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Productivity, Soil Health, and Tree Diversity in Dynamic Cacao Agroforestry Systems in Ecuador

Summer L. Allen [1,*], Lenin Alejandro Robayo [2], Carla D. Martin [1,3] and José Lopez Ganem [1,4]

1 Fine Cacao and Chocolate Institute, Cambridge, MA 02138, USA; cdmartin@fas.harvard.edu (C.D.M.); jose@chocolateinstitute.org (J.L.G.)
2 Union of Cocoa Peasant Organizations, San Jacinto de Yaguachi 092103, Guayas, Ecuador; lenin.robayo@unocace.com
3 Department of African and African American Studies, Harvard University, Cambridge, MA 02138, USA
4 Food Studies Programs, Boston University, Brookline, MA 02446, USA
* Correspondence: summer@chocolateinstitute.org

Abstract: Agroforestry has the potential to support more resilient livelihoods, soil health, and biodiversity, when compared to monocropping. In Ecuador, the Union of Cacao Peasant Organizations (UNOCACE) has been working with producers since 2016 to transition cacao plots to a dynamic agroforestry system that includes timber and fruit species as well as ground cover in addition to cacao. This study evaluates the application of this model and its implications for agricultural production, livelihoods, and soil health through producer surveys and field-based sampling. The program is resulting in significantly more timber and fruit trees on the cacao plots. Despite this, cacao production and income have not decreased in a significant way, once accounting for the number of producing trees on the plots. In addition, while additional labor is utilized on the dynamic agroforestry plots, after utilizing a matching procedure, no significant difference is seen in total crop productivity for each day of labor utilized. Over time, total productivity could increase for the dynamic agroforestry plots as the companion crops and trees mature. As the program is relatively new and has undergone some changes, additional studies are needed to understand the benefits or challenges, especially for soil health, that might be realized further in the lifespan of the program.

Keywords: agroforestry; cacao; soil carbon; livelihoods; Ecuador; tree diversity

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1. Introduction

As pressure on remaining forest ecosystems intensifies, agroforestry has been promoted as a way of safeguarding forest landscapes and advancing the socio-economic goals of local communities [1]. However, the evidence regarding the tradeoffs in terms of overall productivity and especially, the labor requirements for small-scale producers, is limited. In this study, we address that gap by employing an experimental design to evaluate overall farm productivity and labor requirements, soil health at multiple depths, and tree species diversity as an indicator of biodiversity on the plots. This paper first highlights the recent literature that discusses the value propositions of *Theobroma cacao* L. (cacao) agroforestry and the information gaps. This paper then introduces the study area in Ecuador as well as the key components that were included in the research. The sampling and analytical strategy is outlined and followed by the presentation of the empirical results. Finally, the paper discusses the implications of this experimental study in terms of the value proposition of cacao agroforestry and the opportunities for future research.

Agroforestry systems can have important implications for biodiversity and food security [2]. Several meta-analyses have discussed the environmental opportunities from cacao agroforestry such as nutrient cycling, biodiversity conservation, and carbon storage [3–7]. For example, cacao agroforestry can contribute to biodiversity through provision of habitat and resources for plant and animal species, especially in Latin America [5]. A study in coastal

Nicaragua found that well-established systems that include perennials and shrub crops and non-crop trees may be able to provide similar levels of species richness as secondary forests [8]. Shade trees in agroforestry systems can provide additional litterfall, increasing soil organic matter. Soil organic matter can enhance water-holding capacity, bind nutrients, increase microbial biomass, and improve nutrient cycling [4,9]. A study in Belize found that cacao agroforestry can maintain overall soil health (measured through nematode communities) similar to undisturbed rainforests [10]. Agroforestry systems in tropical areas can also increase Calcium (Ca), Magnesium (Mg), Potassium (K), Nitrogen (N), and pH in soils as well as shift physical properties such as water infiltration and soil aggregate formation but responses are influenced by climatic conditions, management, and tree species [11].

Tropical agroforestry systems, especially, have been found to have increased carbon capture above and below ground when compared to agroforestry systems in other regions [12]. For example, in Bolivia, researchers found that biomass and carbon stocks were higher in organic, successional agroforestry cacao systems than in monoculture or simple agroforestry [13]. However, while converting monoculture cacao to agroforestry is estimated to increase total carbon stocks, significant differences were not seen in soil organic carbon rates in Ecuador [14] and research on long-term impacts of cacao agroforestry on soil carbon and nutrients is limited [15]. How much carbon could be sequestered in an agroforestry system depends, ultimately, on effective land management practices that support soil organic matter. Organic carbon inputs to the soil increase with litterfall, but the resulting impacts on soil organic carbon depend on decomposition rates determined by several other factors, such as microclimate, root depth, soil type, tree species richness, the age of the plots, and management practices [16–18].

Agroforestry systems can provide diversified and increased incomes for producers in addition to biodiversity conservation and carbon sequestration [19,20]. Cacao agroforestry systems, in particular, may improve livelihoods through the provision of additional crops for household consumption or the potential to mitigate price variability in cacao [21]. Cacao agroforestry can result in higher total system yields when all crops are considered, which can be important for food security and resilience in smallholder households [22]. Research in Bolivia found that yields from organic agroforestry systems were very similar to organic monoculture but that the return on labor may be higher for cacao agroforestry when compared to monocultures due to the income gain from crops such as banana and plantain [23].

However, the environmental and economic tradeoffs associated with agroforestry are not well documented due to the complexity of measuring productivity for multiple products [21]. A meta-analysis of cacao agroforestry systems found lower cacao yields when compared to monocultures but higher total system yields [3]. In Amazonian Ecuador, recent field experiments found that yields were higher for cacao agroforestry when compared to monoculture [24]. Other experiments in Amazonian Ecuador found that cacao productivity (at least in the short-term) was lower, highlighting the need for monetary payments to sustain the producer's transition to agroforestry [14]. Similarly, models of cacao farms in northern coastal Ecuador also found that improving carbon payments or conservation-related payments is necessary to incentivize native non-cacao tree cover [6].

