards, we obtained 113 plot-level harvest observations over the period of 2015 to 2019. Our main analysis focuses on plots with only one variety, corresponding to 87% of the plots. Furthermore, we dropped a total of 4 plots (2 plots with more than 400 labor days per ha and 2 plots with greater than 2500 USD inputs costs per ha), which could be considered unreasonable values or outliers. Coffee varieties were grouped in either hybrid, introgressed or traditional pure line coffee varieties, accounting for about 40, 42 and 18% of the observations, respectively. We obtained output records for 49% of the plots for at least two years, while the remaining 51% of the plots only appear once in the records over the panel of 5 years as can be seen from Appendix Table A1. Table 1 below presents descriptive statistics.

3.2. Econometric method

We estimate a Cobb-Douglas production function given below, that links plot-level coffee output and various factor inputs used in coffee production.[2] Thus, the model is specified as follows:

$$Output = Land^{\beta_1}\, Labor^{\beta_2}\, Others^{\beta_3} \tag{1}$$

[2] Estimation results using an alternative translog production function is presented in Appendix Table A4, which generally confirms our results from the Cobb-Douglas production function.

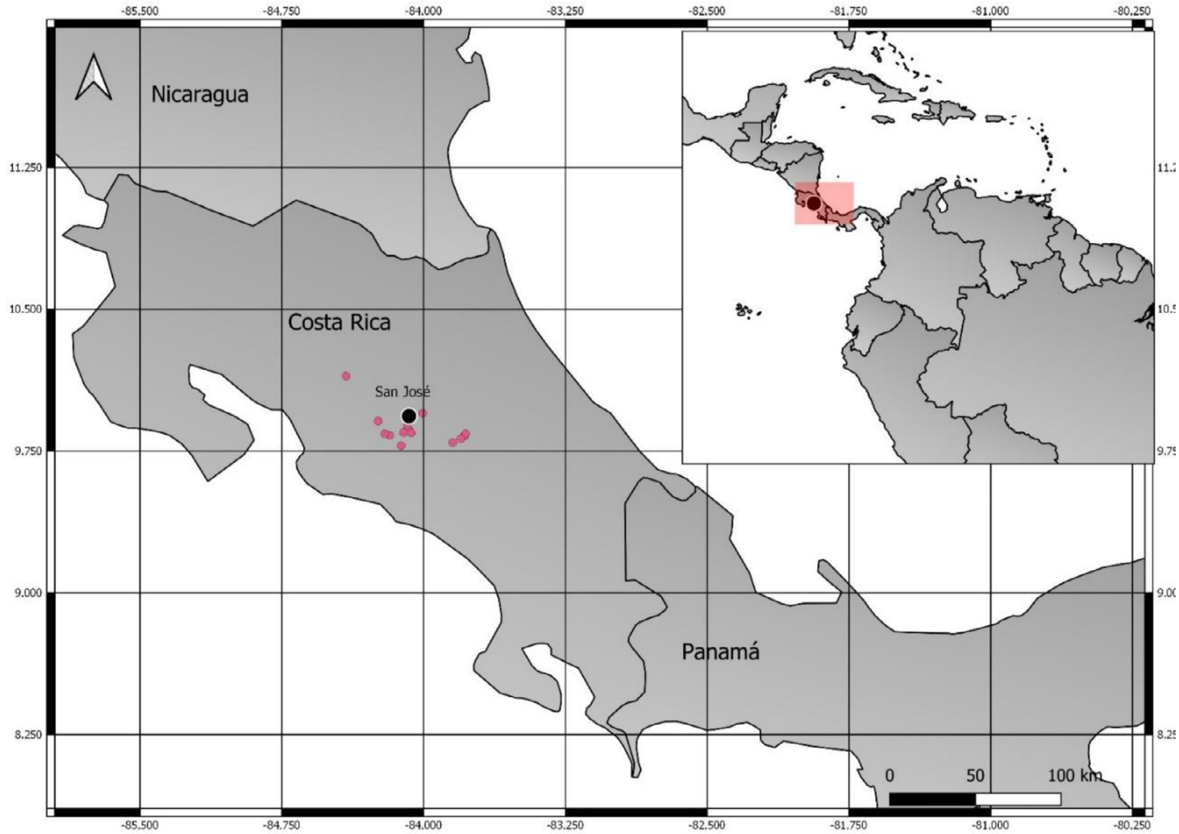

Fig. 2. Location of coffee farms in the study area.

Table 1
Descriptive statistics.

	N	Mean	Std. Dev.
Output (in fanegas)	98	75.654	59.636
Land (in ha)	98	3.824	3.266
Labor (in labor days)	75	231.496	197.939
Input costs (sum of fertilizers, insecticides and pesticides in USD)	63	2328.322	1930.926
Plot age (in years)	89	3.921	1.973
Annual climate data			
Precipitation (mean)	89	201.153	39.585
Minimum temperature (mean)	89	14.783	0.710
Maximum temperature (mean)	89	24.826	0.834
Precipitation (Std. Dev)	89	160.122	22.322
Minimum temperature (Std. Dev.)	89	.682	0.072
Maximum temperature (Std. Dev.)	89	.801	0.147
Seasonal climate data			
Precipitation (mean, dry)	89	319.397	52.721
Precipitation(mean, wet)	89	82.909	38.163
Precipitation (Std. Dev., dry)	89	129.195	39.611
Precipitation(Std. Dev., wet)	89	62.038	23.254
Minimum temperature (mean, dry)	89	15.109	0.672
Minimum temperature (mean, wet)	89	14.456	0.757
Minimum temperature (Std. Dev., dry)	89	.515	0.141
Minimum temperature (Std. Dev., wet)	89	.682	0.092
Maximum temperature (mean, dry)	89	24.65	0.815
Maximum temperature (mean, wet)	89	25.002	0.869
Maximum temperature (Std. Dev., dry)	89	.517	0.175
Maximum temperature (Std. Dev., wet)	89	1.007	0.193

