

Article

Impact of Agronomic Practices and Socioeconomic Factors on Coffee Yield in the Monzón Valley, Peru

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Abstract

Coffee cultivation offers benefits such as biodiversity conservation, economic sustenance for farmers, and health advantages. This quantitative, microsociological, and applied study, with a non-experimental, cross-sectional design and explanatory level, aimed to evaluate the impact of agronomic practices and socioeconomic factors on coffee yields among farmers in the Monzón Valley (Huánuco, Peru). Using the hypothetico-deductive method, logit and probit regression models were employed, employing an ordered probabilistic model with multiple responses. Data were collected through simple random sampling, surveying 152 producers. The probit model proved most suitable for explaining yield levels, classified as low (<0.60 Tn/ha/year), medium (0.61–1.00), and high (1.01–2.20). The most influential indicators were biological and cultural control, crop age, organic farming practices, altitude, cultivation of more than one variety, seed selection, monetary income, and farmer experience. The study concludes that the probit model adequately explains the relationship between the agronomic and socioeconomic variables that determine yield. The findings provide valuable evidence for the design of local agricultural policies and producer support programs. Furthermore, the study explicitly contributes to the advancement of the Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty), SDG 8 (Decent Work and Economic Growth), and SDG 12 (Responsible Consumption and Production), by identifying factors that link sustainable coffee productivity with the socioeconomic well-being of farming communities.

Keywords: altitude; sensitivity analysis; maximum likelihood; organic production; probit; coffee variety



Academic Editors: Jiachao Peng,
Hui Wang, Le Wen, Zhengyang Zhang
and Zhongju Liao

Received: 21 June 2026

Revised: 21 July 2026

Accepted: 28 July 2026

Published: 4 August 2026

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1. Introduction

Peru is the third largest coffee producer in South America, after Brazil and Colombia [1], and the second largest exporter of organic coffee worldwide, making it the country's main agricultural export. According to the Ministry of Agrarian Development and Irrigation [2], this crop occupies 6% of the national agricultural land (425,416 ha). Coffee is of

vital importance to the Peruvian economy: the National Institute of Statistics and Informatics [3] reports that, according to the latest agricultural survey (2018), parchment coffee has the second largest harvested area, being the main permanent crop (15.4%) managed by small- and medium-sized producers. At the regional level, Huánuco is the seventh largest producer nationally, with Leoncio Prado and the Monzón Valley as its most important coffee-growing areas [3].

Coffee is cultivated within the “coffee belt,” located between the Tropics of Cancer and Capricorn [4]. Its development is restricted to this tropical zone due to specific altitude and climate requirements, which influence the incidence of pests and diseases, as well as the final quality and yield of the grain [5–7]. Altitude is a determining factor, as it modulates the microclimate and soil properties. At higher elevations, pH tends to decrease [8], along with the content of organic matter (OM), Ca, Mg, and K [9], due to the drop in temperature and soil water saturation [10], conditions that limit OM decomposition [11]. Overall, altitude can create favorable or adverse environments for crop nutrition and pathogen proliferation, directly affecting yield, making its management by the farmer crucial.

To adapt to these conditions, producers select specific varieties. For example, the Conilón variety shows high yields at higher altitudes [12,13], while Arabica [14] and Robusta [15] predominate in lower areas. However, coffee’s climate sensitivity presents a challenge. Läderach et al. [16] point out that climate change could affect its cultivation at different altitudes, generating negative, positive, or mild impacts in the short and long term. The optimal altitude for cultivation is generally between 1000 and 1600 m a.s.l. [17]. The Monzón Valley, with an altitudinal range of 700 to 1700 m a.s.l., presents, in principle, suitable conditions for its development.

Agronomic practices are key tools for mitigating environmental effects and maintaining crop health and productivity. Shade cultivation is a relevant practice, especially at low altitudes (~640 m a.s.l.), as it allows for regulating light incidence and preventing defoliation [18,19], or compensating for unfavorable environmental conditions [20]. This management approach offers advantages such as protection against insects, pathogens, and extreme weather events, although it also presents disadvantages such as management difficulties, reduced water availability, and a greater risk of erosion [21].

Another fundamental practice is pruning and thinning, which optimize the environment for coffee plants by regulating humidity, light, and competition among plants, thus increasing yield [22]. Pruning systems (light, medium, or heavy), along with the replacement of damaged plants, have been shown to improve productivity in Arabica coffee [23]. Regardless of the management system, a fertilization plan is essential. Both inorganic and organic sources have shown improvements in yield. Khemira et al. [24] recommend inorganic fertilization to increase productivity, while Maroneze et al. [25] and Fernandes et al. [26] highlight the benefits of combining irrigation with organic fertilization. The choice between these methods implies a significant difference: the production of grains with or without contaminant residues.

The application of these practices is influenced by socioeconomic factors. Farmers’ knowledge, acquired through inherited experience or climate change training, allows them to implement more careful management, selective harvesting, improved drying techniques, and reduced input use, contributing to sustainability [27]. However, low income and a lack of government support can negatively affect yields [28].

Among these factors, the producer’s level of education has a positive effect on productivity, especially in organic management systems [29]. When combined with extension visits and training, education promotes the adoption of appropriate varieties, efficient cultivation systems [30], and proper seed management during harvest and post-harvest [31].

This helps avoid low yields associated with aging plantations and soil degradation, thereby reducing pressure to expand the agricultural frontier into protective forests [32].

A gap has been identified in comprehensive studies that quantify, through modeling, the interaction between specific agronomic practices and farmers' socioeconomic characteristics to explain yields in a specific local context such as the Monzón Valley. Understanding these interrelationships is fundamental for designing effective interventions. Furthermore, the application of ordered multiple-response models (probit/logit) to analyze yield levels, explicitly linking the findings to the Sustainable Development Goals (SDGs 1, 8, and 12) [33], represents an innovative approach to guiding concrete actions in coffee systems.

Despite the socioeconomic importance of coffee in Peru and the recognized influence of agronomic and socioeconomic factors on yield, comprehensive studies quantifying the interaction between these dimensions using probabilistic models remain scarce, especially in the specific context of the Monzón Valley. This study addresses this gap by applying ordered probit and logit regression models to explain coffee yield levels based on a combination of agronomic practices (biological and cultural control, crop age, organic production, altitude, varietal diversification, and seed management) and socioeconomic factors (monetary income and farmer experience). We hypothesize that the interaction between technical knowledge—reflected in practices such as pruning and fertilization—and human capital (training and experience) constitutes a critical determinant of productivity. Unlike previous research that focuses primarily on isolated productivity factors, this study explicitly links its findings to the Sustainable Development Goals (SDGs 1, 8, and 12), offering an integrated framework for policy design. The aim is to propose an explanatory model that can serve as a decision-support tool for optimizing agricultural practices and improving both the productivity and living conditions of coffee farmers in the region.