Agroforestry systems could also provide more stability in the face of climate change. For example, a study of cacao agroforestry systems in the Bolivian Andes found buffering against extreme climate events (such as extreme temperature and humidity fluctuations) compared to monocultures [25]. Cacao grown under forest cover in Brazil was also found to reduce vulnerability to climate change by reducing understory temperatures [26]. Farmers in Indonesia noted that agroforestry also helped conserve soil and restore the land [27]. Evidence from Indonesia has also shown that cacao grown under shade can produce for many more years than cacao grown under full sun [18]. While there has been differing results regarding the impacts of cacao agroforestry systems on pest and diseases, research in Bolivia found that cacao agroforestry systems are not associated with increased pests and diseases when compared to monoculture if good management practices are followed [28].

A meta-analysis also found a lower abundance of pests in perennial crops such as cacao when grown in agroforestry systems [29].

Despite the increasing number of studies, there are limited data on the necessary conditions for competitive cacao agroforestry systems [30]. The present study aims to contribute to and further previous research on the potential for cacao agroforestry to provide sustainable production systems for smallholder cacao producers that could support livelihoods and improve biodiversity. This study evaluates the potential changes in soil properties, tree diversity, and cacao production that are associated with the application of a dynamic agroforestry model in two provinces of Ecuador and the implications for livelihoods and conservation. It also provides suggestions for future research that could inform adaptive management strategies.

2. Materials and Methods

The Union of Cacao Peasant Organizations (UNOCACE) is an Ecuadorian organization of 20 associations located primarily in the six provinces of Guayas, Los Ríos, El Oro, Bolivar, Manabí, and Esmeraldas. In 2016, UNOCACE initiated a pilot project called FINCA to test dynamic agroforestry cacao management. The FINCA project is financed by HALBA and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Alter Eco Foundation (now Erol Foundation), and TRIAS. Dynamic agroforestry (DAF) plots, designed by ECOTOP (a consulting firm that provides technical assistance for successional agroforestry systems), were created with interested producers and since 2016, the number of producers enrolled in the FINCA program has grown to 554 with 783 parcels enrolled in the program since 2016. The project provides training and inputs (seedlings, pruning shears, and pruning saws) to producers as they transition their plots to dynamic agroforestry.

The FINCA program provides 840 cacao seedlings, 840 *Inga edulis* (guaba) seedlings, and 840 suckers of *Musaceae* (plantain or bananas) per hectare as well as 140 fruit seedlings, 140 timber or shade seedlings, and a mix of plants and seeds for yuca, beans, maize, sweet potato, squash, sesame, ginger, turmeric, and daisy, as well as *Canavalia* for ground cover. The plants and trees are planted on 1-hectare parcels of cacao. Almost half of the parcels (48%) are not sloped, and the rest have land that ranges from 10 to 30% slope with a minority (13%) having slopes over 40%. The cacao, banana, and shade species are planted at distances of 4 m by 3 m, fruit species planted at distance of 8 m by 9 m, and palm and timber species are planted at a distance of 9 m by 12 m. Trees that do not survive are replaced by the program.

Producers that are part of the FINCA program are visited by the field technicians between 5 and 8 times per year where they are given information on management of the agroforestry system and control of shade including pruning and biomass with pruning brigades organized for the biomass varieties. For comparison, producers that are not part of the FINCA program receive three visits a year with information focused on the organic certification including organic inputs, cacao management, and pruning.

The two main cacao varieties grown in Ecuador are Nacional and CCN51. Nacional, a high-quality variety, is native to Ecuador and Peru and sold as fine cacao, while CCN51 is more disease resistant and sold more for bulk cacao [31]. Of the producers included in the sample, 20% have a parcel of CCN51 in addition to their parcel of cacao Nacional. Cacao Nacional is commonly grown with other crops such as banana and plantain in Ecuador and this is especially the case for the producers that are part of UNOCACE, which sell banana and plantain to UNOCACE in addition to cacao. The producers are offered the opportunity to participate in the FINCA program through conversations with their local cacao associations which are affiliated with UNOCACE. To participate, the producers must be organic certified, attend meetings, have legal documents for the property, be part of a local cacao producers' association that belongs to UNOCACE, and follow the guidelines of the program. Those producers that enroll must have at least a hectare of land they can dedicate to the program. However, producers may have a parcel of their land in the FINCA program, and another parcel of their land not enrolled in the FINCA program.

It is expected that project activities will increase overall agricultural production and reduce inputs, which would positively impact incomes, cacao quality, carbon stored in trees and soils, biodiversity, and marketing opportunities for non-cacao agricultural products. This study investigates the effect of the FINCA program on cacao yield, carbon storage, income diversity, and overall productivity, as well as indicators of soil health and tree species richness. Given the age of the FINCA program, the first hypothesis explored is that income from cacao may be less (at least in the short-term) but additional crops will allow diverse income opportunities with the expectation of higher overall agricultural productivity over the medium- to long-term. The second hypothesis explored is that access to training and inputs will be higher because of the program. The third hypothesis tested is that soil measures will be better, and the fourth hypothesis is that plots participating in the program will have more tree species richness, an indicator for biodiversity. While we would expect that plots that had been part of the program for at least 3 years would see measurable differences, this study is meant to inform future adjustments to the FINCA program. It should be noted that the program underwent changes that could affect our outcomes. For example, the Nacional cultivars that were provided from 2016 to 2019 (EET 103, EET 559, EET 576, EET 577) were not as productive for some producers. From 2020 to 2023, other clones (INIAP 800, INIAP 801) that have shown higher production [32] were provided to FINCA producers. In addition, prior to 2019, producers with a minimum of 0.5 hectares in cacao were enrolled in the program but starting in 2019, producers needed to have 1 hectare in cacao to enroll in the program. These changes to the cultivars and the planting areas likely mean that the results, especially in terms of cacao productivity, could take several more years to materialize in a significant way.

