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Multivariate analysis of the adoption of cacao productive technologies: Evidence from a case study in Colombia

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ABSTRACT: Multivariate and ordered Probit models were used to study the determinants of the adoption and extent of adoption of agronomic practices among cacao farmers in Nariño, Colombia, with data from 353 farmers in the mountain region. Results suggest that farmers' adoption decisions are made on a joint basis, further validating the use of a multivariate approach. The presence of illegal crops creates strong disincentives that affect the possibility of more significant technological improvements. Adequate access to agricultural technical assistance strongly increases rates of adoption. Evidence suggests that efforts are necessary to better target resource-poor farmers.

Análisis multivariado de la adopción de tecnologías productivas de cacao: Evidencia de un estudio de caso en Colombia

RESUMEN: Se usaron modelos Probit multivariado y ordenado para estudiar los determinantes de adopción e intensidad de adopción de prácticas agronómicas entre cacaoteros de la región de cordillera de Nariño, Colombia, partiendo de datos para 353 productores. Los resultados indican que las decisiones de adopción tecnológica suelen ser simultáneas, validando la aproximación multivariada. La presencia de cultivos ilegales supone una posible barrera de incentivos para lograr mejores indicadores de adopción. Acceso efectivo a asistencia técnica agropecuaria aumenta considerablemente las tasas de adopción. La evidencia sugiere una urgente necesidad de mejorar el alcance de las tecnologías para productores de bajos recursos.

KEY WORDS / *PALABRAS CLAVE*: Agricultural technology adoption, illegal crops, technical assistance, Theobroma cacao L., Colombia / *Adopción tecnológica agrícola, cultivos ilegales, asistencia técnica, Theobroma cacao L., Colombia*.

JEL classification / *Clasificación JEL*: C35, O33, Q16.

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1. Introduction

Cacao has a long tradition in the consumption basket of Colombian households, particularly as a beverage. As of 2018, the country harvested 145,471 hectares (ha), produced 52,743 tons (t), and ranked as the tenth-largest in both metrics (FAO, 2020). However, production and commercialization are concentrated in specific regions (Rodríguez-Medina *et al.,* 2019) and among too few companies, respectively (Abbott *et al.,* 2018). In the early XX century, most of Colombia's cacao production was in the Southwestern lowlands, specifically in the provinces of Cauca, Nariño, and Valle del Cauca. Nowadays, production concentrates in the Northeast of the country, in the department of Santander (Rodríguez-Medina *et al.,* 2019). Data from the 2014 National Agricultural Census (DANE, 2016) report roughly 45,500 ha of plantations in Santander that produced over 21,800 t of cacao beans. Meanwhile, Nariño (the second-largest producer in Colombia) reported 19,000 ha and an output barely passing 7,000 t. These relative productive differences show why exploring opportunities for cacao productive improvement in Nariño would be of great value and could provide these farmers with better means to exploit their resources efficiently.

On the other hand, unlike neighboring Ecuador, whose cacao production reaches mostly international markets, cacao production in Colombia targets local buyers-either for beverages or processed candies (Abbott *et al.,* 2018). Therefore, exploring paths for improvement cacao farming systems is of high interest to reach high-value and international markets. Ramírez Sulvarán *et al.* (2014) show that environmental-friendly agriculture joined with improved post-harvest practices that guarantee bean quality, are appropriate means to achieve overall sustainability while also giving access to better revenues via specialty markets. The crop has again regained attention after the historic peace accord signed between the Government of Colombia and the former revolutionary group of FARC, since cacao is a potential mechanism to drive farmers out of illegal crops (Abbott *et al.,* 2018). Despite recent overall reductions of illicit crops, Nariño remains a hotspot for coca production (UNODC, 2020), which implies risks of violence and social vulnerability, so strategies for improving the productivity and marketability of opportunity crops as cacao becomes of the utmost relevance.

Available genetic materials of cacao in Colombia have been long recognized as highly productive (Aranzazu *et al.,* 2009) and recently gaining recognition as fine flavors (Osorio-Guarin *et al.,* 2017). This allows agricultural researchers to select (or develop) varieties that further strengthen farmers' odds of reaching international high-value markets. Nonetheless, these varieties are often developed along with other technologies to achieve the best possible productivity and quality results. Yet, there is no strict guarantee that farmers effectively adopt all these technological packages. Furthermore, developing agricultural technologies (either improved varieties or associated practices) is only a first step towards improving any crop's value chain. Technologies' incidence may be limited if their uptake faces either limitations in availability (incomplete markets) or if they fail to provide the promised gains in productivity or quality during their early dissemination (Laajaj *et al.,* 2020).

Literature on agricultural technology adoption is vast and varied but reflects the continuous need of policymakers and ag-researchers in knowing (a) how and why do farmers implement a given set of technologies and (b) what impact results from their use (Doss, 2006). While some technologies may result in a breakthrough for developing countries and their local economies (Conley & Udry, 2010), it could also be the case that the expected returns or impacts do not occur as a result of unexpected constraints faced by farmers (Laajaj *et al.,* 2020). In this context, studies providing a thorough analysis of the rates of adoption of agricultural practices that favor cacao production in Colombia (particularly in Nariño), and the determinants behind them, are of high interest both for breeders and policymakers.

How to properly explore the determinants of technology adoption? A recently growing body of literature shows that complementariness between agricultural technologies is significant and that multivariate modeling approaches help account for it. The groundbreaking contribution to this topic is Teklewold *et al*. (2013). The authors explored the determinants of the adoption of complementary and substitutable farming practices and the total number of technologies adopted by maize farmers in Ethiopia. The multivariate Probit approach has also been used to understand the adoption of climate-smart agricultural practices (Kassie *et al.,* 2013; Mwungu *et al.,* 2018), different crop varieties (Donkoh *et al.,* 2019; Samal *et al.,* 2011), standard agricultural practices among different crops (Rahman & Daniel-Chima, 2015), and even of communication technologies to access agricultural information (Mittal & Mehar, 2016).