2. Materials and Methods

2.1. Study Area

The Monzón Valley (Figure 1) is located in the districts of Monzón and Marias, belonging to the provinces of Huamaliés and Dos de Mayo, in the region of Huánuco-Peru. This valley extends from the hamlets of Rondos, 750 m above sea level, to Milagros, which reaches 3200 m. The region encompasses a diversity of ecosystems, including very humid tropical forests, premontane tropical forests, premontane tropical forests and low montane tropical forests, with significant variations in temperature and precipitation according to altitude.

Coffee is not the only agricultural activity in the area; cocoa, rice, corn, cassava, beans and coca are also grown. These crops are distributed in various localities, such as: Agua Blanca, Almendra, Alto Peru, Amistad Alta, Camote, Catalán, Chipaco, Chipaquillo, Corvinilla Alta, Cuyacu, Macora, Matapalo, Milagros, Monte Grande, Nueva Dheli, Nueva Esperanza, Nueva Selva Alta, Ocho de Agosto, Palo Wimba, Rinconada, Río Espino, Rondos, Sachavaca, San Cristóbal, Santa Rosa de Chacrita, Selva Alta, Tazo Grande, Tingo Chico and Yanacandado.

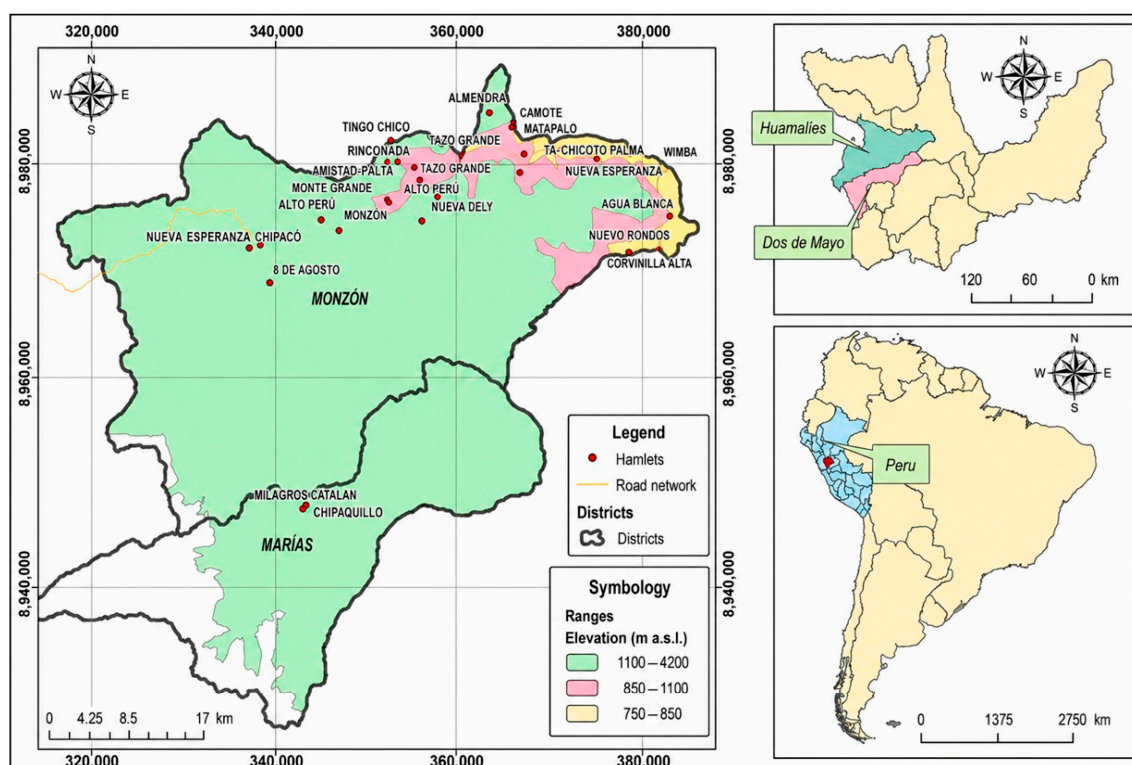


Figure 1. Location of the Monzón Valley according to altitude and localities evaluated.

2.2. Description of Variables Evaluated

The selection of variables was guided by previous scientific literature, and these are presented in detail in Table 1.

Table 1. Operationalization of variables, dimensions and indicators.

Variable	Dimension	Indicator	Operational Definition	Type	Codification	Reference
Dependent variable: Coffee yield	Yield	Yield level	Coffee crop yield is measured through three categories: low, when it ranges between 0 and 0.60 t/ha; medium, between 0.61 and 1 t/ha; and high, between 1.01 and 2.20 t/ha	Qualitative ordinal	1 = Low, 2 = Medium, 3 = High	[14,17,34,35]
Independent variable 1: Agronomic practices	Dimension 1: Agricultural practices	Biological control	Evaluated as the application of <i>Beauveria bassiana</i> or release of <i>Phymastichus coffea</i> for the control of the coffee berry borer	Qualitative	1 = Yes, 0 = No	[29,34]
		Pests and/or diseases	Evaluate the presence of pest and/or disease proliferation in the agricultural plot	Qualitative	1 = Yes, 0 = No	[36]

Table 1. Cont.

Variable	Dimension	Indicator	Operational Definition	Type	Codification	Reference
Independent variable 1: Agronomic practices	Dimension 1: Agricultural practices	Cultural control	Evaluate the application of practices for the removal of remaining berries, pruning before flowering and after harvest, and the removal of plants affected by pests and/or diseases	Qualitative	1 = Yes, 0 = No	[29,37]
	Dimension 2: Crop Location	Low	Evaluate coffee plantations at low altitude (<850 m above sea level)	Qualitative	1 = Yes, 0 = No	[14,17,38–40]
		Medium	Evaluate coffee plantations at medium altitude (851–1100 m above sea level)	Qualitative	1 = Yes, 0 = No	
		High	Evaluate coffee plantations at high altitude (>1100 m above sea level)	Qualitative	1 = Yes, 0 = No	
	Dimension 3: Variety and diversification of the crop	More than 1 variety of coffee is cultivated	Evaluate whether the farmer grows more than one variety of coffee on his farm	Qualitative	1 = Yes, 0 = No	[19,30,41]
		Age of the crop	Average age of the coffee plantation from installation to the evaluated farm	Quantitative	Years	[17,30,40,42]
	Dimension 4: Agricultural extension services	Seed manipulation techniques	Evaluate whether the farmer applies informed technical criteria to choose a seed variety that is resistant to pests and diseases, as well as the variety's ability to adapt to the local climate	Qualitative	1 = Yes, 0 = No	[30,43]
		Organic production	Evaluate whether the farmer uses organic production practices in the production process, without the application of chemicals, pesticides, and any input that is not within the organic production approach	Qualitative	1 = Yes, 0 = No	[22,29,35]
Independent variable 2: Socioeconomic factors	Dimension 1: Socioeconomic	Monthly income	Evaluate the average monthly income that the farmer has and allocates to coffee cultivation	Quantitative	In soles	[42,43]
		Primary education level	Evaluate the level of primary education completed by the farmer	Qualitative	1 = Yes, 0 = No	[37,42,43]
		Secondary education level	Evaluate the level of completed secondary education attained by the farmer	Qualitative	1 = Yes, 0 = No	

Table 1. Cont.