Data collection was overseen by the Fine Cacao and Chocolate Institute (FCCI), a US-based non-profit research organization, and utilized focus groups, interviews with producers, and field visits to collect both qualitative and quantitative data. Field work was conducted by Ecuador's National Institute of Agricultural Research (INIAP). The survey was pre-tested in a field pilot with INIAP and FCCI in Quevedo, Los Ríos. Given the range of farm sizes and the focus on small-scale producers, rather than a random selection of producers, the sample was determined to be the full list of small-scale UNOCACE producers (those with 5 or less hectares of cultivated land).

The field data were collected in June 2023, using KoboToolbox, an open-source Android application. The survey lasted on average 30 to 40 min and was conducted with the person who oversaw the cacao production and who was listed as part of the UNOCACE cooperative. The survey included details on production practices by parcel including the size of the parcels, the amount harvested and sold for all crops produced, training, technical assistance, and inputs received, labor (paid and family) utilized, the challenges faced for production, the percentage of income from other sources, and details about the producer's education, family, and dwelling. To gather additional information about the economic situation of the producers and their households, we utilized the Poverty Probability Index (PPI), a set of 10 questions published in 2022 for Ecuador [33]. The questions include information on occupations, education, household size, the structure of the house, and access to utilities. Using weighting procedures, the PPI was calculated for the households in the survey and then associated with the probability that they would fall under one of the specific poverty lines. The national poverty line in Ecuador is USD 3.60/day (2018), which is equivalent to USD 5.50 (2011 purchasing power parity (PPP) dollars) per day [34]. Using that poverty line, the expected rate of poverty for the households was averaged.

In total, 229 producers, 162 of whom were in Los Ríos and 67 of whom were in Guayas, responded to the survey. In the sample, 99 producers were part of the FINCA program, and 130 were not part of the program, meaning they were not implementing the dynamic agroforestry system supported by UNOCACE. In all, 6 of the 130 producers that were not part of the FINCA program had participated in prior years but were not currently following the management recommendations. Eleven producers were sick, unwilling to participate, or at a distance that would be unfeasible for the full team to reach. These 11 producers were randomly replaced from a list of UNOCACE producers with a range up to 7 hectares of land. To calculate overall agricultural production income, reported quantities and prices of sold crops were utilized. The value of harvested crops that were not sold was estimated using median prices for that crop reported in the sample with crop-specific prices verified by the field team.

Several methodologies were used to account for differences in the FINCA and non-FINCA populations. The populations were matched using a probit estimation of involvement in the program as seen in Equation (1), where Y represents a binary variable of inclusion in the program.

$$Prob(Y_i = 1) = F(Z_i) \tag{1}$$

After various specification attempts, propensity score matching used the MatchIt "optimal" matching procedure in R, version 4.3.1 [35]. Results were robust to the nearest neighbor matching procedure as well.

The sample size for the soil and tree measurements was based upon budgetary constraints, sampling approximately 50% of the full sample of producers in each province. Producers were selected for these samples using a random number generator. In total, 80 soil samples were taken in Los Ríos, and 32 samples were taken in Guayas, at both 10 cm and 30 cm according to the U.N. Food and Agriculture Organization recommendations [36]. Following research recommendations to measure soil organic carbon at 100 cm [37], the team constructed deeper soil pits to measure soil at 1 m for 10 random samples in Los Ríos and 7 random samples in Guayas.

Soil samples at 10 cm and 30 cm were collected using a soil auger and a 1 kg mix of 15 sub-samples from different parts of the plot to account for environmental variability [38]. Soil measurements were also performed on 18 plots using soil pits up to 1 m in depth where a sample was taken between 0 and 30 cm and another sample was taken at a depth of more than 30 cm. Samples of 1 kg were taken at the deepest point possible, up to 103 cm. The depth of the samples varied based upon the soil depth for each pit and therefore, in order to compare soils at similar depths, the sample was split based upon samples that were taken a depth greater than 32 cm and those that were taken a depth less than that. The calculation of the physical and chemical soil properties was performed in the Soil, Plant and Water Analysis Lab at INIAP using colorimetric and volumetric methods as established by INIAP [39] and outlined in other studies [40]. Soil organic carbon (tons/ha) was calculated using dry combustion using the weight of the soil, the depth of the sample, and the density of the soil [41]. Bulk density was calculated using the Uhland volumetric ring method [42].

The tree measurements were collected using parcel-level forms to capture the diversity, size, and age of the tree species. Tree surveys were performed on 65 randomly selected plots of 1000 m^2 each; 40 plots were from producers in Los Ríos and 25 plots were from producers in Guayas. The methodology utilized follows that of Quiroz and Mestanza [43] which inventories the diversity and richness of species that are present within cacao agroforestry systems. The surveys captured information on the number and size of cacao trees, timber and fruit trees, and the age of the cacao trees. Shade cover was estimated visually by the trained technicians from INIAP. The survey locations are shown in Figure 1.