Using data from a sample of farmers in the mountain region of Nariño, our paper contributes to this literature by modeling the determinants of six productive technology adoption (grafting, irrigation, sanitary control, fertilization, soil testing), testing whether illegal crops and technical assistance present a statistically significant effect on adoption. Moreover, we also model whether there are underlying correlations in unobservables for observed adoption rates and whether the extent of adoption responds accordingly to households' non-technical attributes. To do so, we use both a multivariate probit model and an ordered probit approach, similarly to studies as Teklewold *et al*. (2013) and Kassie *et al*. (2014). From our results, we discuss the needs to target for strengthening cacao farmers in the mountain region of Nariño, Colombia, and provide insights for future policies and research.

2. Background

2.1. Context of cacao in Colombia

Although cacao production and consumption in Latin America dates back into the pre-Columbian era, the largest expansion for commercial purposes took place between the late XIX century and early XX century (Rodríguez-Medina *et al.,* 2019), during its industrialization and rise of its international commercialization. A natural country to compare Colombia is Ecuador, which shares strong similarities in environment, landscape, and culture. The period in which Colombia's cacao boom took place was the second in the region. Ecuador, the neighboring southern country, faced a first major expansion between 1770-1842 (Abad *et al.,* 2020), giving them a comparative advantage entering the late XIX century boom– they were the world's largest producers until the early 1920s.

The current differences between the two countries have other historical causes too. During the first half of the XX century, most of Colombia's cacao production occurred in Cauca and Valle del Cauca provinces. The incidence of machete disease (*Ceratocystis* sp. - *Xyleborus* sp. complex) displaced the crop's production to other areas of similar suitability (Rodríguez-Medina *et al.,* 2019) like the departments of Santander and Nariño. Conversely, cacao remained relatively stable in Ecuador and gradually attached to the communities' culture, even though some additional expansion did occur. Nowadays, most of Colombia's cacao production targets local demands from large companies like Luker and Compañía Nacional de Chocolates (Abbott *et al.,* 2018), while in the case of Ecuador, there is a significant segment of the sector that targets high-value markets in Europe (Loor Solorzano *et al.,* 2012). Nevertheless, Colombia is now gaining recognition for having a broad base of flavor cacao varieties (Osorio-Guarín *et al.,* 2017), thus opening new markets and opportunities.

The crop gained further traction since 2014 when the Colombian Government decided to promote cacao production to drive agricultural households out of illegal crops (Abbott *et al.,* 2018). This strategy also has further support from European countries, as Colombia can access these markets due to the active free-trade agreement signed with the EU (Cely Torres, 2017). However, access is conditional upon abiding by specific standards productive and sanitary standards, including *Good Agricultural Practices* (GPA). In Colombia, this certification for cacao farmers requires, but is not limited to, (a) use of registered materials[1]; (b) renewal of aging trees (via grafting); (c) irrigation; (d) monitoring of trees and pods to avoid diseases (phytosanitary control); (e) fertilization; (f) practice of soil testing to make decisions on input use (Fedecacao, 2018). Other procedures as bookkeeping and those related to post-harvest and handling are also required. Still, most government and research centers' efforts focus on the first production stages by incentivizing technology adoption (CIAT, 2018); otherwise, there is no feasible warranty for bean quality. Our research will focus on the former six practices.

Previous research suggests a need to strengthen this industry via improved practices in each segment of its value chain (Escobar *et al.,* 2020). While some experts argue that national production should focus more broadly on supplying unsatisfied local demand for cacao (Abbott *et al.,* 2018), others emphasize that high-value markets should remain a target for the mid-and long-run (Cely Torres, 2017; Escobar *et al.,* 2020). Either way, there is a consensus on an urgent need to improve farmers' technical capacities. Nevertheless, data that focus on productive technology rough adoption rates do not provide a comprehensive evaluation of farmers' decision-making. Such gap motivated this research.

[1] Varieties acquired from nurseries or clonal gardens that are certified by the Colombian Agricultural Institute (ICA, for its acronym in Spanish). These materials are selected and/or improved.

Barriers to technology adoption among farmers can be either exogenous (e.g., institutional) or due to their behavior and initial conditions. For example, illegal crops have proven to restrain productivity at a national level (Santa Maria & Gracia, 2007). Nonetheless, such an effect scales up partially from a household level in the agricultural sector. There are strong monetary incentives to cultivate illegal crops (Thoumi, 2005), but their production results in severe impacts on soils and the environment (UNODC, 2006), not to mention the subsequent adverse social effects. Hence, despite a short-term favorable condition (revenue), illegal crops disincentivize legal crops and investments to their improvement in the long-run, indirectly affect their productive possibilities via degraded soil capabilities, and endanger environmental sustainability.

Another significant limitation to improving cacao systems and other crops is a lack of comprehensive technical assistance systems. Evidence from other producing countries proves that technical assistance has a substantial impact on cacao farmer's efficiency (Binam *et al.,* 2008) and in the adoption of improved practices (Ehiakpor *et al.,* 2016). According to Abbott *et al.* (2018), the current assistance programs are usually short-term initiatives with no accompanying strategies to measure their impact, with no stable financing from the public sector. Fragmented systems fail to create long-lasting relations among farmers, so attempts to deliver new technologies are likely to be ineffective. Knowledge of local systems' needs, their means of proper communication, and specific demands of adaptation is a key to successful technology transfer programs in developing countries (Hartwich *et al.,* 2007). However, this does not necessarily imply that the existent are strictly ineffective. Rather than assuming whether a specific factor may have a particular effect on the adoption of a set of agricultural practices, we define a theoretical and empirical setting to later test if they hold statistically significant.

2.2. A model of technology adoption

We start by proposing a household model with risk-neutral farmers who are assumed to allocate their land for a specific technology (or practice) with the target of maximizing profits. We take that each of the *i=1, ..., N* farmers decide whether to adopt a technology ($t = 0.1$), and each of them owns L_i units of land. The maximization problem for the *i*-th farmer is:

$$\max_{w^t,x^t} \sum_{t=0,1} w_i^t L_i [p_i q_i^t(x_i^t) - r_i^t x_i^t] \qquad [1]$$
$$\text{s.t.} \sum_t w_i^t = 1.$$

In the previous specification w_i^t is the share of land dedicated either to a productive system with (t = 1) or without (t = 0) using the technology, q_i^t describes the production function, p_i is the output's price, and w_i^t and r_i^t are the vectors of inputs (e.g., labor) and inputs' prices, respectively. Such a setting implies that a farmer will increasingly adopt the technology if it proves to be more profitable than restraining themselves from using it. More specifically, the intensity of adoption of the technology would follow:

$$w_i^* = f(q_i^*, p_i, r_i^t), \quad [2]$$

so the decision relies solely on market and productive-specific factors; i.e., production decisions are independent of households' consumption choices.