Where $Others$ refer to others inputs such as fertilizers, sprays and age of the plot as well as climate variables. To facilitate estimation, we log-linearize Eq. (1) and specify our baseline model as follows.

$$\begin{aligned}\ln\left(Output_{it}\right) = {} & \beta_0 + \beta_1 \ln\left(land_{it}\right) + \beta_2 \ln\left(labor_{it}\right) + \beta_3 \ln\left(input\_costs_{it}\right) \\ & + \beta_4 \ln\left(plote\_age_{it}\right) + \beta_5 \ln\left(mean\_precipitation_{ft}\right) \\ & + \beta_6 \ln\left(mean\_minimum\_temp_{ft}\right) \\ & + \beta_7 \ln\left(mean\_maximum\_temp_{ft}\right) + \beta_8 \ln\left(SD\_precipitation_{ft}\right) \\ & + \beta_9 \ln\left(SD\_minimum\_temp_{ft}\right) + \beta_{10} Variety_{it} + \mu_i + \varepsilon_{it} \end{aligned} \quad (2)$$

Where $Output_{it}$ refers to total coffee output for plot i at time t. $plote\_age_{it}$ refers to age of the coffee plot (since establishment) for plot i at time t, which controls for differences in coffee output due to differences in the age of the plot. $input\_costs_{it}$ refers to costs of fertiliz-

Table 2
T-test results of coffee output and inputs by coffee variety.

	Mean values			P-values from tests		
	Traditional	Introgressed	Hybrid	Traditional vs Introgressed	Traditional vs Hybrid	Introgressed vs Hybrid
Output per ha (in fanegas)	20.764 (N = 18,SE=7.80)	17.941 (N = 41,SE=8.20)	30.495 (N = 39,SE=18.38)	0.222	0.036	0.000
Labor per ha (in labor days)	64.197 (N = 10,SE=12.60)	57.895 (N = 34,SE=40.88)	86.168 (N = 31,SE= 84.56)	0.636	0.422	0.087
Input costs per ha (in USD)	542.114 (N = 6,SE=160.68)	506.521 (N = 30,SE=218.43)	639.087 (N = 27,SE=413.72)	0.709	0.58	0.131
Plot age (in years)	5.33 (N = 12, SE=4.14)	3.95 (N = 40, SE=1.28)	3.43 (N = 37, SE=1.26)	0.068	0.016	0.078

ers, insecticides and pesticides for plot i at time t. To control for the effect of climate on coffee output, we control for $mean\_precipitation_{ft}$, $mean\_minimum\_temp_{ft}$ and $mean\_maximum\_temp_{ft}$, which respectively refer to annual mean precipitation, minimum temperature and maximum temperature of farm f at time t. As shown by previous studies, coffee output is affected not only by the level of precipitation and temperature, but also by their variability ([7,35]; and [26]). We, therefore, include $SD\_precipitation_{ft}$, $SD\_minimum\_temp_{ft}$ and $SD\_maximum\_temp_{ft}$ in the model, which respectively refer to intra-annual standard deviations of precipitation, minimum temperature and maximum temperature of farm f at time t. $Variety_{it}$ refers to coffee variety for plot i at time t, which is a categorical variable (traditional, introgressed and hybrid varieties). μ_i refers to unobserved plot specific (time invariant) effects while ε_{it} is the error term. Note that in the empirical models, we used costs instead of quantities of fertilizers, insecticides and pesticides because: (i) the different products used in fertilization and spraying are measured in different units, so measuring it in terms of costs homogenize the unit of measurement; and (ii) using different variables for the different products substantially reduces the number of observations given that not all farmers applied all products.

We want to estimate the impact of coffee variety on coffee output controlling for factor inputs. Ideally, we would have liked to estimate fixed effects and random effects models and use Hausman test to choose between the two models. However, there are two main limitations to this. First, given that each plot has the same variety over the years ($Variety_{it}$ collapse to $Variety_i$), we cannot estimate fixed effects models. Thus, we have estimated a random effects model, which assumes that the unobserved plot-level fixed effect μ_i is uncorrelated with the included explanatory variables. Second, we have a completely unbalanced panel and in about 50% of the plots, we have unrepeated (cross-sectional) observations. To increase our sample size, we pooled the observations and estimate a simple Ordinary Least Squares (OLS) model controlling for year and farm fixed effects. Controlling farm fixed effects helps alleviate potential unobserved effects from farm characteristics, while year fixed effects control for potential unobservable time effects including extreme weather events. For instance there were volcanic eruptions (Poas) in 2017 that affected coffee production followed by an infestation of the red spider mite that defoliates coffee, which might shade the effect of climate. Finally, we extended the basic model in (2) by including farm-level climate data for both the random effects and pooled ordinary least squares (OLS) models. In all our models, the Breusch-Pagan Lagrange multiplier (LM) test for random effects suggest that there is no evidence of significant differences across plots and that pooled OLS an appropriate model.

4. Results

Table 2 below shows t-test results of output per hectare, key inputs and plot age by coffee variety. Plot age refers to number of years since last renovation of the establishment of the plot. The hybrid varieties give higher output per ha than traditional and introgressed varieties do. This is based on the raw data, without controlling for other inputs such as labor, fertilizer, spray and plot age as well as farm characteristics and climate.