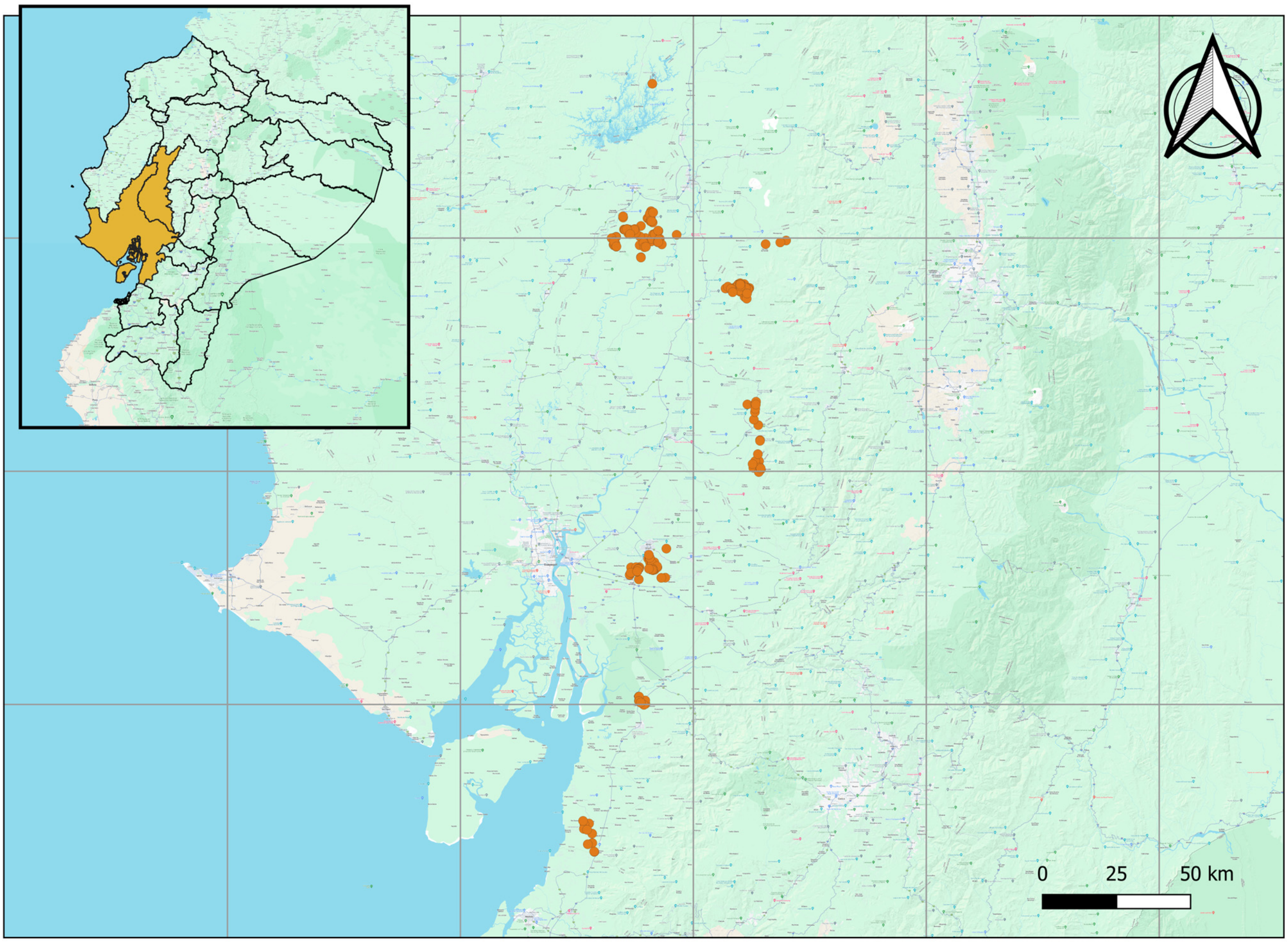

Figure 1. Map of the study area. The yellow dots indicate the sites where the surveys were applied.

3. Results

The research was designed to compare the production and plot-level characteristics between plots that were enrolled in the FINCA program and those that had never been enrolled in the program but were managed by producers that were part of the same cooperative. Therefore, the results that follow focus on comparing the two groups using statistical techniques in Stata [44] that treat the FINCA plots as the treatment group and the non-FINCA plots as the control group.

Quantitative data were collected per plot of land as well as by household. From the 229 households sampled, 99 were currently part of the FINCA program (FINCA producers) and 130 were not part of the FINCA program (non-FINCA producers). In total, information from 304 plots with Nacional was collected in addition to more limited information on the plots without Nacional. Approximately 20% of the producers that are part of the FINCA program and those that are not enrolled have another parcel for a total of 89 additional plots that include CCN51 and other crops. As mentioned earlier, producers may have one parcel enrolled in the FINCA program while another parcel is not enrolled in the program. Given the possibility that FINCA producers manage their non-FINCA plots differently because of the training in the program, the non-FINCA plots for these producers (20 plots) were eliminated from the comparison. For the purposes of estimation, we utilized a total of 283 plots (159 plots of cacao Nacional that were not part of FINCA and 124 plots that were part of the program).

Most producers had more than 30 years of experience growing cacao and 23% of the producers identified as female. Demographics between FINCA and non-FINCA producers tended to be similar. Producers had on average around 2.9 hectares in total production, most of which was cacao (Table 1). Given the unequal variances among some of the indicators and the smaller sample size, Welch's *t*-test for unequal variances [45] and a test for equal proportions (prtest) was utilized in the sample means shown in Table 1 in which the asterisks represent the significance of the difference between the means of indicators for the households that are part of FINCA and those that are not part of the FINCA program. While the number of plots of cacao was higher for FINCA producers, the number of hectares was not significantly different. Most of the cacao is sold to the local association which aggregates the production to sell to UNOCACE. The producers receive most of their income from agriculture, despite many of them having other occupations. Of the producers interviewed that had children, about half of them responded that their children were interested in participating in cacao production. Producers were also asked about food insecurity in their household, and more than half of the respondents expressed some level of concern. Most producers responded that women were not involved in the decision-making related to agricultural production.

Table 1. Household-level indicators.