Nevertheless, although such an approach is appealing, in the presence of land and labor market imperfections (common in developing and agricultural settings), results differ from those of competitive equilibria since the separability condition no longer holds (Bardhan & Udry, 1999; Sadoulet & De Janvry, 1995; Singh et al., 1986). Under non-separability, production and consumption decisions are interconnected, thus households optimize their overall utility. In this setting, factors beyond market prices (e.g., education, gender, household composition) may affect production decisions and technology adoption choices. Moreover, if the adoption decision is binary (either you use it or you do not), then we could assume that a latent variable A_i^*, that follows:

$$A_i^* = X_i'\Pi + \varepsilon_i, \quad [3]$$

explains their adoption status; observed adoption ($A_i = 1$) implies that $A_i^* > 0$. Otherwise, we have $A_i > 0$. In this final specification, X_i is a vector of determinants that include both technical attributes of the farm and observed characteristics of the farmers and their household members. We further expand on the model and its empirical implications in the following section.

3. Materials and methods

3.1. Data

Most previous studies in Colombia rely on secondary information and primary data from traditional productive areas, following non-probabilistic approaches or group interviews. None of these studies ensure either data representativeness or depth of information at the farm level. Our research aims to fill that gap partly by using a detailed dataset for a case study. We use a dataset provided by the Spanish foundation *Ayuda en Acción* from a development program in Colombia to strengthen the cacao value chain in Nariño (a province in the southwest). The original purpose of the survey was to serve as an instrument to characterize cacao production and identify types of farming that adequately describe the farming households of the sector in the region, as an input to a project for delivering low-cadmium cacao productive recommendations. While studying the adoption patterns of critical practices, we realized that there were asymmetries in reported adoption and input use related to socio-economic attributes. That result further motivated our analysis, leading us towards a sound theoretical background for modeling joint adoption of inputs and practices.

Collected information comes from the program beneficiaries, who are by large (+ 96 %) the decision-makers in the household. According to the latest data from the Colombian Agricultural Census (DANE, 2016), the cacao farmers' population in these five municipalities was 576 households. To our knowledge, farmers' selection was essentially random. Consequently, with a size that covers just over 61 % of the whole population, we are confident to interpret the results as valid for this specific region. However, we do not directly extrapolate any of our results and argue instead for the methods used here to be implemented in much-needed future research efforts. The data consists of household members' socio-economic information and agricultural (productive) and financial practices for 353 households in Policarpa, Cumbitara, El Rosario, Leiva, and Los Andes, municipalities located in the Andes mountains. Median altitude in these municipalities ranges between 1,400 and 1,900 m.a.s.l., yet these farmers are in altitudes ranging around 800 m.a.s.l. (± 250 m.) thus within the average elevation range for cacao suitability in Colombia (León-Moreno *et al.,* 2019).

3.2. Empirical approach

Following the rationale presented on our technology adoption model, we assume the non-separability of production and consumption decisions; thus, households maximize their overall utility rather than profit. Here we specify the model for a case of several practices under analysis. Without loss of generality, we assume a finite set of technologies $j = 1, ..., J$, and a finite number of farmers $i = 1, ..., n$, where n is the final sample size. For a given technology j, if a household i decides to adopt such technology, then perceives a utility of $U_{i,j=1}$ and a utility of $U_{i,j=0}$ otherwise. Hence, following a random utility model, the house eventually adopts the technology if

$$U_{i,j=1} - U_{i,j=0} > 0 \quad [4]$$

which we further set with an observable vector of k attributes x_i as

$$U_{i,j=1} - U_{i,j=0} = x_i'\beta_j + \varepsilon_{ij} = \beta_{1j} + \sum_{k=2}^{K} \beta_{kj} x_{ik} + \varepsilon_{ij} > 0. \quad [5]$$

Thus, the decision to adopt a technology is not exogenous and may well respond to observable and unobservable characteristics of the farmers and the productive system. In this setting, β coefficients are unknown parameters to estimate and εij are random shocks on households' perceived utilities across technologies. Let Adoptioni j be an index variable with a value of 1 if household i adopts technology j, and zero otherwise. Assuming a symmetric probability density function f for ε_{ij}, we could model the probability of adoption of the j-th technology as

$$\Pr(Adoption_{ij} | x_{ik}) = \Pr(x_i'\beta_j + \varepsilon_{ij} > 0) = \Pr(\varepsilon_{ij} > -x_i'\beta_j) = F_j(x_i'\beta_j), \quad [6]$$

where F_j is the correspondent marginal cumulative distribution function (CDF) of f.

We allow for unobserved correlation between shocks rather than assuming they are identically and independently distributed across technologies. In a general setting of J different choices (technologies), if the ε shocks follow a joint standardized normal distribution, this leads to the j-dimensional multivariate Probit model (Cameron & Trivedi, 2005; Greene, 2012). In this model, we assume that $(\varepsilon_{1i}, \varepsilon_{2i}, \dots, \varepsilon_{Ji}) \sim N_J(\mathbf{0}, \mathbf{\Omega})$, $E[\varepsilon_{ji}|\boldsymbol{x}_i] = 0$, $Var[\varepsilon_{ji}|\boldsymbol{x}_i] = 1$, and $Cov[\varepsilon_{ji}\varepsilon_{hi}|\boldsymbol{x}_i] = \rho_{jh}$ for $j \neq h$ and $j = 1, \dots, J$.