Variable	Dimension	Indicator	Operational Definition	Type	Codification	Reference
Independent variable 2: Socioeconomic factors	Dimension 1: Socioeconomic	Sufficient work experience	Evaluate the years of experience the farmer has in the coffee value chain (planting, cultivation, harvesting and marketing)	Quantitative	Years	[37,42,43]

2.3. Population and Sample

According to DEVIDA, the Monzón Valley has about 1500 farmers (N) dedicated to coffee cultivation. The minimum initial number of surveys conducted (n_0) is 127 farmers. This sample was calculated using simple random sampling (SRS). For this purpose, a confidence level ($1 - \alpha$) of 95% was used, achieving a critical point ($Z_{\alpha/2}$) of 1.96 according to the theoretical standard normal probability distribution function; as well as a probability of success (p) of 0.90 and of failure (q) of 0.10. In addition, a margin of error (e) of 5% was considered.

$$n_0 \geq \frac{Z_{\alpha/2}^2 pqN}{e^2(N-1) + Z_{\alpha/2}^2 pq} \quad (1)$$

In Equation (1), n_0 is substituted as follows:

$$n_0 \geq \frac{(1.96)^2(0.90)(0.10)(1500)}{(0.05)^2(1500-1) + (1.96)^2(0.90)(0.10)} \Rightarrow n_0 \geq 127 \text{ coffee growers.}$$

To guarantee the number of n_0 , the non-response rate (NRR) of 20% is considered. For this reason, the final minimum sample (n) is expressed in Equation (2):

$$n \geq n_0(1 + \text{NRR}) \quad (2)$$

By replacing, the final sample (n) is obtained:

$$n \geq 127(1 + 0.20) \Rightarrow n \geq 152 \text{ coffee growers.}$$

2.4. Probabilistic Multiple-Response Model

When the dependent variable is of an ordinal qualitative nature, it is common to use ordered logit and probit regression models, these models are based on a latent model and known threshold values [44]. According to Greene [45], both types of models are highly recommended to analyze the order of the numbers within the same classification, and are constructed from a latent variable (Y_i^*) as the dependent variable, which represents the different categories, while X_i represents the independent variables, as shown in Equation (3):

$$Y_i^* = F(\beta X_i) + \varepsilon_i \quad (3)$$

where $F(\beta X_i)$ is the logistic or normal distribution function, βX_i is the linear combination of the estimated values of the parameters (β) by maximum likelihood (ML) with respect to the variable X_i , and ε_i represents the stochastic component of the model of the i th unobservable observation.

From the unobserved variable Y_i^* , we derive the observed or real variable Y_i , which quantifies the different categories. Consider the following case of four categories:

$$Y_i = \begin{cases} 1 & \text{if } Y_i^* \leq C_1 \\ 2 & \text{if } C_1 \leq Y_i^* \leq C_2 \\ 3 & \text{if } C_2 \leq Y_i^* \end{cases} \quad (4)$$

The variables C_i ($i = 1, 2$ and 3) are estimated simultaneously with β . These variables are known as thresholds, since they represent the point at which the change from one category to another occurs: from 0 to 1, from 1 to 2 and from 2 to 3, respectively. Equation (5) expresses the relationship in terms of probability:

$$\begin{aligned} \text{Prob}[Y_i = 1/X_i, \beta, C] &= F(C_1 - X_i\beta) \\ \text{Prob}[Y_i = 2/X_i, \beta, C] &= F(C_2 - X_i\beta) - F(C_1 - X_i\beta) \\ \text{Prob}[Y_i = 3/X_i, \beta, C] &= 1 - F(C_2 - X_i\beta) \end{aligned} \quad (5)$$

In these models, heteroscedasticity in ε is not present, since the sample is evaluated in groups according to each category. As for the interpretation of β_{ML} , sensitivity analysis is used to understand how the probability changes due to an increase in X_i . These analyses are specified in Equations (6) and (7):

In case the indicator X_k is quantitative in nature:

$$\begin{aligned} \frac{\partial \text{Prob}[Y_i=1/X_i, \beta, C]}{\partial X_k} &= -f(C_1 - X_i\beta)\beta_k \\ \frac{\partial \text{Prob}[Y_i=2/X_i, \beta, C]}{\partial X_k} &= [f(C_2 - X_i\beta) - f(C_1 - X_i\beta)]\beta_k \\ \frac{\partial \text{Prob}[Y_i=3/X_i, \beta, C]}{\partial X_k} &= f(C_2 - X_i\beta)\beta_k \end{aligned} \quad (6)$$

where

$$f(C_1 - X_i\beta) = \frac{\partial F(C_1 - X_i\beta)}{\partial X_k} \text{ and } f(C_2 - X_i\beta) = \frac{\partial F(C_2 - X_i\beta)}{\partial X_k}$$

In case the indicator is of a qualitative nature:

$$\begin{aligned} \frac{\Delta \text{Prob}[Y_i=1/X_i, \beta, C]}{\Delta X_k} &= \text{Prob}[\cdot]_{X_k=1} - \text{Prob}[\cdot]_{X_k=0} \\ \frac{\Delta \text{Prob}[Y_i=2/X_i, \beta, C]}{\Delta X_k} &= \text{Prob}[\cdot]_{X_k=1} - \text{Prob}[\cdot]_{X_k=0} \\ \frac{\Delta \text{Prob}[Y_i=3/X_i, \beta, C]}{\Delta X_k} &= \text{Prob}[\cdot]_{X_k=1} - \text{Prob}[\cdot]_{X_k=0} \end{aligned} \quad (7)$$

where

$$\begin{aligned} \text{Prob}[Y_i = j/X_i + \Delta X_i, \beta, C] &= \text{Prob}[\cdot]_{X_k=1} \text{ and} \\ \text{Prob}[Y_i = j/X_i, \beta, C] &= \text{Prob}[\cdot]_{X_k=0} \\ \forall j &= 1, 2, 3. \end{aligned}$$

2.5. Causal Inference and Limitations of the Study

The probabilistic multiple-response models (logit or probit) used in this manuscript capture the probabilistic dependence between variables; however, this dependence does not equate to causal relationships in the strict sense. In this regard, Henningsen et al. [46] point out that estimating causal effects with cross-sectional data requires a rigorous research design and an explicit discussion of the identification assumptions. Consequently, the approach adopted is methodologically relevant and widely supported in the agricultural economics literature for:

- Identifying determining causes: Several coffee studies use regression models with cross-sectional data to elucidate the factors that influence yield [42,43].