	Control (Non FINCA) N = 130		Treatment (FINCA) N = 99		Statistical Analysis
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Welch-*t*-Test; Prtest for Proportions**
Age of producer	58.68	−16.26	59.84	−14.11	
Household size	3.46	−1.61	3.52	−2.09	
Highest level of education in household (range of 0–3)	1.95	−0.94	2.27	−0.79	**
Number of plots with cacao	1.22	−0.57	1.44	−0.73	*
Hectares in cacao	2.28	−1.86	2.18	−1.85	
% of income from cacao	43.92	−21.03	38.73	−24.79	
% of income from agriculture	67.61	−27.4	63.59	−32.69	
% of cacao sold to the association (N = 191)	90.25	−27.7	89.14	−30.54	
producer has non-agriculture related occupations	60.77%		61.62%		
children have interest in cacao (N = 100)	49.15%		46.34%		
women not involved in decisions	70.00%		69.70%		
concerned about food insecurity	60.77%		57.57%		

Notes: *, ** Statistical significance at $p < 0.1$; $p < 0.05$.

Using the Poverty Probability Index calculation, of the non-FINCA households, 52.3% were estimated to be below the poverty line, while 45.9% of the FINCA households were estimated to be below the poverty line, a difference that was statistically significant.

Producers that were not part of the FINCA program were asked why they had not yet joined. Reasons included not having the opportunity (37.74%), not having the resources to implement it (32.08%), and not having time (20.75%), while the remaining producers noted other reasons that included health constraints. Producers that were previously part of the program were asked why they had left and cited reasons such as the difficulty in following the suggestions, a lack of time, not seeing benefits or involvement from the technicians, or growing species that did not produce well. These answers correspond to what was discussed in the focus groups.

In line with the second hypothesis, the producers that are part of the FINCA program are more likely to receive inputs (56.73%), training (76.77%), and technical assistance (55.56%) compared to non-FINCA producers in which 38.40% received inputs, 56.92% received training, and 40% received technical assistance. These differences are statistically significant. This question was not time-bound so it included any training, inputs, or technical assistance they received. The source of these deliverables was overwhelmingly UNOCACE, and most producers noted that these benefits were seen in 2022 and/or 2023, which highlights the need to conduct further analysis of the impacts of the program once additional time has passed and the systems are more established.

The FINCA plots had significantly higher levels of younger trees with 37.9% of the FINCA plots having cacao less than or equal to three years old, compared to 8.81% of the non-FINCA plots. The FINCA plots also had significantly higher rates of replanting with 51.61% of the FINCA plots being replanted and 32.08% of the non-FINCA plots being replanted. Welch t-tests comparing the two groups are shown in Table 2. The tests find significantly more crop species and timber trees on the FINCA plots when compared to the non-FINCA plots as well as a higher number of developing trees and plants. There were various ages of cacao trees with FINCA plots having a significantly higher number of younger trees that were not yet producing cacao.

Table 2. Parcel-level variables.

	Control (Non FINCA) *N* = 159		**Treatment (FINCA) *N* = 124**		**Statistical Analysis**
	Mean	**Standard Deviation**	**Mean**	**Standard Deviation**	**Welch-*t*-Test**
number of producing cacao trees per ha	670.7	343.41	488.36	558.46	**
number of growing cacao trees per ha	85.92	−272.15	306.22	−351.48	***
quintals of cacao per ha	14.27	−19.45	8.12	−11.26	**
quintals of cacao per producing tree	0.02	−0.02	0.02	−0.02	
income from cacao Nacional by hectare (USD)	676.65	−1041.08	659.67	−1952.53	
timber trees per ha	8.72	−35.85	66.45	−244.48	*
number of crops per parcel	0.5	−0.81	1.39	−1.5	***
income other crops by hectare (USD)	518.55	−1839.49	570.31	−967.73	
total productivity (in USD) for all crops by hectare	2477.09	−12,744.86	3011.44	−10,324.67	
number of developing crops (plants per ha)	22.47	−87.13	145.91	−410.11	**
clusters of plantains per ha (*N* = 120)	205.78	−269.4	365.54	−483.69	*
% of cacao harvested (not lost)	89.38	−22.41	81.1	−30.16	**
labor days per hectare of cacao (paid and family)	27.71	−30.76	42.21	−51.28	**
total productivity (in USD) for all crops per labor day used	199.99	−1062.06	110.26	−443.08	

Notes: *, **, *** Statistical significance at $p < 0.1$; $p < 0.05$; $p < 0.01$.

Significant differences were not seen in total income per hectare or income from cacao per hectare on the plots although the FINCA plots contain cacao trees that are younger. While a difference was seen in the number of quintals produced per hectare (in line with the first hypothesis that cacao production may decrease in the short-term), this difference does not remain significant after controlling for the number of producing trees, implying that productivity per tree is not less for FINCA plots. A recent meta-analysis on the impact of simple or complex agroforestry systems on cacao yield has also shown limited impacts from complementary crops on cacao production [46]. Table 2 shows the estimations of total production value for the full range of crops harvested. Comparisons are also shown between crops that are generally harvested similarly and more widely produced, such as banana, plantain, and orange. While no significant differences were seen in total productivity, there was significantly more production of plantain in FINCA plots compared to non-FINCA plots, which aligns with the first hypothesis that overall productivity may be higher on more diverse plots.

Producers were asked about the difficulties they face and there were few statistically significant differences between their experiences. However, 36% of FINCA producers and 22% of non-FINCA producers noted drought, a difference that was statistically significant. Producers were also asked about the changes they have seen over the past five years; interestingly, more FINCA producers noted better quality, higher production, higher prices, and lower incidence of drought (Figure 2). Despite the additional shading, no significant differences were seen with respect to the impact from diseases according to the FINCA producers.