The flexibility of this model allows to test an essential question beyond the determinants behind the adoption of specific technologies, which is whether unobserved correlations are making it more likely that agricultural technology adoption happens jointly (as a "package" or "parts of a package") instead of separately and independently. To further understand the process of technology adoption, we model the total number of practices adopted by the farmers as in Teklewold *et al*. (2013) and Wollni *et al*. (2010), defining an ordered Probit model. In this model, we assume that the farm household decide to adopt a given number of practices based on the maximization of a utility function

$$U_i = V_i(x_i'\Gamma) + \epsilon_i, \quad [7]$$

so households use an additional technology if the utility from adoption is greater than the utility of not doing so. Although we do not directly observe the utility, we assume that the number of adopted practices P_i follows

$$\begin{aligned} P_i &= 0 && \text{if } U_i \leq \alpha_1, \\ P_i &= \ell && \text{if } \alpha_\ell < U_i \leq \alpha_{\ell+1}, \text{ for } \ell \in \{2, 3, 4, 5\} \\ P_i &= 6 && \text{if } \alpha_6 < U_i, \end{aligned} \quad [8]$$

where $\alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \alpha_5$ are unknown parameters, to be estimated along with Γ. Finally, assuming ϵ follows a normal distribution, the probabilities of adopting each specific number of technologies are defined as

$$\begin{aligned} &\Pr(P_i = 0|x_i) = \Phi(\alpha_1 - x_i'\Gamma), \\ &\Pr(P_i = \ell|x_i) = \Phi(\alpha_{\ell+1} - x_i'\Gamma) - \Phi(\alpha_\ell - x_i'\Gamma), \text{ for } \ell \in \{2, 3, 4, 5\} \\ &\Pr(P_i = 6|x_i) = 1 - \Phi(\alpha_6 - x_i'\Gamma), \end{aligned} \quad [9]$$

where Φ is the standard normal cumulative distribution for ϵ. Coefficients in Γ report the overall direction of the effect that a given regressor (determinant) x_k has in the total number of adopted technologies, yet the marginal effects may be of either the same or a different sign.

3.3. Dependent variables

This research focuses on six cacao-related technologies that describe a good management of the crop and a higher likelihood of both higher productivity and odds to connect with high-value markets. Namely, our binary dependent variables are (1) exclusive use of improved/selected varieties of cacao, (2) practice of grafting, (3) irrigation, (4) phytosanitary control, (5) fertilization, and (6) practice of soil testing to make decisions on input use. As we have already stated, combining these six practices is part of the basic requirements to receive a certification in GPA. Cacao farmers may still prefer to incur in partial adoption if they consider that the payoff of using a part of all the practices is still profitable.

The use of certified materials (either improved or hybrid) makes it highly likely that the output keeps a substantial homogeneity, highly relevant for accessing industrial or high-value markets. However, it could also be the case that farmers prefer to keep using their local materials. These may be more appropriately suited to their villages' specific conditions and more appealing to local demands (Contreras-Díaz *et al.,* 2017). Grafting is the standard practice for the renewal of elder cacao trees whose productivity started decreasing, but properly doing such procedure usually requires direct learning from technical assistants since a graft failure may compromise the tree itself (Sodré & Gomes, 2019). On the other hand, the adoption of irrigation implies that the water requirements are adequately covered and that the crop is highly likely to avoid ponding risks. Rainfed systems in the mountain region are not as productive and imply additional hydric stress for the trees.

Despite its high value, cacao remains a delicate permanent crop–recall that a disease nearly depleted Southwestern Colombia's production (Rodríguez-Medina *et al.,* 2019). Furthermore, there are further stresses in the country (e.g., witches' broom frosty pod rot, as described by Jaimes Suárez & Aranzazu Hernández, 2010) that demand an established system of phytosanitary control. Farms that do not report this practice's adoption are risking the overall sales' suitability since these diseases make it particularly difficult the production (even in bulk denominations). Finally, fertilization helps to achieve the crop's full productive capacity; farms located on steep hillsides or mountainsides suffer from soil erosion (by rains and gravity); thus, fertilization helps supply trees' nutritional needs. Yet, there are adequate fertilizer intensities that are not directly observable to the farmers and are only revealed solely through physical-chemical soil analysis.

3.4. Explanatory variables

The covariates set includes the use of hired labor force–beyond family work, which virtually every surveyed farm use–, the total area of the farm planted in cacao[2], age of the plot, and the plantation density (in log-scale). Hired labor reflects the agricultural household's capacity to adopt labor-intensive practices while also indicating

[2] Cacao represents 97 % of the land coverage in this sample so this measure highly correlates with overall farm size. Therefore, the latter is not included to avoid high collinearity.

an additional investment ability to increase production. Yet, since some practices may be more labor-intensive, we make no point-interpretations of the effect because of the potential endogeneity. Next, by including both the total area and the plantation density, we control for both farmers' latent wealth endowments (they are owners of the land in over 96 % of the cases) and the initial degree of specialization. Including the plot's age helps us isolate confounding effects from comparing crops in different productive stages indiscriminately.

We include the years of experience of the beneficiary producing cacao, their sex and ethnic origin, and if there is a spouse in the household. These variables capture knowledge and specific attributes that may affect social, cultural, or productive behavior. Further experience with cacao makes it more likely for farmers to be more exposed to training and to have more knowledge of dealing with unexpected shocks. However, this effect may attenuate by being confounded with farmers' age; elder farmers are often reluctant, despite their valuable knowledge capital, may paradoxically restrain themselves from adopting improved technologies by a precautionary principle. Household heads' sex and ethnic origins work as a sort of fixed effects. While we cannot credibly interpret an *impact* from these variables, it can be argued that if differences in adoption in these attributes are significant (and large), then they are partially a result of social biases.

Finally, we include two of the most important variables: access to agricultural technical assistance (ATA) and the presence of illegal crops (specifically coca) in the plot. First, we test whether (a) traditional transfer systems as ATA prove to be successful in explaining current technology adoption and if (b) illegal crops strongly discourage the improvement of other crops. The first comes from the arising doubts on the effectiveness of ATA due to problems in its continuity and quality (Fedesarrollo, 2014), and the second comes from the disinterest that illegal crops create for improving any accompanying legal crop due to the former's higher profitability (Thoumi, 2005).