- Establishing intervention priorities: Identifying variables with statistical significance (1% and 5% levels) allows for directing policies and outreach programs toward those factors with the greatest associated impact [37].
- Generating causal hypotheses: The findings of this research provide empirical evidence that can be corroborated through experimental designs and longitudinal studies [41].

3. Results

3.1. Agronomic Practices

According to Figure 2a, coffee farmers in Monzón Valley implement various agricultural practices based on their previous knowledge and experiences. First, a minority trend corresponds to a small group of farmers implementing practices such as biological control (17 farmers, equivalent to 11.18%), pest and/or disease assessment (37 farmers, 24.34%) and ethological control (13 farmers, 8.55%). Secondly, a more common trend is observed in the use of practices such as cultural control, adopted by 86.18% (131 farmers), and chemical control, employed by 96.71% (147 farmers). Finally, a third trend highlighted is the practice of physical control, carried out by 54.61% (83 farmers).

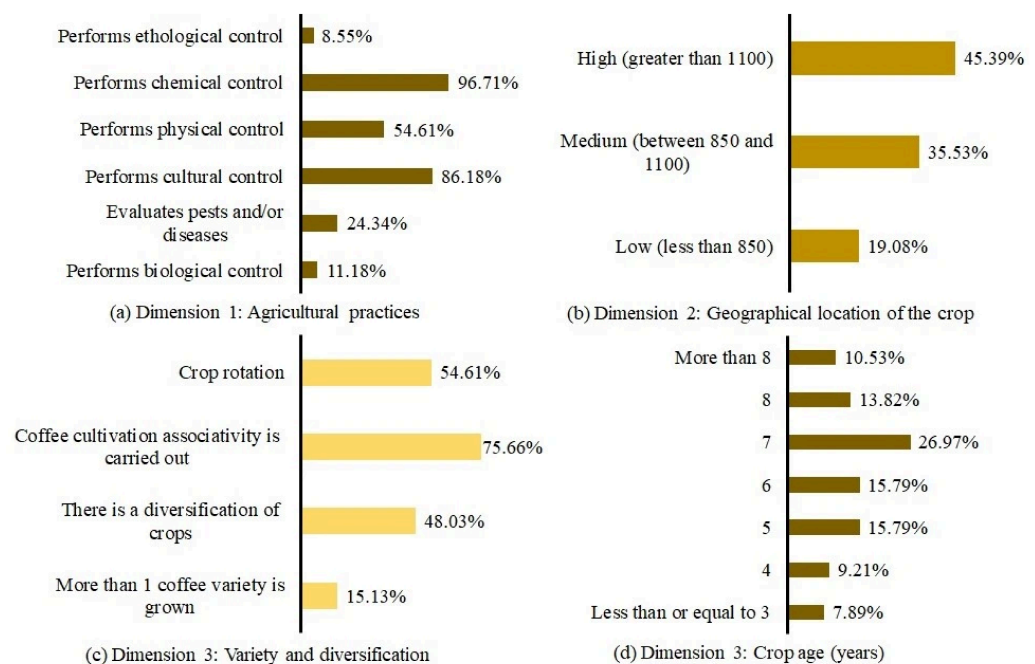


Figure 2. Agronomic practices according to Dimensions 1 to 3.

On the other hand, there are other less common and more heterogeneous practices that are not uniform characteristics among farmers. About 25% of these farmers carry out activities such as renewal pruning, weed control, integrated pest management, shade management with wood and other crops, as well as clear-cutting and deforestation to install new crop areas. The latter involves burning the area in the belief that it increases soil fertility and crop production, an aspect explained by Florida Rofner and Acuña Núñez [47].

According to Figure 2b, the farms dedicated to coffee cultivation are in an altitudinal range that oscillates between 700 and 1700 m above sea level (m a.s.l.) in the provinces of Huamalíes and Dos de Mayo, belonging to the region of Huánuco. The data collected show that there are 29 plots located at low altitudes (between 700 and 850 m a.s.l.), 54 plots at medium altitudes (between 850 and 1100 m a.s.l.) and 69 plots located at higher altitudes

(between 1100 and 1700 m a.s.l.). The lowest altitude farm is located in the hamlet of Rondos, while the highest altitude farm is in Macora.

Figure 2c shows that the majority of farmers in the Monzón Valley, represented by 129 (84.87%), are used to growing only one variety of coffee. The variety preferred by most farmers is Catimor, with 80.92% representativeness, followed by Costa Rica and Geisha, which are options adopted by other farmers. However, a smaller group of farmers, represented by 23 (15.13%), believe in the feasibility of having more than one coffee variety. These combinations include Catimor and Caturra, Catimor and Gran Colombia, and Catimor and Catuai.

Likewise, 90% of the farmers cultivate between 1 and 3 hectares of coffee. The cultivation areas of the different varieties are as follows: Catimor 1.70 ± 0.89 hectares, Caturra 0.95 ± 0.39 hectares, Catuai 1.88 ± 1.59 hectares, Costa Rica 1.40 ± 0.22 hectares and Geisha 0.75 ± 0.35 hectares.

According to the crop diversification indicator, slightly less than half of the farmers claim to practice it. Complementary crops include banana (70.80%), maize (26.58%) and some farms grow cassava, cacao, coca, citrus and pitahaya. In terms of associativity, about three quarters (75.66%) of the farmers conserve timber trees (65.83%) such as pine, cedar, mohená and tornillo, along with guaba (21.95%) and plantain (12.22%) in the same coffee plots. In reference to crop rotation, this practice consists of substituting crops in the same plot to avoid the presence of pests, diseases and the depletion of soil nutrients. This practice is carried out by 83 (54.61%) coffee growers. On the other hand, 69 (45.39%) farmers do not implement it because the plots are not suitable for another crop, as they were previously used for coca cultivation and the farmers lack experience. In addition, there is land that has not yet been used, which represents an average of 2 ± 3.8 hectares per farmer.

Figure 2d shows that the average age of a coffee plant will depend on the management and cultivation system adopted by the farmer. The age of coffee plants planted by farmers in Monzón Valley is between 1 and 14 years; therefore, in terms of average value and variability it is 6 ± 2 years. When analyzing the age of the crop divided into quartiles, 25% (quartile 1) are between 1 and 5 years old, 50% (quartile 2) and 75% (quartile 3) are between 1 and 7 years old, while the remaining 25% (quartile 4) are between 7 and 14 years old.