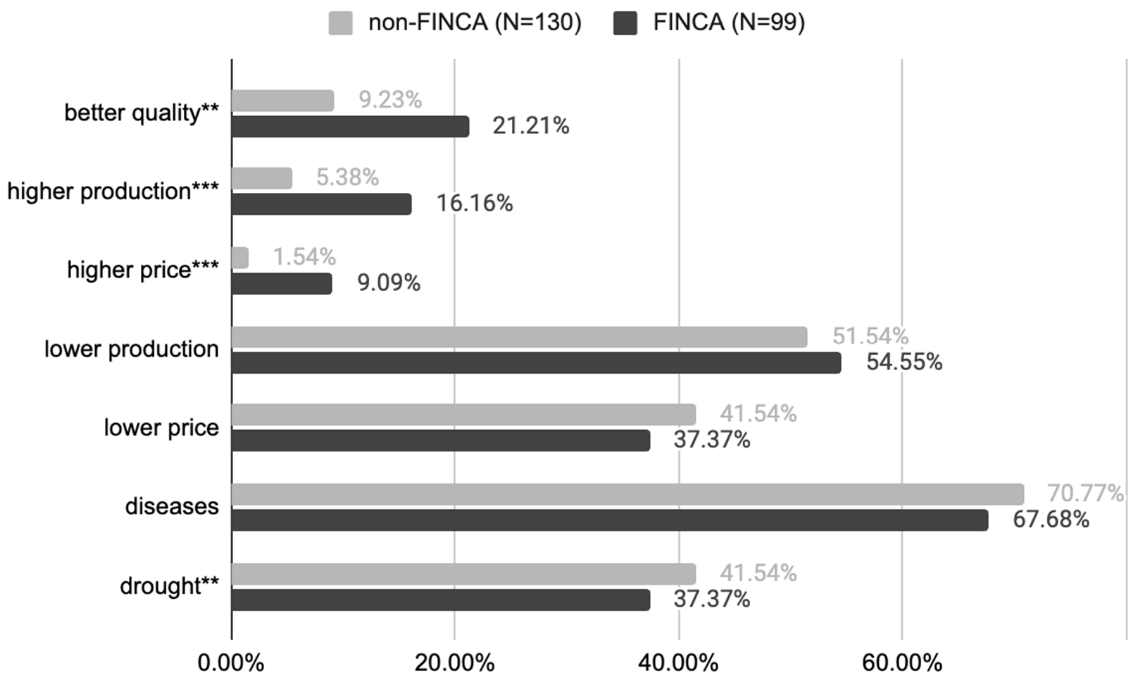

Figure 2. Changes over last five years in cacao production. ** $p < 0.05$, *** $p < 0.01$.

As mentioned previously, propensity score matching was used for FINCA program participating with results shown in Table 3 with controls for the region and the association. The results show that FINCA participants are more likely to have more additional lots of cacao, are more likely to live on the farm, and have higher levels of education in the household.

Table 3. Probit regression results (dependent variable = FINCA plot).

	Marginal Effect	Standard Errors	Significance
Association	−0.210	−0.06	**
Live in farm	0.524	−0.18	**
Hectares with cacao	−0.163	−0.05	**
Own car	0.237	−0.19	
Education in household	0.301	−0.11	**
Years producing cacao	0.012	−0.01	*
PPI score	0.026	−0.01	**
Number of lots in cacao	0.539	−0.13	***
Los Ríos province	1.033	−0.28	***
Food security	−0.149	−0.12	
Constant	−1.758	−0.52	**
N	275		
LR chi2(11)	73.39		
Psuedo R2	0.194		

Notes: *, **, *** Statistical significance at $p < 0.1$; $p < 0.05$; $p < 0.01$.

After matching based upon the propensity scores, the differences were estimated between the matched samples. There is not a significant difference in income from cacao per hectare or labor days per hectare (Table 4) after matching the variables mentioned in Table 3. After matching, there is a significant difference in the quintals of cacao produced per hectare as well as the number of labor days utilized on the plots (Table 4). Income per hectare remains similar, implying that after controlling for other factors that vary between the plots, plots that are part of FINCA and those that are not part of FINCA result in similar gross income levels. However, after controlling for labor days required for the FINCA program, it would be expected that these calculations would shift, at least in the short term. Over time, it will be important to capture and compare labor use as well as overall productivity as the plots that are part of the FINCA program mature. Table 4 shows the results of the paired t tests for selected variables. It should be noted that after matching, the sample size is substantially less than with the full sample, as shown with the degrees of freedom *(df)*, which can affect results and interpretation.

Table 4. Matched sample differences plot-level outcomes.

	Mean Difference FINCA vs. Non-FINCA	t-Stats	*df*	Significance
quintals of cacao per ha	−5.12	−3.018	122	**
quintals of cacao per producing tree	−0.001	−0.243	77	
income from cacao Nacional per ha	−138.29	−1.28	76	
income per ha (all sold products)	−99.298	−0.343	122	
price per quintal	−2.793	−1.989	76	
% of cacao harvested (not lost)	−6.457	−1.592	80	
days of labor per ha (including family labor)	13.188	−2.416	122	*
total estimated productivity (USD) for all crops per ha	181.234	−0.111	122	
total productivity (USD) per labor day used	−110.823	−0.958	122	

Notes: *, ** Statistical significance at $p < 0.1$; $p < 0.05$.

Using the matching procedure above, the average treatment effect (ATT) for the program on the income from cacao Nacional per hectare as well as total productivity (in equivalent dollar value) for all harvested crops was estimated. No significant difference was seen for total income from cacao Nacional, total productivity by hectare, or total productivity per labor day between the plots that were part of the program and those that are not part of the program (Table 5). According to the first hypothesis, one would expect that income from cacao Nacional would be lower in the short term.

Table 5. ATT (of FINCA) for outcome plot-level variables.