3.5. Descriptive statistics

Farms under analysis have an average size of nearly 2 ha in cacao (Table 1), while the average density of trees is 775 per ha[3], which is low since the recommended density is about 1,282 or 1,111 trees per ha if plants follow a 3x3 meters triangular or rectangular system, respectively (Barón Urquijo, 2016). Cacao plots have a mean age of 8 years, so the average farmer within our sample is one whose crop has reached full productivity levels. Multi-cropping is the most common production system, while barely 16.4 % of farmers produce cacao exclusively; this is a favorable metric regarding sustainability since farmers have additional sources for income and consumption. Yet, the financial dependence remains high, so the risk of exogenous shocks in cacao markets impact these farmers through the value chain remains high. Moreover, these farms are mainly family agricultural systems, with only 29.5 % of them using hired farm labor. Most of them are in the municipality of Policarpa (38.8 %,

[3] This is the overall average of density, but the geometric mean (which is the exponential of mean log-density) shows barely over.

base category-fixed effect not included for collinearity). The rest of the farms are next distributed across Cumbitara and Leiva in similar proportions (18.5 %), followed by Los Andes (14.7 %) and El Rosario (9.6 %).

TABLE 1

Descriptive statistics of the variables used in the model

Variable	Mean / Percentage	Std. Dev.
Uses only improved varieties (Yes = 1)	60.6 %	0.49
Grafting (Yes = 1)	32.6 %	0.47
Irrigation (Yes = 1)	50.4 %	0.50
Phytosanitary Control (Yes = 1)	84.9 %	0.36
Fertilization (Yes = 1)	52.7 %	0.50
Soil Testing (Yes = 1)	21.8 %	0.41
Area planted in cacao (ha)	1.98	1.62
Experience with cacao (years)	8.95	5.33
Age of the plot (years)	8.33	3.53
Density of plants (trees/ha) (log)	6.38	0.89
Farmer only produces cacao (Yes = 1)	16.43 %	0.37
Receives ag-technical assistance (Yes = 1)	59.77 %	0.49
Makes use of hired labor force (Yes = 1)	29.46 %	0.46
Is there coca on the farm? (Yes = 1)	55.35 %	0.50
Age of the beneficiary	51.79	13.20
Sex of the beneficiary (Male = 1)	62.89 %	0.48
Beneficiary is of an ethnic origin (Yes = 1)	5.10 %	0.22
Is there a spouse in the household? (Yes = 1)	58.92 %	0.49
Fixed effect: *Cumbitara*	18.41 %	-
Fixed effect: *El Rosario*	9.63 %	-
Fixed effect: *Leiva*	18.41 %	-
Fixed effect: *Los Andes*	14.73 %	-
Fixed effect (base category): *Policarpa*	38.82 %	-

Source: Own elaboration.

Surveyed beneficiaries are about 52 years old on average. Most of them are males (62.9 %), and barely over 5 % of them come from an ethnic origin–which in this sample included indigenous or black backgrounds. These metrics highlight a set of recurrent problems among agricultural households, namely (a) an aging population, (b) concentration of male decision-makers, and (c) low improvement and participation of minorities. Although elderly farmers are more experienced, having them as the households' decision takers show how little intergenerational replacement exists, with offspring usually preferring to move to cities. Furthermore, technology adoption may be ineffective in the medium and long-run since elderly farmers tend to be less likely to change their agricultural practices. Another included determinant is whether there is a spouse in the family. With just over 58 % of cases, many decision-takers may have limitations in focusing solely on their production. This last condition further strengthens our case for assuming non-separability of production and consumption choices across farm households.

Technology adoption levels, as reported, are dissimilar and reveal different possible concerns for the proper exploitation of the crop. Exclusive use of improved (or selected) materials happens in over 60 % of farms. Still, grafting was reported only in 32.6 % of cases, so rehabilitation of trees does not occur as often as expected. Irrigation happens in just over 50 % of plots, so production does not solely rely on rainfall. Fertilization occurs in nearly 53 % of the plots, so most of the cacao fields have an improved productive capability; however, only a fifth of the farmers do soil testing. Therefore, even though a considerable amount of farmers have adopted a practice (fertilizer), they may not be using it most efficiently. Finally, phytosanitary control (plant health) practices are the most common, reaching up to 85 % of cases, reflecting the broader exposure to cacao diseases in Colombia (Jaimes Suárez & Aranzazu Hernández, 2010) in the overall adoption.

Finally, we focus on effective access to ATA and coca cultivation on the farm. Although most farmers (59.8 %) have received ATA, a better interpretation is that over 40 % of farmers lack support for an appropriate and progressive improvement of their cacao crops. Such coverage does not imply a direct guarantee that the assistance is of high-quality, though, which is why we only test whether it roughly has an average effect over technology adoption. On the other hand, the presence of coca is considerable, reaching 55.3 % of farms. Therefore, we decided to test whether its presence affects adoption, as illegal crops have a considerably higher expected return for farmers, hence relegating the priority of improving legal crops.

4. Results

We summarize the adoption determinants across the six technologies, following a multivariate probability model, in table 2. Farmers with larger plots and increased density levels are statistically more likely to use improved varieties and practice grafting to renovate their crops. Since cacao's share represents over 97 % of the sample's farms, this could also be interpreted as that better organized, and highest resource farmers are more likely to adopt these technologies. Farmers that exclusively produce cacao are less likely to adopt phytosanitary control practices, but this attribute does not seem to affect the implementation of other technologies on their plots. Also, farms that use hired labor force are more likely to adopt phytosanitary control and fertilization practices. This is an expected finding, as these are labor-intensive activities; thus, as mentioned earlier, we are cautious with this result for possible simultaneity bias. Because of this, we restrain ourselves from interpreting any change as an *impact*. Any mention of an effect comes from the sense of a marginal effect in probability, not from a causal effect. Regarding farmers' attributes, the beneficiary's age (or first decision taker in the farm) seems to be statistically related to higher rates of practicing grafting. However, the expected size of the effect is low.