The hybrid coffee varieties give the highest output per ha, but it also uses highest labor and inputs costs per ha and the plots are on average slightly youngest. We conducted a two-way t-test to see whether the output and input use per ha are statistically different among the three varieties. As can be seen from the p-values in Table 2, the differences in output and labor per ha as well as plot age between hybrid and introgressed coffee varieties are statistically significant. This is very interesting. Hybrid coffee varieties give higher output per ha, but this comes at the cost of higher labor per ha. While hybrids coffee varieties incur more inputs costs than introgressed varieties, the differences are not statistically significant to each other. Similarly, hybrid varieties give a significantly higher output per ha than traditional varieties, but there are no statistically significant differences between the two in terms of labor and input costs per ha. In Appendix Fig. A1, we presented a scattered plot regarding the relationship between coffees output per ha and labor and inputs costs per ha for each of the coffee varieties. The average output per ha for traditional and introgressed varieties appears to be slightly lower than the national average, which is about 23 fanegas. However, this is intuitive given plots in our sample are still relatively young. The plots with introgressed varieties are younger than the plots with traditional varieties, which explains why we do not yet see expected higher output of the introgressed varieties; the plants are not yet at their full potential. Another plausible explanation is the relatively low level of inputs among the introgressed varieties, as they, much like hybrids, require more inputs to reach full potential. . While the average plot age for the hybrid plots are even lower than the traditional and introgressed plots, hybrid varieties mature faster than the other two varieties.

Given the differences in input use, we estimate a log-linearized Cobb-Douglas production function controlling for these differences as well as climate and farm characteristics. In Table 3 below, we report estimation results from both pooled OLS and random effects models. Columns (1)-(4) and (5)-(8) present estimation results from pooled OLS[3] and random effects models respectively. Columns (1) and (5) present estimated results from pooled OLS and random effects respectively by including plots that also have additional varieties.[4] Columns (2)-(4) present estimated results from pooled OLS for the sample of plots specialized in one coffee variety without factor input controls, with factor input controls, and with factor input and climate controls respectively. Columns (6)-(8) present these results from random effects model.[5]

[3] We also run pooled OLS modes with plot fixed effects (see Appendix Table A3). While this controls for unobserved plot level characteristics such as soil quality and slope, caution should be made when interpreting the results since identification of the effect of coffee varieties depends on some of the fixed effects dropping out of the model due to collinearity

[4] Plots with more than one coffee variety have one dominant variety that accounts for a larger share of the plot.

[5] In Appendix Table A2, we present estimation results from both pooled OLS and random effects models by using seasonal instead of annual climate variables.

Table 3
Productivity of hybrid, introgressed and traditional coffee varieties.

	Pooled OLS					Random effects			
	All plots	Sample of plots specialized in one coffee variety				All plots	Sample of plots specialized in one coffee variety		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Coffee varieties									
Traditional									
Introgressed	−0.132	−0.157	−0.097	0.023	0.010	0.003	0.028	0.459**	0.337
	(0.106)	(0.110)	(0.195)	(0.199)	(0.178)	(0.127)	(0.137)	(0.210)	(0.367)
Hybrid	0.287**	0.294**	0.494*	0.651**	0.635***	0.471***	0.484***	1.114***	1.012***
	(0.129)	(0.130)	(0.247)	(0.250)	(0.228)	(0.098)	(0.100)	(0.211)	(0.308)
Inputs									
Ln(land)	0.945***	0.940***	1.023***	1.021***	1.027***	0.998***	1.017***	1.289***	1.268***
	(0.055)	(0.058)	(0.069)	(0.076)	(0.074)	(0.048)	(0.054)	(0.103)	(0.216)
Ln(labor)			0.190*	0.270	0.197			−0.075	0.159
			(0.103)	(0.183)	(0.123)			(0.132)	(0.169)
Ln(input costs)			−0.393***	−0.476**	−0.408***			−0.135	−0.555*
			(0.105)	(0.201)	(0.140)			(0.213)	(0.301)
Plot age			0.023	0.007	0.006			0.113	0.036
			(0.040)	(0.047)	(0.044)			(0.069)	(0.043)
Annual climate									
Ln(precipitation, mean)				2.945	4.555**				1.287
				(7.358)	(2.176)				(4.129)
Ln(minimum temperature, mean)				144.028	498.576				107.064*
				(510.536)	(361.774)				(55.220)
Ln(maximum temperature, mean)				−2.061	−774.512				−89.007*
				(939.279)	(573.455)				(45.643)
Ln(precipitation, sd)				−2.263	−1.350				−0.691
				(2.779)	(1.405)				(2.437)
Ln(minimum temperature, sd)				4.971	6.938*				2.708
				(5.017)	(3.587)				(6.410)
Ln(maximum temperature, sd)				0.137	−4.435				−7.209**
				(8.043)	(5.600)				(3.265)
Year fixed effects	Yes	Yes	Yes	Yes	No	No	No	No	No
Farm fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.123***	3.101***	4.293***	−377.846	1130.348	2.853***	2.795***	2.950***	2312.759*
	(0.142)	(0.162)	(0.844)	(1667.639)	(876.768)	(0.182)	(0.206)	(0.840)	(1325.400)
R^2 (overall)	0.834	0.842	0.874	0.898	0.895				
Observations	113	98	58	51	51	83	70	37	31

Note: Robust standard errors in parentheses,.
* $p < 0.10$,.
** $p < 0.05$,.
*** $p < 0.01$).