Regarding the average age and variability by coffee variety, the following values were found for Catimor it is 6 ± 2 years, for Caturra and Gran Colombia it is 7 ± 3 years, for Catuai it is 5 ± 1.5 years, for Costa Rica it is 6 ± 0.5 years and for Geisha it is 1.5 ± 0.5 years. Regarding the average quantity and its variability by variety, farmers maintain the following quantities: for Catimor it is 3191 ± 720 plants, for Caturra it is 2763 ± 595 plants, for Catuai it is 2917 ± 589 plants, for Costa Rica it is 3600 ± 418 plants and for Geisha it is 1750 ± 1061 plants. In addition, one farmer grows the Gran Colombia variety with 3000 plants.

In Figure 3a, when analyzing the various agricultural extension services according to the most frequent answers expressed by farmers, we find that most of them apply certain practices. For example, seed management is performed by 107 (70.39%) farmers, while the use of manures and fertilizers is applied by 149 (98.03%) of them. These techniques are applied in the Catimor variety in 85.12%, in Caturra in 8.26%, and in other varieties such as Gran Colombia, Catuai, Costa Rica and Geisha in 6.61%.

In addition, in relation to the use of fertilizers and fertilizers according to coffee variety, 83.53% are applied in Catimor, 10% in Caturra and 6.47% in other varieties such as Gran Colombia, Catuai, Costa Rica and Geisha. On the other hand, few of the farmers carry out soil analysis, as indicated by 49 (32.24%) farmers; 5.26% (8 farmers) produce organic coffee and 46 (30.26%) farmers carry out other agricultural practices.

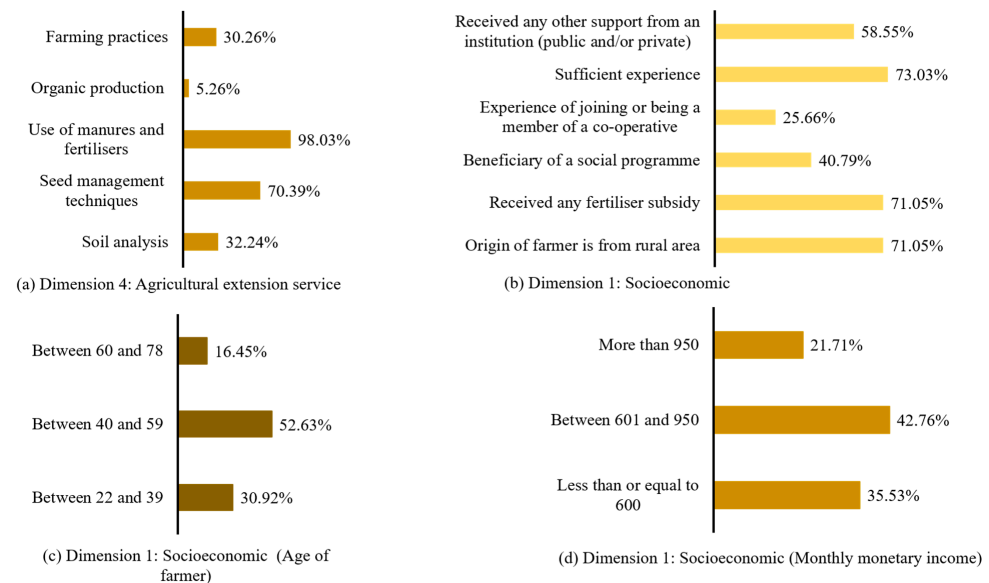


Figure 3. Agronomic practices according to Dimension 4 and socioeconomic data according to Dimension 1.

The results in Figure 3b show the participation of the National Commission for Development and Life Without Drugs (DEVIDA) in the Monzón Valley. This participation consists of providing support throughout the entire production and value chain to farmers who voluntarily wish to replace coca leaf cultivation with other legal crops, as well as to those who are not part of this program. In this regard, 83 farmers have been identified as beneficiaries of some type of assistance from DEVIDA, while 69 are not part of the program. Among the farmers who received support from DEVIDA, 74.70% (62 farmers) received technical assistance, 15.66% (13 farmers) obtained inputs, and 9.64% (8 farmers) benefited from pulping machines, seeds, and forestry plantations.

Figure 3c shows the age distribution of the farmers surveyed, ranging from 22 to 78 years. The average age value is 46 ± 13 years, evidencing a remarkable variation. When analyzing the quartiles, it is observed that 25% (quartile 1) of the farmers are between 22 and 37 years old, the next 25% (quartile 2) between 37 and 45 years old, another 25% (quartile 3) between 45 and 55 years old, while the remaining 25% (quartile 4) are between 55 and 72 years old. Regarding the composition of the data, 86.84% corresponds to heads of household, while 13.16% are spouses, children or siblings. Furthermore, in terms of gender, 76.97% are women and 23.03% are men.

Figure 3d shows the distribution of farmers' monthly monetary income, which ranges from 150 to 3000 soles. Despite this variability, the average income value is 770.36 ± 333.58 soles. When analyzing the quartiles, it is observed that 25% (quartile 1) of the farmers have monthly incomes between 150 and 600 soles, the next 25% (quartile 2) have incomes between 600 and 750 soles, the next 25% (quartile 3) are in the range of 750 to 930 soles, and the remaining 25% (quartile 4) have monthly incomes between 930 and 3000 soles. The data show that farmers' incomes are insufficient for two main reasons. First, it is linked to the family burden, which on average is 3 ± 2 people, being that 50.27% of the farmers have a family burden between three and five people. Secondly, this insufficiency is attributed to dependence on social programs and lack of basic services.

3.2. Socioeconomic Factors

Figure 4a shows the level of education attained by the farmers, where a large proportion is at the primary and secondary levels, representing 86.18% of the respondents. Within this group, approximately 30% have not completed these educational levels. In addition,

less than 10% have higher education, with 2.63% with non-university higher education and another 2.63% with university studies.