TABLE 2

Results of multivariate Probit regression model of technology adoption

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	IV	Grafting	Irrigation	Phyt Cont	Fertilizer	Soil Tests
Area planted in cacao	0.156**	0.135*	0.130	0.018	0.028	0.065
	(0.069)	(0.075)	(0.082)	(0.083)	(0.065)	(0.084)
Experience with cacao	0.029	0.001	0.014	-0.011	0.003	0.016
	(0.026)	(0.022)	(0.017)	(0.018)	(0.020)	(0.023)
Age of the plot	-0.029	-0.023	-0.040	0.025	-0.044	-0.008
	(0.033)	(0.030)	(0.034)	(0.030)	(0.029)	(0.030)
Density of plants (log)	0.263*	0.388***	0.199	0.104	0.163	0.024
	(0.136)	(0.143)	(0.148)	(0.140)	(0.127)	(0.170)
Farmer only produces cacao	-0.008	0.072	-0.139	-0.462*	-0.144	0.221
	(0.242)	(0.221)	(0.272)	(0.268)	(0.219)	(0.250)
Receives ag-technical assistance	0.805***	0.556***	0.604***	0.315	0.480***	0.886***
	(0.188)	(0.198)	(0.193)	(0.246)	(0.181)	(0.242)
Makes use of hired labor force	-0.219	0.142	-0.322	0.948***	0.513***	0.026
	(0.215)	(0.210)	(0.241)	(0.319)	(0.197)	(0.254)
Is there coca on the farm?	0.233	-0.427**	-0.313	-0.506**	-0.102	0.081
	(0.195)	(0.186)	(0.222)	(0.209)	(0.176)	(0.213)
Age of the beneficiary	0.003	0.026***	0.007	-0.005	-0.002	0.006
	(0.007)	(0.007)	(0.008)	(0.008)	(0.006)	(0.007)
Sex of the beneficiary	0.135	-0.088	0.100	0.224	0.083	-0.091
	(0.180)	(0.175)	(0.207)	(0.191)	(0.161)	(0.201)
Beneficiary is of an ethnic origin	-0.413	0.027	-0.252	0.497	0.269	0.648*
	(0.266)	(0.345)	(0.424)	(0.377)	(0.344)	(0.355)
Is there a spouse in the h/hold?	-0.085	-0.070	-0.195	-0.137	-0.458***	0.042
	(0.172)	(0.177)	(0.198)	(0.193)	(0.170)	(0.231)
Fixed effect: *Cumbitara*	-0.802***	-0.223	-0.723***	0.355	0.101	0.525*
	(0.244)	(0.240)	(0.260)	(0.287)	(0.219)	(0.286)
Fixed effect: *El Rosario*	0.547	-1.725***	-5.455***	0.761	-1.183***	-0.391
	(0.408)	(0.468)	(0.321)	(0.558)	(0.361)	(0.428)
Fixed effect: *Leiva*	-1.777***	-1.640***	2.451***	-1.342***	-0.282	-0.533
	(0.346)	(0.369)	(0.535)	(0.410)	(0.301)	(0.459)
Fixed Effect: *Los Andes*	0.823**	-0.389	2.026***	0.401	0.933***	2.912***
	(0.408)	(0.316)	(0.473)	(0.465)	(0.349)	(0.450)
Constant	-1.912*	-4.091***	-1.898*	0.524	-0.704	-2.722**
	(1.006)	(1.048)	(1.081)	(1.008)	(0.917)	(1.269)

Wald test of overall coefficient significance
χ^2 (96) = 2343.5, Prob > χ^2 = 0.000
Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$
Source: Own elaboration.

We found an unexpected sign regarding a spouse's presence in the household and a lower level of adoption of fertilization practice: We waited to be a positive effect resulting from feasible specialization after average household chores diminished for the decision-maker. A possible explanation could be the increased expense in house consumption that limits technology adoption, yet we cannot specify this effect with total certainty. There is no statistically significant relationship between adoption of any of the six technologies and reported experience managing the crop, nor with the sex of the beneficiary.

The presence of coca in a farm's productive setting negatively affects the adoption of grafting and phytosanitary control practices, both of which are important for the crop's improvement and sustainability. We are aware that this illegal crop's presence is not strictly exogenous; thus, the correlations may be biased towards zero. Yet, this finding is crucial as it supports the hypothesis that (at least to some degree) agricultural practices may not reach the desired levels when competing with illegal crops. Finally, one of the most important results is the consistent and strong significant correlation between receiving ATA and five out the six technologies (not with phytosanitary control). This finding supports the strengthening of regional technology transfer systems as a valid mechanism to improve technology adoption among cacao farmers in Nariño.

Studying the correlation coefficients among technologies unobservables (complementariness), we find that these are jointly significant hence validating the need to use a multivariate approach (Table 3). Without considering such joint distribution with other technologies, adoption studies may risk falling into bias and inconsistent variance. Table 3 resembles the off-diagonal section of the (symmetric) recursive covariance matrix in the multivariate Probit model, in which we find that exclusive use of improved varieties appears to go hand in hand with irrigation, fertilization, and soil testing.

However, one of the most important results is the strong and significant pairwise correlation between soil testing and fertilization. Despite being a small share, farmers who make a thorough analysis of their soil capacities decide how much fertilizer following scientific evidence at the plot level. Besides, those using irrigation appear to be systematically related to those making a sanitary control of their cacao plants. This is also important as irrigated cacao systems with robust health monitoring practices reduce the risk of plant diseases of high-impact as witches' broom (*Moniliophthora perniciosa*) and frosty pod rot (*Moniliophthora roreri*) (Jaimes Suárez & Aranzazu Hernández, 2010).

The ordered Probit model (Table 4) further corroborates the indications from the multivariate Probit model. Farmers with more extensive cacao areas, higher crop density, using hired labor force, and effectively receiving ATA are more likely to adopt technologies to a greater extent. Conversely, those who report the presence of illegal crops adopt technologies at a lower rate. More specifically, farms with larger sizes are slightly over 4 % more likely to adopt four or more practices. In comparison, those with higher densities are up to 9 % more likely to find themselves in that upper tier. Similarly, cases in which the labor force includes hired labor have a 5 percent more probability of adopting over four technologies.