The results indicate that hybrid coffee varieties give higher coffee output than traditional variety do, across both pooled OLS and random effects models as well as alternative specifications: without factor controls, with factor input controls and with factor input and climate controls. The estimated effects in the pooled OLS suggest that hybrid coffee varieties give 29–61% higher output than traditional coffee varieties do. The estimated coefficient for the introgressed varieties is only statistically significant in the random effects model when controlling for factor inputs. Moreover, the estimated coefficient for hybrid coffee varieties is statistically different from that of the introgressed varieties implying that hybrids give the highest output. Looking at the factor and climate inputs, coffee area positively affects output consistently across all models and specifications as expected. The effect of input costs appears to be negative in both pooled OLS and random effects models. While this appears to be counter intuitive, it does make sense considering that younger plots often have higher costs but are associated with lower output. Plot age positively affects output, albeit significant only in the random effects model. Again, given the average age of our sample plots, higher age indicates a more mature harvest. Finally, none of the climate variables significantly affect output in the pooled OLS model when year fixed effects are included. This seems intuitive given the changes in precipitation, temperature and their standard deviations across the years can be captured the year fixed effects. When the year fixed effects are dropped, mean precipitation, mean minimum temperature and its standard deviations positively affect coffee output while the effect of mean maximum temperature is negative. Given that all the plots are rain-fed, the climate effects are quite intuitive. In the random effects models, both mean and standard deviations of maximum annual temperature affects output negatively while the effect of minimum annual temperature is positive.

5. Discussion and policy implications

5.1. Discussion

The hybrids were developed with resilience to climate change in mind, both in terms of increased variability and more extreme weather patterns, which may be buffered in shaded agroforestry systems [2]. Marie et al. [29], using data from on-farm trials under controlled management, confirm that the hybrids are producing more and with more stability across different environments than traditional varieties. Though we do not have a particular focus on variety performance across agro-ecological environments, we do find, for the first time in commercial plantations conditions, the hybrid varieties to generally outperform pure line traditional and introgressed varieties in terms of productivity. Our results are also in line with previous studies using experimental plots or on-farm trials under controlled management, that find improved performance of the same F1 hybrid varieties [2,3].

Other studies have investigated F1 hybrids' performance in terms of cup quality (Starmaya and H1 varieties, [29]), tolerance to adverse soil moisture conditions (H1 and H10, [32]), pests and diseases (Starmaya hybrid, [17]); and the ability to produce in both sun and agroforestry systems (group of hybrids, [2,29]). Unpublished data collected from field trials in Vietnam in the H2020 European Breedcafs project (https://www.breedcafs.eu/) show similar results. These studies are based on both on-farm trials and experimental plots, and it is not clear to what extent the superiority of the hybrid coffee varieties as compared to their traditional or introgressed counter parts remain in real life coffee production.[6]

With the hybrid coffee varieties outperforming especially the traditional varieties, combined with expected climate changes and a growing specialty coffee market that offers higher prices for better quality, we can expect to see a fast increase in the use of the recently developed Arabica hybrids. To the extent hybrids are adapted to shaded agroforestry systems in which they maintain high yields [2], additional ecosystem services may accompany the uptake of hybrid varieties. However, the adoption rate of the new coffee hybrids remains limited and they have mainly been adopted by medium and large farms.

There are several factors that contribute to the lower adoption of hybrids. Firstly, the purchase costs of coffee seedlings could be a hindrance to some farmers. Even though Georget et al. [16] showed that the hybrids can be propagated in nurseries by horticultural rooted mini-cuttings, which is much cheaper than the conventional somatic embryogenesis propagation processes that must be carried out in vitro cultures laboratories, the price per seedling is still around 40% – 160% higher than a seedling of a traditional coffee variety. This is different for the Starmaya variety seedlings, which have a competitive price to seedling of the traditional varieties due to their less expensive reproduction process. Secondly, with larger productivity comes also the need for more labor and other inputs such as fertilizers. As can be seen from Table 2, while hybrid coffee varieties, on average, give 47% higher coffee output than traditional coffee varieties, they use 90% more labor day and increase the cost of other inputs by 48%. Thus, even though the hybrids' pest resistance/tolerance may result in lower costs on pesticides, the added fertilizer costs as well as higher demands for management know-how may discourage especially smallholder farmers from replacing traditional varieties with hybrids. This highlights the need of agroecological approaches for nutrient management to improve livelihood and environmental outcomes [13]. Finally, Turreira-García [39] documented that one of the factors often mentioned by smallholder farmers for the limited adoption of new coffee varieties is the uncertainty related to long-term performance these varieties. This makes sense given the limited investment capacity of smallholders.

While we believe that our results provide a unique insight into the real world production of different coffee varieties, care should be taken in over-interpreting these results. First, our empirical results depend on a relatively small sample. While the estimated effect of hybrid coffee varieties on output is robust across alternative models and specifications, we hope future research will shed more light on this using a larger sample of plots. Second, the plot-level data records accounts for a fraction of the number of plots managed by the farms. Thus, the choice of large farms in keeping data records on selected plots is arguably not random. This has implication on the external validity of our results even within the coffee growing areas covered by our study

5.2. Policy implications

The results imply that hybrid coffee varieties have a potential for improving the welfare and enhancing resilience of smallholder farmers against climate change as well contributing towards efficient land use systems. However, despite almost three decades of experience with production of hybrid coffee varieties, the adoption rate remains very low. This requires coordinated policy interventions that increase adoption of these varieties among smallholder farmers. Firstly, as highlighted above, it appears that small scale farmers lack information and empirical evidence on the long-term performance of hybrid varieties. Targeted information and training campaigns, creating dialog and innovation platforms, and follow-up extension support may enhance the awareness of smallholder farmers. Secondly, the high price of hybrid seedlings and time-lag in production is expected to limit investment in hybrid coffee varieties, particularly by low-income smallholder farmers. Policy interventions in the form of subsidizing prices of hybrid seedlings, encouraging cost-effective seedling production, and expanding credit facilities are more likely to overcome liquidity constrains of smallholder farmers in adopting hybrid coffee varieties. Finally, expanding hybrid nurseries to all coffee growing areas including remote farmers will increase their accessibility.