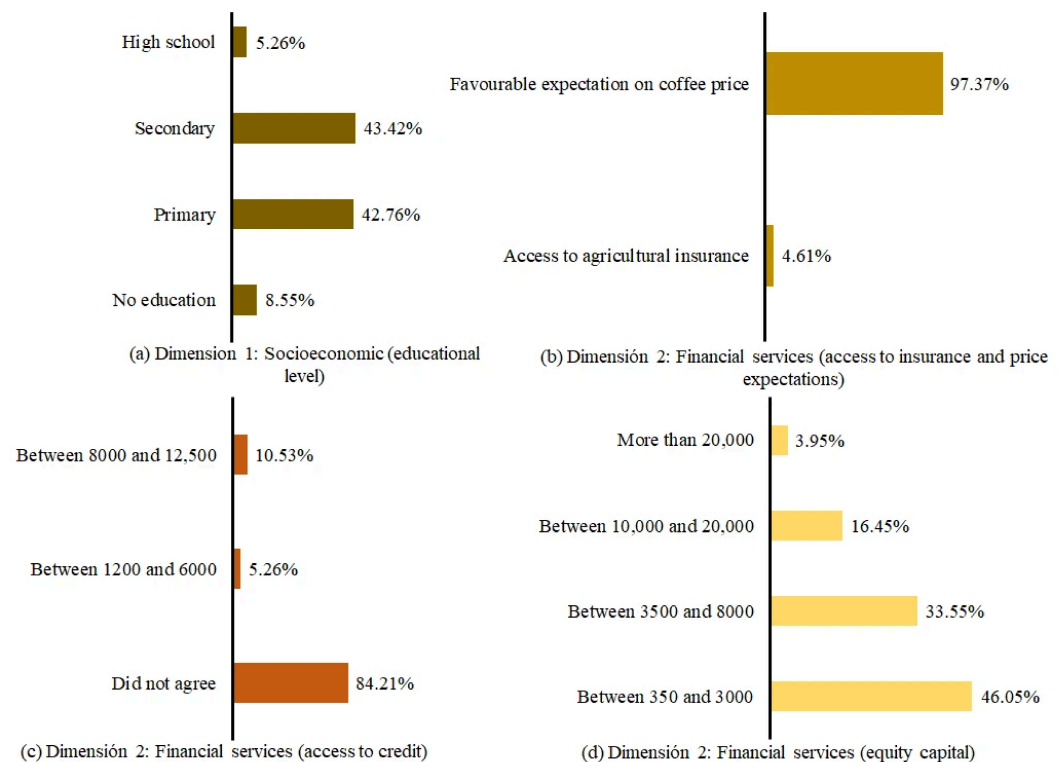


Figure 4. Socioeconomic data according to Dimensions 1 and 2.

Figure 4b reveals a favorable outlook towards coffee prices, suggesting an interest on the part of farmers to improve their yields in order to obtain higher profits. A total of 148 farmers (97.37%) expressed agreement with this statement. Despite this optimism regarding the price of coffee, it is observed that financing with their own resources is a predominant characteristic among farmers in the Monzón Valley, since only seven farmers (4.61%) have access to some type of agricultural insurance.

According to the results in Figure 4c, it is evident that 128 farmers (84.21%) lack access to some type of third-party financing. Among those who have had access to some type of agricultural credit, eight farmers (5.26%) obtained amounts ranging between 1200 and 6000 soles, while 16 farmers (10.53%) claimed to have had access to amounts ranging between 8000 and 12500 soles.

Figure 4d shows that although only a small number of farmers have been able to access some type of credit, the amount obtained is not sufficient. In contrast, invested capital stock is the most represented, with an average value and standard deviation of 5771 ± 6488 soles. Thus, it is observed that most of the amounts invested by 121 farmers (79.60%) are in the range of 350 to 8000 soles, while 25 farmers (16.45%) claim to have used between 10,000 and 20,000 soles, and only six farmers (3.95%) declared having invested a sum greater than 20000 soles.

3.3. Coffee Crop Yield

Table 2 classifies farmers in the Monzón Valley into three groups according to their coffee yield. The low level comprises values between 0 and 0.60 tons per hectare, the medium level between 0.61 and 1.00, and the high level ranges between 1.01 and 2.20 t per hectare. These intervals are determined according to quartiles.

Table 2. Yield level of the coffee crop of the farmer settled in the Monzón Valley, Huánuco-Peru region.

Performance Level (t/ha)	Number of Farmers	% of Farmers
Low (0.00 to 0.60)	43	28.29
Medium (0.61 to 1.00)	38	25.00
High (from 1.01 to 2.20)	71	46.71
Total	152	100.00

It is important to highlight some relevant aspects, such as the extension of hectares according to coffee variety. Catimor coffee, the variety preferred by most farmers, is present in the agricultural plots of 145 (95.39%) farmers, ranging from 0.5 to 7.0 hectares on average and with a variability of 1.70 ± 0.90 hectares. However, other varieties, such as Caturra, Gran Colombia, Catuai, Costa Rica and Geisha, are less frequent, with average sizes of 0.95 ± 0.39 , 11.88 ± 1.59 , 1.4 ± 0.22 and 0.75 ± 0.35 hectares, respectively. In addition, some farmers plant two coffee varieties, such as 26 farmers who combine Catimor with other varieties and four farmers who mix Caturra with other varieties.

In terms of coffee crops yields by variety, the data varies significantly. For example, Catimor has a yield of 1360 ± 1112 kg, with 25%, 50% and 75% of farmers producing 800, 1200 and 1500 kg respectively. In the case of Caturra, the yield is 1029 ± 587 kg, with 25%, 50% and 75% of farmers harvesting 500, 900 and 1200 kg. Gran Colombia shows an average yield of 717 ± 29 kg, with 25%, 50% and 75% of farmers harvesting 700, 700 and 750 kg. In the case of Catuai, the yield reaches 1900 ± 1556 kg, with 25%, 50% and 75% of farmers harvesting 800, 1900 and 3000 kg respectively, while Costa Rica has a yield of 1260 ± 577 kg, with 25%, 50% and 75% of farmers harvesting 1200, 1500 and 1500 kg.

3.4. Modeling and Criteria for Model Selection

To select the appropriate model, we based ourselves on the characteristics of the indicator of the dependent variable (Table 3). In this case, the variable is qualitative and ordinal, suggesting the adoption of a multiple-response ordered probabilistic model. The probit and logit models are relevant options, since both are based on normal and logistic distribution functions, respectively.

Table 3. Goodness-of-fit test of the probabilistic model.

Goodness-of-Fit Indicator	Model	
	Probit	Logit
Pseudo coefficient of determination (R^2)	0.3894	0.3871
Logarithmic probability (LV)	−98.3137	−98.6930
Constrained log likelihood ratio (LVR)	−161.0197	−161.0197
LR statistic (gl = 32)	125.4120	124.6534
Prob [LR statistic].	0.0000 ***	0.0000 ***
Information criteria		
Akaike	1.7410	1.7460
Schwarz	2.4174	2.4224
Hannan–Quinn	2.0157	2.0207

*** $p < 0.01$.

To make the decision, it is crucial to evaluate the goodness-of-fit indicators. This evaluation is divided into two parts. First, we look for a model that shows higher values in terms of R^2 , LV, LVR and the LR (likelihood ratio) statistics. The probit model seems to have a better fit compared to the logit. Although the LR statistics show high significance

with degrees of freedom of 32 for both models ($p < 0.01$), the probit model stands out for its superior fit.