TABLE 3

Multivariate Probit correlation estimates across technologies

P_{21}	P_{31}	P_{41}	P_{51}	P_{61}
0.115	0.355***	-0.111	0.316***	0.811***
(0.125)	(0.127)	(0.117)	(0.111)	(0.290)
	P_{32}	P_{42}	P_{52}	P_{62}
	-0.152	0.514***	0.431***	0.004
	(0.125)	(0.140)	(0.108)	(0.143)
		P_{43}	P_{53}	P_{63}
		0.093	0.173	0.313**
		(0.123)	(0.120)	(0.142)
			P_{54}	P_{64}
			0.590***	0.051
			(0.123)	(0.140)
				P_{65}
				0.421***
				(0.148)

LR test of overall significance of correlation coefficients
$X^2(15) = 80.33$, Prob > $X^2 = 0.000$
Robust standard errors in parentheses. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$
Source: Own elaboration.

The presence of coca presents a downward effect, but its absence does not necessarily mean higher-than-average levels of adoption. Point estimates suggest that farmers with coca crops are up to eight percent more likely to use only two-or-less technologies, but no significant adverse effects in the upper tiers of adoption. Evidence also suggests that the extent of technology adoption is spatially distributed. Farms in the municipalities of El Rosario, Leiva, and Cumbitara are 38, 30, and 6 percent more likely, respectively, to use only two or fewer technologies compared to the largest share of farmers in Policarpa. On the other hand, the contrary happens with farms in Los Andes, where there is up to 55 percent more probability of adopting four or more technologies than those in Policarpa. These average differences and their relative scale seem to correlate with the sizes of the local populations (Rosario < Leiva < Cumbitara < Policarpa < Los Andes) and with the distance (conversely ordered) from these to the departments' capital, San Juan de Pasto—location of the main food markets.

TABLE 4

Ordered Probit coefficients and marginal effects for the total number of agricultural practices adopted by cacao farms

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Variables	Coeff.	Pr (P = 0)	Pr (P = 1)	Pr (P = 2)	Pr (P = 3)	Pr (P = 4)	Pr (P = 5)	Pr (P = 6)
Area planted in cacao	0.12**	-0.00*	-0.02**	-0.02**	0.00	0.02**	0.02**	0.00*
	(0.05)	(0.00)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.00)
Experience with cacao	0.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
	(0.02)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Age of the plot	-0.03	0.00	0.01	0.01	-0.00	-0.01	-0.00	-0.00
	(0.02)	(0.00)	(0.01)	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)
Density of plants (log)	0.26**	-0.00*	-0.05**	-0.05**	0.01	0.05**	0.03**	0.01*
	(0.11)	(0.00)	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.00)
Farmer only produces cacao	-0.08	0.00	0.02	0.01	-0.00	-0.02	-0.01	-0.00
	(0.20)	(0.00)	(0.04)	(0.04)	(0.01)	(0.04)	(0.02)	(0.01)
Receives ag-technical assistance	0.82***	-0.01*	-0.16***	-0.13***	0.04**	0.15***	0.09***	0.03**
	(0.15)	(0.01)	(0.03)	(0.03)	(0.02)	(0.03)	(0.02)	(0.01)
Makes use of hired labor force	0.26*	-0.00	-0.05*	-0.05	0.00	0.05*	0.03	0.01
	(0.16)	(0.00)	(0.03)	(0.03)	(0.01)	(0.03)	(0.02)	(0.01)
Is there coca on the farm?	-0.20*	0.00	0.04*	0.04*	-0.01	-0.04	-0.02	-0.01
	(0.12)	(0.00)	(0.02)	(0.02)	(0.00)	(0.02)	(0.02)	(0.01)
Age of the beneficiary	0.01	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00
	(0.01)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Sex of the beneficiary	0.10	-0.00	-0.02	-0.02	0.00	0.02	0.01	0.00
	(0.14)	(0.00)	(0.03)	(0.02)	(0.01)	(0.03)	(0.02)	(0.00)
Beneficiary is of an ethnic origin	0.16	-0.00	-0.03	-0.03	0.00	0.03	0.02	0.01
	(0.23)	(0.00)	(0.04)	(0.05)	(0.00)	(0.04)	(0.03)	(0.01)
Is there a spouse in the h/hold?	-0.21	0.00	0.04	0.04	-0.01	-0.04	-0.03	-0.01
	(0.13)	(0.00)	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)	(0.01)
Fixed effect: *Cumbitara*	-0.37*	0.01	0.07	0.06**	-0.02	-0.07*	-0.04**	-0.01*
	(0.20)	(0.01)	(0.05)	(0.03)	(0.02)	(0.04)	(0.02)	(0.01)
Fixed effect: *El Rosario*	-0.99***	0.04*	0.24***	0.10***	-0.12***	-0.17***	-0.07***	-0.02**

Variables	(1) Coeff.	(2) Pr (P = 0)	(3) Pr (P = 1)	(4) Pr (P = 2)	(5) Pr (P = 3)	(6) Pr (P = 4)	(7) Pr (P = 5)	(8) Pr (P = 6)
	(0.22)	(0.02)	(0.06)	(0.02)	(0.04)	(0.03)	(0.01)	(0.01)
Fixed effect: *Leiva*	-0.85***	0.02	0.19***	0.11***	-0.08**	-0.15***	-0.07***	-0.02**
	(0.24)	(0.02)	(0.06)	(0.02)	(0.04)	(0.04)	(0.02)	(0.01)
Fixed Effect: *Los Andes*	1.50***	-0.01*	-0.13***	-0.24***	-0.17***	0.11***	0.24***	0.20***
	(0.25)	(0.00)	(0.02)	(0.03)	(0.05)	(0.03)	(0.06)	(0.06)
α_1	-0.28							
	(0.82)							
α_2	1.14							
	(0.82)							
α_3	2.00**							
	(0.81)							
α_4	2.87***							
	(0.82)							
α_5	3.71***							
	(0.82)							
α_6	4.54***							
	(0.87)							

Wald test of joint significance: X^2 (16) = 161.61, Prob > X^2 = 0.00

Robust standard errors in parentheses. *** p < 0.01, ** p < 0.05, * p < 0.1

Source: Own elaboration.