6. Conclusion

Using unique plot-level panel data on coffee output and factor inputs as well as farm-level temperature and precipitation data among large commercial coffee farms in Costa Rica, we find that F1 hybrid coffee varieties give a higher output than traditional or introgressed varieties do. This result is robust over a number of specifications of pooled OLS and random effects models. We therefore find the F1 hybrids to have a potential role in the coffee sector's adaptation strategies towards climate change. Despite the superior performance of the F1 hybrids, also in terms of cup quality and pest resistance as reported in other studies, the adoption of hybrid varieties have been modest since the release of the first F1 hybrids in 2000 in Costa Rica. Access to hybrid plant material as well as perceived increased inputs costs may be among the barriers for further uptake. Further studies are needed on the (i) agronomic performance of the F1 hybrids in real life commercial farms, small and large; (ii) barriers for improved hybrid adoption rates; and (iii) the effect of climate change on hybrids including simulating the impact of different climate scenarios and resulting changes in input and management regimes.

Declarations of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Appendix Table A1
: Frequency of observations per panel.

Number of panels	Freq.	Percent
1	30	50.85
2	14	23.73
3	6	10.17
4	8	13.56
5	1	1.69

[6] Cup quality is the exception here, as F1 hybrid coffee from commercial farms dominated the Cup of Excellence competition in Nicaragua in 2018 (see https://www.baristamagazine.com/hybrid-varieties-cup-of-excellence-nicaragua/).

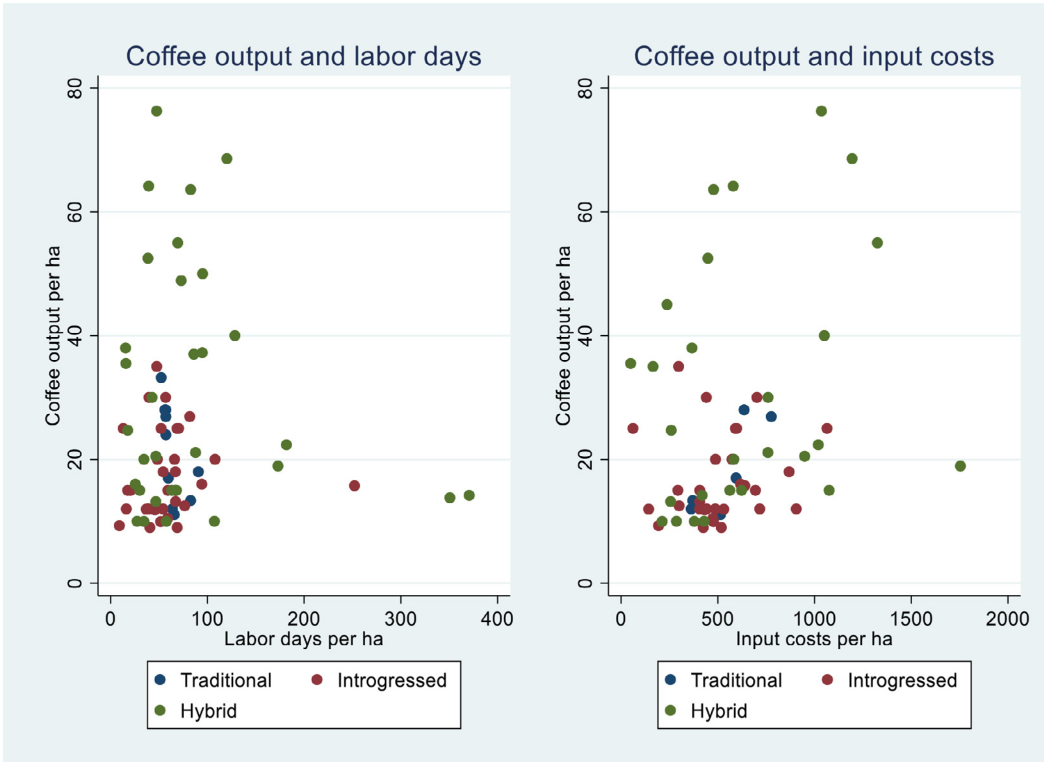

Fig. A1. Coffee output and input use, by type of coffee variety.

Appendix Table A2
Productivity of hybrid, introgressed and traditional coffee varieties, with seasonal climate variables.

	Pooled OLS (1)	Random effects (2)
Coffee varieties		
Traditional		
Introgressed	0.306	0.475***
	(0.210)	(0.139)
Hybrid	0.726***	0.898***
	(0.191)	(0.112)
Inputs		
Ln(land)	0.906***	1.007***
	(0.070)	(0.094)
Ln(labor)	−0.026	−0.145
	(0.174)	(0.224)
Ln(input costs)	−0.234	−0.295
	(0.159)	(0.241)
Plot age	0.142	0.297**
	(0.217)	(0.116)
Seasonal climate		
Dry season		
Ln(precipitation, mean)	−96.996**	−17.853
	(45.353)	(17.791)
Ln(minimum temperature, mean)	7272.365**	0.000
	(3326.957)	(.)
Ln(maximum temperature, mean)	−10,923.551**	0.000
	(5040.293)	(.)
Ln(precipitation, sd)	14.170*	1.749
	(7.244)	(1.877)
Ln(minimum temperature, sd)	−17.729*	9.970*
	(9.066)	(5.978)
Ln(maximum temperature, sd)	−11.272**	−14.189
	(4.496)	(9.613)
Wet season		
Ln(precipitation, mean)	0.000	0.000
	(.)	(.)
Ln(minimum temperature, mean)	−2336.943**	20.914
	(1088.184)	(88.799)
Ln(maximum temperature, mean)	3459.603*	12.188