Secondly, the Akaike, Schwarz and Hannan–Quinn criteria are considered where a lower value is preferred. In this respect, again the probit model is shown to be the most appropriate option since it presents lower values.

The results presented in Table 4 show that the implementation of biological and cultural control strategies by farmers is a statistically significant predictor ($p < 0.01$) of coffee crop yield. The negative nature of this relationship suggests that their adoption is associated with a higher probability of falling into a lower-yielding category. This adverse effect could be attributed to the high initial costs involved in adopting these practices. On the other hand, the use of conventional pest and disease control techniques did not show a statistically significant influence on yield, possibly reflecting their appropriate and widespread application among producers.

Table 4. Probit model of coffee crop yield level.

Independent Variables, Dimensions of the Indicator	β_{ML}	SE (β_{ML})	Z Statistic	p-Value
Independent Variable 1: Agronomic practices				
Dimension 1: Agricultural practices				
Biological control (Yes = 1 and No = 0)	−2.4668	0.4818	−5.1199	0.0000 ***
Pests and/or diseases (Yes = 1 and No = 0)	0.4430	0.3104	1.4274	0.1535
Cultural control (Yes = 1 and No = 0)	−1.1569	0.4328	−2.6732	0.0075 ***
Dimension 2: Crop location				
Low (Yes = 1 and No = 0)	−0.5346	0.3235	−1.6528	0.0984 *
Medium (Yes = 1 and No = 0)	−0.4738	0.2688	−1.7624	0.0780 *
Dimension 3: Variety and diversification of the crop				
More than one coffee variety is grown (1 = Yes and 0 = No)	1.2403	0.3967	3.1268	0.0018 ***
Crop age (Years)	−0.1998	0.0607	−3.2932	0.0010 ***
Dimension 4: Agricultural extension services				
Seed handling techniques (Yes = 1 and No = 0)	0.5145	0.2405	2.1391	0.0324 **
Organic production (Yes = 1 and No = 0)	−1.7899	0.5933	−3.0171	0.0026 ***
Independent Variable 2: Socioeconomic factors				
Dimension 1: Socioeconomic				
Monthly monetary income (in soles)	1.3394	0.4059	3.2996	0.0010 ***
Level of primary education (Yes = 1 and No = 0)	0.5771	0.3755	1.5367	0.1244
Secondary education level (Yes = 1 and No = 0)	0.3290	0.3653	0.9005	0.3679
Sufficient experience (Years)	0.1075	0.0312	3.4419	0.0006 ***
Cut-off point				
C1	−0.9869	0.6620	-	-
C2	−0.0050	0.6579	-	-
Pseudo coefficient of determination (R^2)	0.2710	Information criterion of		
Logarithm of logarithmic plausibility	−117.3845	Akaike		1.7419
Logarithm of restricted probability	−161.0197	Schwarz		2.0403
LR statistic (gl = 13)	87.2705	Hannan–Quinn		1.8631
Prob [LR statistic].	0.0000 ***			

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The altitude of the crop also proved to be a significant factor ($p < 0.10$) in yield, with a particularly negative effect observed in low- (<850 m a.s.l.) and mid-altitude

(850–1100 m a.s.l.) zones, where the probability of obtaining a high coffee yield decrease. This phenomenon can be attributed to suboptimal climatic conditions, such as the temperature and precipitation prevalent at these altitudes. On the other hand, other factors showed positive and statistically significant influences: the presence of different varieties ($p < 0.01$) and the use of specific seed management techniques ($p < 0.05$). These findings suggest that farmers apply these practices efficiently. Finally, both older crop age and organic production showed a significant negative influence ($p < 0.01$) on yield. This negative relationship can be explained, in the first case, by the natural senescence of the plants, and in the second, by a greater incidence of diseases such as rust (caused by *Hemileia vastatrix*), whose management in organic systems may be more limited.

Since older coffee crops have decreasing yields, farmers must carry out renewal activities, such as pruning or replanting, to maintain an optimal crop age, which on average is around 6 years.

It was found that socioeconomic factors, such as monthly monetary income and the farmer's experience in coffee cultivation, were determinant for the yield level, with values of $p < 0.01$. On the other hand, it was observed that the level of primary and secondary education did not have a significant influence on this component.

According to the limiting value of C_1 of -0.9869 , this refers to the case of a farmer with a low yield level in coffee cultivation. Similarly, a farmer with a medium yield level lies between C_1 , with a value of -0.9869 , and C_2 , with a value of -0.0050 , while a farmer with a high yield level exceeds the C_2 limit of -0.0050 . In relation to the R^2 statistic, it is observed that the variation of the indicators that compose the independent variable explains 27.10% of the probability of the yield level of the coffee crop in Monzón Valley. This value is considered acceptable, especially due to the predominant nature of the independent indicators, which are mostly qualitative and dichotomous.

In addition, the Akaike, Schwarz and Hannan–Quinn information criteria show the lowest values, indicating that the β_{ML} estimated by ML are more appropriate than those obtained by the ordinary least squares (OLS) method. In this context, the model is expressed as follows:

$$\begin{aligned}\text{Prob}[\text{NiRen}_i = 1/X_i, \beta, C] &= F(-0.9869 - X_i\beta_{ML}) \\ \text{Prob}[\text{NiRen}_i = 2/X_i, \beta, C] &= F(-0.0050 - X_i\beta_{ML}) - F(-0.9869 - X_i\beta_{ML}) \\ \text{Prob}[\text{NiRen}_i = 3/X_i, \beta, C] &= 1 - F(-0.0050 - X_i\beta_{ML})\end{aligned}$$

where

F = the normal distribution function.

$$\begin{aligned}X_i\beta_{ML} &= -2.47*PA_{1i} + 0.44*PA_{2i} - 1.16*PA_{3i} - 0.53*UC_{1i} - 0.47*UC_{2i} + 1.24*VyDC_{1i} - 0.20*VyDC_{2i} \\ &+ 0.51*SEA_{1i} - 1.79*SEA_{2i} + 1.34*AS_{1i} + 0.58*AS_{2i} + 0.33*AS_{3i} + 0.11*AS_{4i}\end{aligned}$$

Figure 5a illustrates the behavior at three levels (low, medium and high) calculated by means of equations expressed in terms of probability. The first equation, $\text{Prob}[\text{NiRen} = 1/X_i, \beta, C]$, represents the probability of the low yield level of the coffee crop. It is shown by the green colored curve with a negative slope, indicating that an increase in the combination $X_i\beta_{ML}$ translates into a decrease in the probability of improving the yield level of the crop.