	Estimate	SE	z Stat	*p* Value	Conf. Low	Conf. High
ATT for income from cacao Nacional per hectare	−15.2	324	−0.047	0.963	−649	619
ATT for total productivity (USD) per hectare	99.3	3531	0.028	0.978	−6958	7019
ATT for total productivity (USD) per labor day	−114	251	−0.455	0.649	−606	378

Soil and Tree Samples

The soils were primarily clay or clay loams with a median of 31.6% sand, 46% silt and 20.4% clay. Despite the third hypothesis that one would expect to see measurable changes in soil health, there are significant differences only between Phosphorus (higher for FINCA plots at 10 cm) and Calcium (higher for non-FINCA plots at 10 cm) (Table 6). The soil pH is optimal across all samples and not significantly different between the two types of plots. Estimated soil organic carbon (SOC) measured in tons per hectare, and soil organic matter (SOM) (%), is higher at 30 cm when compared to 10 cm across all plots, but is not significantly different between the two groups. It should be noted that most non-FINCA producers (80%) have other trees or crops on their cacao plots, so any comparison of soil composition is not between agroforestry and monocropping but rather simple agroforestry and more diverse agroforestry systems, all of which are grown organically. Bulk density (apparent density) was similar across the samples at both 10 cm and 30 cm and is in line with recommended densities [47].

Table 6. Soil measurements [1].

	Non-FINCA (*N* = 58)		**FINCA Program (*N* = 53)**	
Variable	**10 cm**	**30 cm**	**10 cm**	**30 cm**
N (mg/kg)	26.72	22.23	24.06	22.11
P (mg/kg)	20.07	17.28	*27.76*	21.39
S (mg/kg)	16.73	16.49	16.63	15.24
K (meq/100 mL)	0.79	0.70	0.70	0.70
Ca (meq/100 mL)	*12.54*	11.06	10.56	11.24
Mg (meq/100 mL)	3.35	3.36	3.43	3.39
pH	6.53	6.41	6.41	6.51
C (%)	3.12	2.08	2.88	2.15
C (t/ha)	32.34	66.73	30.32	68.99
SOM (%)	5.38	3.58	4.97	3.71
Bulk density (g/cm^3)	1.07	1.11	1.08	1.12
Porosity	51.25	50.27	51.42	51.36

[1] Significant differences > 5% shown in italics.

Soil measurements were also performed on 18 plots using deep pits where a sample was taken between 0 and 30 cm and another sample was taken at a depth of more than 30 cm (up to 100 cm). The depth of the samples varied based upon the soil depth for each pit and therefore, the sample was split based upon samples that were taken at a depth greater than 32 cm and those that were taken at a depth less than that. While there are some differences in soil quality between the FINCA and non-FINCA plots at one meter depth, most of the differences including for bulk density, C (t/ha) and SOM (%) are not statistically significant (Table 7). The exception is Sulfur, which is higher in the greater depths of the FINCA plots than the non-FINCA.

Table 7. Soil measurements up to 1 m [1].

	Non-FINCA		**FINCA Program**	
	<32 cm (*N* = 10)	**>32 cm (*N* = 8)**	**<32 cm (*N* = 10)**	**>32 cm (*N* = 8)**
N (mg/kg)	26.892	18.796	23.515	14.389
P (mg/kg)	12.455	6.238	14.946	10.691
S (mg/kg)	16.486	7.019	16.101	*14.487*
K (meq/100 mL)	0.793	0.325	0.538	0.570
Ca (meq/100 mL)	12.482	9.007	12.616	8.333
pH	6.480	6.516	6.606	6.679
C (%)	2.668	0.503	1.620	0.633
C (t/ha)	48.822	35.988	55.054	38.552
SOM (%)	4.600	0.866	2.793	1.090
Bulk density (g/cm^3)	1.120	0.995	1.185	1.125
Porosity	52.540	58.478	48.950	55.118

[1] Significant differences at >5% shown in italics.

Measurement of on-farm tree diversity and growth was performed on 65 plots of 1000 m^2 (25 plots in Guayas and 40 in Los Ríos). The tree counts collected information on all the woody and herbaceous species in the cacao agroforestry systems. In the study, 58 tree species were observed: 34 species of fruit trees, 21 species of timber species, and 3 other species. In line with the fourth hypothesis, in FINCA plots, the number of trees per hectare are significantly higher, the shade level is higher, and the trees are generally younger (Table 8). Above-ground carbon storage was not estimated but the differences in the number of trees is significant. The FINCA plots have an average of 53% shade cover than the non-FINCA plots (with 29% on average). Interestingly, there are no significant differences observed in the level of diseased pods, despite the increased shade canopy, which corresponds to the data in the producer survey.

Table 8. Indicators of tree diversity and cacao tree health (averages).

	Non-FINCA (*N* = 33)		**FINCA Program (*N* = 32)**	
	Mean	**SD**	**Mean**	**SD**
cacao nacional trees per hectare	762.12	480.84	942.19	628.85
cacao trinitario trees per hectare	161.82	300.33	63.13	254.16
Number of fruit tree species/ha ***	2.82	1.89	5.84	2.48
Number of timber tree species/ha ***	0.85	1.12	2.53	1.85
Number of all tree species/ha ***	3.73	2.63	8.50	3.34
Number of shade trees/ha **	234.55	201.99	417.81	234.37
Shade cover (%) ***	29.00	17.43	52.75	18.22
Diseased nacional pods (%), N = 46	0.270	0.251	0.295	0.269

Notes: **, *** Statistical significance at $p < 0.05$; $p < 0.01$.

To better understand the opportunities and challenges of the FINCA program, 4 focus groups were conducted with a total of 30 producers in Los Ríos and 18 producers in Guayas. Separate focus groups were conducted for producers that were not part of the FINCA program, with one focus group of FINCA participants and one focus group of non-FINCA participants conducted in each of the two provinces. Interestingly, most of the producers in Los Ríos (67%) and in Guayas (56%) that were not part of the FINCA program did not know how to define an agroforestry system, and many reported that they had never heard the term. The main reasons that producers gave for participating in the FINCA program included receiving inputs such as training and trees that could enhance the soil and cacao production. Producers mentioned a need for more training on shade management and pruning. When asked about the impacts of climate change, responses were similar across all groups and included excessive rain and resulting fungal diseases, such as frosty pod rot and witch's broom.