(continued on next page)

Appendix Table A2 (*continued*)

	(1765.149)	(97.411)
Ln(precipitation, sd)	0.000	0.000
	(.)	(.)
Ln(minimum temperature, sd)	1.504	−5.498
	(4.567)	(5.533)
Ln(maximum temperature, sd)	−56.237*	−2.850
	(30.524)	(6.744)
Year fixed effects	Yes	No
Farm fixed effects	Yes	Yes
Constant	10,783.002**	3.274***
	(5082.605)	(0.196)
R^2 (overall)	0.934	0.961
Observations	51	31

Note: Robust standard errors in parentheses,.
* $p < 0.10$,.
** $p < 0.05$,.
*** $p < 0.01$.

Appendix Table A3
: Productivity of hybrid, introgressed and traditional coffee varieties, pooled OLS with plot fixed effects.

	Pooled OLS			
	All plots	Sample of specialized plots		
	(1)	(2)	(3)	(4)
Coffee varieties				
Traditional				
Improved	−0.670	−0.670	1.478	10.579
	(0.705)	(0.743)	(2.470)	(43.139)
Introgressed	0.482**	0.481**	1.547	5.354
	(0.230)	(0.225)	(1.005)	(17.515)
Inputs				
Ln(land)	0.702**	0.702**	1.400**	2.857
	(0.327)	(0.338)	(0.598)	(9.215)
Ln(labor)	(0.238)	(0.246)	(0.428)	(5.167)
			0.115	−1.906
Ln(input costs)			(0.405)	(4.695)
			−0.630**	−0.376
Plot age			(0.270)	(1.033)

(continued on next page)

Appendix Table A3 (*continued*)

	Pooled OLS All plots (1)	Sample of specialized plots (2)	(3)	(4)
			−0.442	−6.528
Annual climate			(2.024)	(30.734)
Ln(precipitation, mean)				
				14.362
Ln(minimum temperature, mean)				(23.060)
				−27,467.049
Ln(maximum temperature, mean)				
				(219,808.481)
				47,115.656
Ln(precipitation, sd)				
				(379,223.358)
				−17.340
Ln(minimum temperature, sd)				(115.170)
				−64.060
Ln(maximum temperature, sd)				(493.572)
				188.769
Year fixed effects	Yes	Yes	Yes	Yes
Farm fixed effects	Yes	Yes	Yes	Yes
Constant	4.593***	4.612***	4.471*	
				−77,037.004
	(1.422)	(1.476)	(2.426)	
				(624,149.771)
R^2	0.912	0.911	0.939	0.995
Observations	113	98	58	51

Note: Robust standard errors in parentheses,.
* $p < 0.10$,.
** $p < 0.05$,.
*** $p < 0.01$.

Table A4
: Productivity of hybrid, introgressed and traditional coffee varieties, pooled OLS with Translog production function.

	(1)	(2)
Coffee varieties		
Traditional		
Introgressed	0.032	0.220
	(0.212)	(0.377)
Hybrid	0.368	1.040**
	(0.259)	(0.456)
Inputs		
Ln(land)	−0.861	254.097
	(0.615)	(342.093)
Ln(labor)	−0.327	−106.590
	(1.298)	(688.118)
Ln(input costs)	−0.442	46.459
	(0.994)	(689.668)
Plot age	0.003	0.121
	(0.044)	(0.084)
Annual climate		
Ln(precipitation, mean)		−113.517
		(392.157)
Ln(minimum temperature, mean)		−3989.557
		(19,474.273)
Ln(maximum temperature, mean)		8268.546
		(22,460.635)
Ln(precipitation, sd)		3.409
		(84.606)
Ln(minimum temperature, sd)		−83.400
		(67.214)
Ln(maximum temperature, sd)		73.570
		(142.523)
Squared terms	Yes	Yes
Interaction terms	Yes	Yes
Year fixed effects	Yes	Yes
Farm fixed effects	Yes	Yes
Constant	5.443*	−14,400.536
	(2.971)	(65,918.063)
R^2	0.883	0.963
Observations	70	63

Note: Robust standard errors in parentheses,.
* $p < 0.10$,.
** $p < 0.05$,*** $p < 0.01$.

References

[1] M. Baca, P. Läderach, J. Haggar, G. Schroth, O. Ovalle, An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee growing families in Mesoamerica, PLoS One 9 (2) (2014) e88463, doi:10.1371/journal.pone.0088463.

[2] B. Bertrand, E. Alpizar, L. Lara, R. Santacreo, M. Hidalgo, J. Quijano, C. Montagnon, F. Georget, H. Etienne, Performance of Coffea arabica F1 hybrids in agroforestry and full-sun cropping systems in comparison with American pure line cultivars, Euphytica 181 (2) (2011) 147–158, doi:10.1007/s10681-011-0372-7.

[3] B. Bertrand, H. Etienne, P. Lashermes, B. Guyot, F. Davrieux, Can near-infrared reflectance of green coffee be used to detect introgression in Coffea arabica cultivars? J. Sci. Food Agric. 85 (6) (2005) 955–962, doi:10.1002/jsfa.2049.