Finally, we emphasize the strong effect that ATA has over the extent of adoption. Those receiving ATA are 31 percent more likely to use three or more technologies, with a 27 % higher likelihood of using four or more practices. In developing countries as Colombia, finding a consistent and favorable effect from the access to ATA is valuable for recommending a further strengthening and enforcement of recent local efforts like the National System of Agricultural Innovation (Law 1876 of 2017, Colombia[4]). Although some findings in Latin America suggested that efforts from both Governments and NGOs may deem ineffective in improving the livelihoods of small-scale farming households (Hartwich *et al.,* 2007), these kinds of results help build a case in favor of ATA better. Despite some discouraging aggregate rates of technology adoption, it is worth remembering that ATA's impact is not immediate but gradual. This result suggests that it is useful to some degree and worthy of being further improved.

[4] Retrieved from: https://www.minagricultura.gov.co/Normatividad/Leyes/Ley%20No%201876%20de%202017.pdf.

5. Discussion

Once one of the largest productive regions of cacao in Colombia, the southwestern department of Nariño is passing through a period of social transformation, and this crop may be one of the keys towards new paths for better livelihoods and regional peace (Abbott *et al.,* 2018). However, a limited use of productive technologies needed for accessing high-value markets and the persistence of illegal crops that allegedly affect the incentives to invest in legal production may result in limited effectiveness of any transformational effort. Hence, this paper is an effort towards that end, providing insights about technology adoption determinants for six cacao technologies and how these also affect the total extent of adoption. We identify the main mechanisms driving the decision on whether to use specific practices. In particular, the focus is on cacao farmers in the mountain region of Nariño, a current target of intervention from international organizations.

Although most cacao farmers rely on selected/improved materials (60 %) for their production, there is still a large share of them whose outputs would remain unsuitable for reaching high-value markets. Other relevant practices for the appropriate management of the crop report drastically low adoption rates, as is the case of grafting for the reinstatement of unproductive trees (32.6 %) and physical-chemical soil testing (21.8 %) to manage input use in the cacao plot. The latter is particularly concerning, as cacao is particularly sensitive to soil conditions. An inappropriate input management may result in the ineffectiveness of other practices like fertilization (i.e., no certainty on the plot's actual needs). On the other hand, practices like phytosanitary control, irrigation, and fertilization are present in most cacao farms (84.9, 50.4, and 52.7 %, respectively). The former two are of high importance in Colombia due to the crop's vulnerability to diseases and putrescence in the absence of these controls (Jaimes Suárez & Aranzazu Hernández, 2010). On the other hand, although encouraging, the latter should be interpreted with some level of skepticism as the decision to use fertilization may not be a well-informed one, considering the mentioned low level of soil testing among cacao farms.

Our results suggest that the analysis of farmers' adoption of agricultural practices should be made on a joint-decision framework. This considers the potential pairwise complementarity and substitutability across practices, further building on the growing body of literature that relies on multivariate modeling of technology adoption (Teklewold *et al.,* 2013; Wollni *et al.,* 2010). The exclusive use of selected/improved varieties and practice of grafting is concentrated among larger farms with more specialization (crops managed at a higher density). In contrast, those who report the use of hired labor force, i.e., more capable of implementing time-consuming practices, are more likely of both phytosanitary control and fertilization. At first glance, this side of the results highlights a need for better target resource-poor farmers.

An additional and crucial result is the negative relationship between the presence of illegal crops (namely coca) and the practices of grafting and sanitary control for cacao. We found the result to be robust also in terms of the extent of adoption. Such an illegal crop likely increases the probability that the farm limits the number of adopted productive practices to a maximum of two. The result is consistent with previous evidence that illustrates how the (considerably higher) returns to illegal crops may alter the behavior and preference of farms (Thoumi, 2005) regarding other sources of income. With no clear paths or political trends with a favorable view towards drug legalization in Colombia, efforts to provide technological and access to low-intermediation high-value markets remain as the best alternatives to give an option for farmers gradually and voluntarily going out of illegal crops.

Finally, a determinant behind the adoption of most technologies is the access to agricultural technical assistance (ATA), an effect that holds robustly in terms of the extent of adoption of farming households. The striking result favors current efforts that promote the strengthening and proper enforcement of the National System of Agricultural Innovation in Colombia (Law 1876 of 2017, Colombia) and similar efforts taking place across other developing countries. Although ATA among small communities in Latin American has further challenges to address regarding the mechanisms for appropriating knowledge among their diverse and education-limited backgrounds (Hartwich *et al.,* 2007), these findings that there is an existent degree of effectiveness to be leveraged, with room for further improvement in the median-and long-run.

6. Conclusions

Colombia has an opportunity at hand for entering high-value cacao markets and further compete with neighboring countries that have long dominated segments as fine flavor cacao. Yet, to seize that possibility, a great deal of institutional and governmental efforts must be put in place so that farmers may learn how to make good use of the available resources and technologies to boost their productivity, output quality, and final competitiveness. We argue that bottom-up improvements are the best way to kick-start such change.

Our analysis of the determinants of technology adoption among cacao farmers in the mountain region of Nariño, Colombia, reveals that there are strong complementarities between practices that may favor their joint adoption. Promoting and ensuring the adoption of all these basic practices is a first step towards the sector's competitiveness improvement. However, evidence suggests that larger extents of adoption happen among wealthier farmers, calling for a better targeting of resource-poor agricultural households. Although the Colombian case has received several critiques regarding the quality and continuity of technical support and extension services in rural areas, ATA proved to be a substantial factor behind adoption. Therefore, despite the critiques, there is a degree of effectiveness from the available ATA systems, and both local and national government efforts should build upon what proved to be useful. Finally, although cacao is extensively being promoted as a strategy to go out of illegal crops, data suggests that the latter may create barriers to technology adoption and thus to the strategy's viability.

These findings are in line with evidence from other developing countries. Nevertheless, further research efforts that rely on nationally (or regional) representative samples are necessary to properly understand the regional dynamics of cacao production in Colombia and deliver better insights for national policies that may deliver a more substantial impact. Future agricultural policies should draw their insights from more detailed and purpose-specific data that allows us to analyze, in-depth, the underlying complexities of farming systems, just as the one we present for cacao in northeastern Nariño.

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