4. Discussion

As mentioned previously, the majority of non-FINCA producers have other trees or crops on their cacao plots, so any comparison made in this analysis is not between cacao monocropping and agroforestry but between the most common cacao systems in these regions of Ecuador and more diverse agroforestry systems. The FINCA program has been implemented since 2016, but in 2019, the team decided to change the promoted cacao variety as well as some management practices to best respond to the needs of producers. The non-FINCA producers are also growing organically, and previous research has found that organic cacao production enhances soil quality when compared to non-organic production [48]. Even a meta-analysis on cacao agroforestry did not find significant differences in soil chemical properties between cacao agroforestry and monocultures but noted differences across studies that related to soil sampling locations and the distribution of biomass in the plots [3].

As previous studies on cacao agroforestry in Brazil have found, SOC is higher in the shallower layers of the soil [17]. Contrary to the third hypothesis, there are not significant differences between soil properties including SOM. It may be that chemical and physical properties and changes in SOC will take longer to materialize, especially at the deeper soil layers. A longer-term study on cacao agroforestry in Brazil, for example, found improvements in soil nutrients and pH when plots were measured 12 years after establishment [49]. In Cameroon, previous land uses were found to influence the ecosystem services provided by cacao agroforestry systems (including soil quality and nutrient cycling) for decades [50]. A study on cacao agroforestry in Indonesia also demonstrated that changes in soil properties are gradual, especially when compared to above-ground changes [51], and other studies have found primarily localized effects [52]. The sampled plots (both FINCA or non-FINCA) are all in organic production and this may play a role in the soil measurements seen across all plots. Soil properties would need to be tracked after more time passes from program implementation to understand any potential shifts in soil nutrients and carbon sequestration at these deeper soil levels.

The FINCA program is resulting in significantly more timber and fruit trees on the cacao plots (which is in line with the fourth hypothesis). The FINCA plots had an average of almost double the amount of shade trees when compared to non-FINCA plots, which provide an opportunity for above-ground carbon storage in addition to habitat. In terms of productivity, after matching, there is a significant difference in the quintals of cacao produced per hectare (in line with the first hypothesis). Given the number of developing trees on the FINCA plots, this is to be expected, and is reflected in the lack of a significant difference in the quintals of cacao per producing cacao tree. Interestingly, cacao production and income has not decreased in a significant way once accounting for the number of producing trees on the plots. After matching the two groups, total productivity is not significantly different between FINCA plots and non-FINCA plots. We would also assume that over time, total productivity increases for the FINCA plots as the companion crops and trees mature. The age of the farms that are not part of the program may also be older on average and there is also likely to have been less disturbance on the non-FINCA plots when compared to the disturbance necessary for renovation of the FINCA plots. Given these factors, involvement in the FINCA program is unlikely to show the full benefits at this stage, especially for slower growing trees such as timber species.

The findings indicate that the FINCA program is resulting in additional training and inputs for FINCA producers (in line with the second hypothesis). However, the amount of labor involved was significantly greater for plots that were part of the FINCA program. Although additional labor is utilized on the FINCA plots, after matching, there is not a significant difference in total crop productivity for each day of labor utilized. However, it is important that differences in management requirements and the resulting labor needs not be ignored, especially given the high levels of shade maintained on the plots and the potential need for additional pruning. Previous studies have found that pruning of shade trees is critical for cacao yield but that management costs can be high [53].

Participants in the focus groups noted a concern with the amount of pruning and management that was necessary to sustain the agroforestry systems. This is also reflected in the high levels of shade witnessed on the FINCA plots during the tree surveys. Recent studies on cacao agroforestry systems have noted a need to provide producers with information on the functions of beneficial insects and the role of shade in managing pests [54]. As the program expands, it will be important to assist producers to best manage the shade trees in a labor-efficient manner that does not sacrifice productivity. Evaluation of the needs and providing additional training for producers would assist in expanding dynamic agroforestry in these regions. Support with market linkages for other products may also provide incentives to produce crops in addition to cacao.

5. Conclusions

This study has evaluated a range of indicators for cacao producers that are part of the UNOCACE cooperative and compared the plots that are part of the dynamic agroforestry (FINCA) program and those that are not part of the program in two provinces of Ecuador. All parcels studied are under organic production. After matching FINCA and non-FINCA plots, there are no significant differences in incomes from cacao despite the plots that are part of the program having younger cacao trees on average, and a diverse mix of crops.

Given the number of developing trees on the FINCA plots, the expectation is that total productivity per hectare increases for the FINCA plots as those trees mature. In terms of soil characteristics, there are some differences between the plots, but most differences are not statistically significant. This is in line with other studies that have not found significant differences in soil characteristics as a result of agroforestry or suggested that soil chemical changes under various management practices are not rapid. Further studies would be needed over time to fully capture changes at the surface as well as changes to deeper soil health and structure.

The experience of the FINCA program has highlighted the importance of adaptive management strategies that can adapt to the local constraints. The ability of the FINCA program to adjust the cacao variety to respond to concerns about productivity was critical for expansion of the model. The findings of the research are in line with previous research finding that while tree diversity and above-ground biomass may shift more rapidly, changes in soil characteristics are likely to be gradual. The livelihood-related effects of the program will depend heavily on the prices received for the cacao and the ability to utilize or sell other products consistently. Additional training and support on pruning is likely necessary to assure that shade levels are optimal for production of all crops, including cacao.

A follow-up survey after the program has been implemented for a longer period would be able to provide more insights into the dynamics of production on the FINCA plots, ongoing constraints for shade management, and potential gains in terms of tree diversity, soil health, or climate resilience. Additional research to understand the most critical tree species and planting designs to support productivity and ecosystem health could guide future program recommendations. Future research could also evaluate the impacts for food security and the market constraints for the companion crops as well as the potential opportunities to support livelihoods through diversified production.

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