[4] B. Bertrand, C. Montagnon, F. Georget, P. Charmetant, H. Etienne, Création et diffusion de variétés de caféiers Arabica: quelles innovations variétales? Cahiers Agric. 21 (2–3) (2012) 77–88 71, doi:10.1684/agr.2012.0547.

[5] E. Bryan, T.T. Deressa, G.A. Gbetibouo, C. Ringler, Adaptation to climate change in Ethiopia and Sohttps://doi.org/10.1016/j.envsci.2008.11.002uth Africa: options and constraints, Environ. Sci. Policy 12 (4) (2009) 413–426.

[6] C. Bunn, P. Läderach, O.O. Rivera, D. Kirschke, A bitter cup: climate change profile of global production of Arabica and Robusta coffee, Clim. Change 129 (1) (2015) 89–101, doi:10.1007/s10584-014-1306-x.

[7] J. Cabas, A. Weersink, E. Olale, Crop yield response to economic, site and climatic variables, Clim. Change 101 (3) (2010) 599–616, doi:10.1007/s10584-009-9754-4.

[8] A. Craparo, P.J. Van Asten, P. Läderach, L.T. Jassogne, S. Grab, Coffea arabica yields decline in Tanzania due to climate change: global implications, Agric. For. Meteorol. 207 (2015) 1–10, doi:10.1016/j.agrformet.2015.03.005.

[9] FbM DaMatta, R.T. Avila, A.A. Cardoso, S.C. Martins, J.C. Ramalho, Physiological and agronomic performance of the coffee crop in the context of climate change and global warming: a review, J. Agric. Food Chem. 66 (21) (2018) 5264–5274, doi:10.1021/acs.jafc.7b04537.

[10] A.P. Davis, T.W. Gole, S. Baena, J. Moat, The impact of climate change on indigenous arabica coffee (Coffea arabica): predicting future trends and identifying priorities, PLoS One 7 (11) (2012) e47981, doi:10.1371/journal.pone.0047981.

[11] T.-.T. Deressa, R.-.M. Hassan, C. Ringler, T. Alemu, M. Yesuf, Determinants of farmers' choice of adaptation methods to climate change in the Nile Basin of Ethiopia, Glob. Environ. Chang. 19 (2) (2009) 248–255, doi:10.1016/j.gloenvcha.2009.01.002.

[12] T. Duangsodsri, L. Villain, I.R. Vestalys, S. Michalet, C. Abdallah, J.-.C. Breitler, M. Bordeaux, A.M. Villegas, M. Raherimandimby, L. Legendre, 5-CQA and mangiferin, two leaf biomarkers of adaptation to full sun or shade conditions in Coffea arabica L, Metabolites 10 (10) (2020) 383, doi:10.3390/metabo10100383.

[13] FAO. (2018). The 10 elements of agroecology: guiding the transition to sustainable food and agricultural systems.

[14] S.E. Fick, R.J. Hijmans, WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas, Int. J. Climatol. 37 (12) (2017) 4302–4315, doi:10.1002/joc.5086.

[15] E. Frank, H. Eakin, D. López-Carr, Social identity, perception and motivation in adaptation to climate risk in the coffee sector of Chiapas, Mexico, Global Environ. Change 21 (1) (2011) 66–76, doi:10.1016/j.gloenvcha.2010.11.001.

[16] F. Georget, P. Courtel, E.M. Garcia, M. Hidalgo, E. Alpizar, J.-.C. Breitler, B. Bertrand, H. Etienne, Somatic embryogenesis-derived coffee plantlets can be efficiently propagated by horticultural rooted mini-cuttings: a boost for somatic embryogenesis, Sci. Hortic. 216 (2017) 177–185, doi:10.1016/j.scienta.2016.12.017.

[17] F. Georget, L. Marie, E. Alpizar, P. Courtel, M. Bordeaux, J.M. Hidalgo, P. Marraccini, J-c Breitler, E. Déchamp, C. Poncon, Starmaya: the first Arabica F1 coffee hybrid produced using genetic male sterility, Front. Plant Sci. 10 (2019) 1344, doi:10.3389/fpls.2019.01344.

[18] M. Glenn, S.-.H. Kim, J. Ramirez-Villegas, P. Laderach, Response of perennial horticultural crops to climate change, Hortic. Rev. (Am. Soc. Hortic. Sci.) 41 (2013) 47–130, doi:10.1002/9781118707418.ch02.

[19] Z. Guido, C. Knudson, T. Finan, M. Madajewicz, K. Rhiney, Shocks and cherries: the production of vulnerability among smallholder coffee farmers in Jamaica, World Dev. 132 (2020) 104979, doi:10.1016/j.worlddev.2020.104979.

[20] I. Harris, P.D. Jones, T.J. Osborn, D.H. Lister, Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset, Int. J. Climatol. 34 (3) (2014) 623–642, doi:10.1002/joc.3711.

[21] C.A. Harvey, M. Saborio-Rodríguez, M.R. Martinez-Rodríguez, B. Viguera, A. Chain-Guadarrama, R. Vignola, F. Alpizar, Climate change impacts and adaptation among smallholder farmers in Central America, Agric. Food Secur. 7 (1) (2018) 1–20, doi:10.1186/s40066-018-0209-x.

[22] E. Hisali, P. Birungi, F. Buyinza, Adaptation to climate change in Uganda: evidence from micro level data, Glob. Environ. Chang. 21 (4) (2011) 1245–1261, doi:10.1016/j.gloenvcha.2011.07.005.

[23] G. Hochachka, Integrating the four faces of climate change adaptation: towards transformative change in Guatemalan coffee communities, World Dev. 140 (2021) 105361, doi:10.1016/j.worlddev.2020.105361.

[24] P. Imbach, E. Fung, L. Hannah, C.E. Navarro-Racines, D.W. Roubik, T.H. Ricketts, C.A. Harvey, C.I. Donatti, P. Läderach, B. Locatelli, Coupling of pollination services and coffee suitability under climate change, Proc. Natl. Acad. Sci. 114 (39) (2017) 10438–10442, doi:10.1073/pnas.1617940114.

[25] J. Jaramillo, A. Chabi-Olaye, C. Kamonjo, A. Jaramillo, F.E. Vega, H.-.M. Poehling, C. Borgemeister, Thermal tolerance of the coffee berry borer Hypothenemus hampei: predictions of climate change impact on a tropical insect pest, PLoS One 4 (8) (2009) e6487, doi:10.1371/journal.pone.0006487.

[26] G.-.A. Kahsay, L-G Hansen, The effect of climate change and adaptation policy on agricultural production in Eastern Africa, Ecol. Econ. 121 (2016) 54–64, doi:10.1016/j.ecolecon.2015.11.016.
[27] I. Koh, R. Garrett, A. Janetos, N.D. Mueller, Climate risks to Brazilian coffee production, Environ. Res. Lett. 15 (10) (2020) 104015, doi:10.1088/1748-9326/aba471.
[28] P. Läderach, J. Ramirez–Villegas, C. Navarro-Racines, C. Zelaya, A. Martinez–Valle, A. Jarvis, Climate change adaptation of coffee production in space and time, Clim. Change 141 (1) (2017) 47–62, doi:10.1007/s10584-016-1788-9.
[29] L. Marie, C. Abdallah, C. Campa, P. Courtel, M. Bordeaux, L. Navarini, V. Lonzarich, A.S. Bosselmann, N. Turreira-García, E. Alpizar, G× E interactions on yield and quality in Coffea arabica: new F1 hybrids outperform American cultivars, Euphytica 216 (5) (2020) 1–17, doi:10.1007/s10681-020-02608-8.
[30] C. Montagnon, P. Marraccini, B. Bertrand, in: Breeding for Coffee quality. Specialty Coffee, Managing Quality International Plant Nutrition Institute, Southeast Asia Program, 2012, pp. 93–122.
[31] O. Ovalle-Rivera, P. Läderach, C. Bunn, M. Obersteiner, G. Schroth, Projected shifts in Coffea arabica suitability among major global producing regions due to climate change, PLoS One 10 (4) (2015) e0124155, doi:10.1371/journal.pone.0124155.
[32] E. Pappo, C. Wilson, S.L. Flory, Hybrid coffee cultivars may enhance agroecosystem resilience to climate change, AoB Plants 13 (2) (2021) plab010, doi:10.1093/aobpla/plab010.
[33] S. Quiroga, C. Suárez, J.D. Solís, Exploring coffee farmers' awareness about climate change and water needs: smallholders' perceptions of adaptive capacity, Environ. Sci. Policy 45 (2015) 53–66, doi:10.1016/j.envsci.2014.09.007.
[34] S. Quiroga, C. Suárez, J.D. Solís, P. Martinez-Juarez, Framing vulnerability and coffee farmers' behaviour in the context of climate change adaptation in Nicaragua, World Dev. 126 (2020) 104733, doi:10.1016/j.worlddev.2019.104733.
[35] P. Rowhani, D-B Lobell, M. Linderman, N. Ramankutty, Climate variability and crop production in Tanzania, Agric. For. Meteorol. 151 (4) (2011) 449–460, doi:10.1016/j.agrformet.2010.12.002.
[36] H.A.M. Shaffril, S.E. Krauss, S.F. Samsuddin, A systematic review on Asian's farmers' adaptation practices towards climate change, Sci. Total Environ. 644 (2018) 683–695, doi:10.1016/j.scitotenv.2018.06.349.
[37] V.A. Silva, J.C.D.R. Abrahão, A.M. Reis, M.D.O. Santos, A.A. Pereira, C.E., ... Botelho, A.C.B.D. Oliveira, Strategy for selection of drought-tolerant arabica coffee genotypes in Brazil, Agronomy 12 (9) (2022) 2167.
[38] L. Toniutti, J.-.C. Breitler, H. Etienne, C. Campa, S. Doulbeau, L. Urban, C. Lambot, J.-.C.H. Pinilla, B. Bertrand, Influence of environmental conditions and genetic background of arabica coffee (C. arabica L) on leaf rust (Hemileia vastatrix) pathogenesis, Front. Plant Sci. 8 (2017) 2025, doi:10.3389/fpls.2017.02025.
[39] N. Turreira-García, Farmers' perceptions and adoption of Coffea arabica F1 hybrids in central America, World Dev. 1 (100007) (2022), doi:10.1016/j.wds.2022.100007.
[40] L. Villers, N. Arizpe, R. Orellana, C. Conde, J. Hernandez, Impacts of climatic change on coffee flowering and fruit development in Veracruz, México. Interciencia 34 (5) (2009) 322–329.
[41] P. Vaast, J.-.M. Harmand, B. Rapidel, P. Jagoret, O. Deheuvels, Coffee and cocoa production in agroforestry—a climate-smart agriculture model, in: Climate Change and Agriculture Worldwide, Springer, 2016, pp. 209–224, doi:10.1007/978-94-017-7462-8_16.
[42] J. Waller, M. Bigger, R. Hillocks, Coffee pests, Diseases and Their Management, CABI, UK, 2007.