On the other hand, the second equation, $\text{Prob}[\text{NiRen} = 2/X_i, \beta, C]$, reflects the probability of a farmer with a medium level of yield in the coffee crop. This curve, in light blue, indicates that the farmer can improve his yield by up to 37.64% probability by increasing the combination of $X_i\beta_{ML}$. However, once this point is reached, a further increase in the combination of $X_i\beta_{ML}$ decreases that yield probability. The third equation, $\text{Prob}[\text{NiRen} = 3/X_i, \beta, C]$, shows the probability of a high-yielding farmer, represented by

the red curve. Here, an increase in the combination of $X_i\beta_{ML}$ translates into an increase in the probability of crop yield.

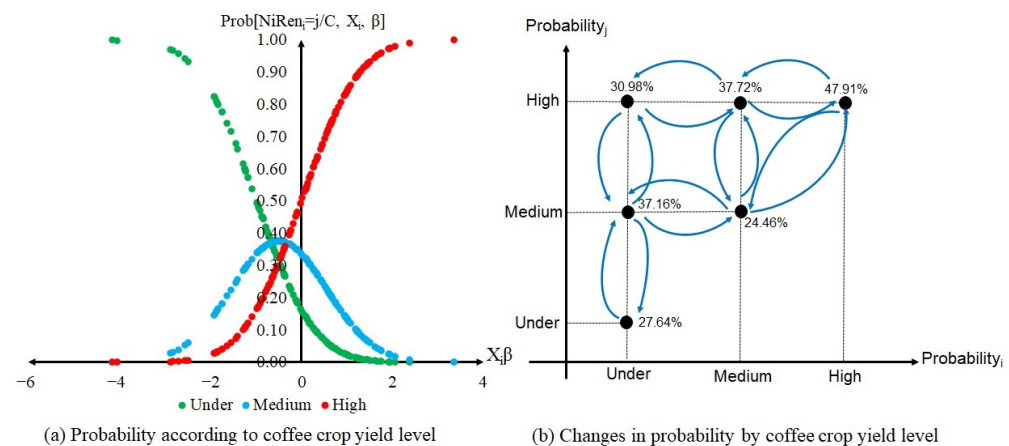


Figure 5. Behavior of probabilities according to the yield level of the coffee crop.

In Figure 5b, the various probabilities associated with the permanence, improvement or decrease in the farmer's coffee yield levels are presented. The results show that the probabilities of the farmer maintaining the yield at the same level are 27.64%, 24.46% and 47.91% for the low, medium and high levels, respectively. On the other hand, it is observed that the farmer has a 37.16% probability of improving his yield from the low to the medium level, and a 30.98% probability of improving from the low to the high level. Likewise, there is a 37.72% probability of improving from medium to high.

3.5. Sensitivity Analysis

The probability distribution of average coffee crop yield is estimated at 19.14% for the low yield level, 35.20% for the medium yield level, and 45.66% for the high yield level. The marginal effects analysis for each category reveals differentiated impacts of the evaluated indicators:

Table 5. Effect of the impact on the yield level of the coffee crop.

Dependent Variable: Indicators	Change Marginal	Level Under	Level Medium	Level High
Independent Variable 1: Agronomic practices				
Dimension 1: Agricultural practices				
Biological control (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	0.7809 ***	−0.2254 ***	−0.5555 ***
Pests and/or diseases (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	−0.1086	−0.0667	0.1753
Cultural control (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	0.2072 ***	0.2115 **	−0.4187 ***
Dimension 2: Crop location				
Low (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	0.1651	0.0381 *	−0.2032 *
Medium (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	0.1363 *	0.0481 *	−0.1844 *
Dimension 3: Variety and diversification of the crop				
More than one coffee variety is grown (1 = Yes and 0 = No)	$\Delta Y/\Delta X$	−0.2195 ***	−0.2244 ***	0.4440 ***
Crop age (Years)	dY/dX	0.0545 ***	0.0248 **	−0.0792 ***
Dimension 4: Agricultural extension services				
Seed management techniques (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	−0.1521 **	−0.0464 **	0.1985 **

Table 5. Cont.

Dependent Variable: Indicators	Change Marginal	Level Under	Level Medium	Level High
Organic production (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	0.6279 ***	−0.1694	−0.4585 ***
Independent Variable 2: Socioeconomic factors				
Dimension 1: Socioeconomic				
Monthly monetary income (in soles)	dY/dX	−0.3651 ***	−0.1661 **	0.5312 ***
Level of primary education (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	−0.1512	−0.0754	0.2266
Secondary education level (Yes = 1 and No = 0)	$\Delta Y/\Delta X$	−0.0879	−0.0423	0.1302
Sufficient experience (Years)	dY/dX	−0.0293 ***	−0.0133 **	0.0426 ***

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

For low yield, the implementation of biological control increases the probability of belonging to this level by 78.09% ($p < 0.01$), while cultural control increases it by 20.72% ($p < 0.01$). Pest and disease control did not show a significant effect. Location at medium altitude (850–1100 m a.s.l.) increased the probability by 13.63% ($p < 0.10$). Cultivation with more than one variety reduced it by 21.95%, while a 1% increase in crop age increased it by 5.45% ($p < 0.01$). Seed management techniques decreased the probability by 15.21% ($p < 0.05$). Organic production increased the probability by 62.79% ($p < 0.01$). Regarding socioeconomic factors, a 1% increase in monthly income and experience reduced the probability by 36.51% and 2.93%, respectively ($p < 0.01$), possibly due to resource reallocation or crop renewal. Primary or secondary education showed no significant impact.

For average yield, biological control decreased the probability by 22.54% ($p < 0.01$), while cultural control increased it by 21.15% ($p < 0.05$). Both low and medium altitude increased the probability (3.81% and 4.81%, respectively; $p < 0.10$). Maintaining more than one variety reduced the probability by 22.44% ($p < 0.01$), and a 1% increase in crop age increased it by 2.48% ($p < 0.05$). Seed management techniques decreased it by 4.64% ($p < 0.05$). Organic production did not have a significant effect. A 1% increase in income and experience reduced the probability by 16.61% and 1.33%, respectively ($p < 0.01$). Education showed no statistically significant impact.

For high yields, both biological and cultural control reduced the probability (55.55% and 41.87%, respectively; $p < 0.01$). Low and medium altitudes also decreased it (20.32% and 18.44%; $p < 0.10$). Cultivating more than one variety increased the probability of failure by 44.4% ($p < 0.01$), while a 1% increase in crop age reduced it by 7.92% ($p < 0.01$). Seed management techniques increased it by 19.85% ($p < 0.05$). Organic production decreased it by 45.85% ($p < 0.01$). A 1% increase in income and experience increased the probability by 53.12% and 4.26%, respectively ($p < 0.01$). Educational level did not show statistical significance.

Key implications and synthesis: The main findings suggest that the impact of agromonic practices and contextual factors varies substantially according to yield level. Practices such as biological control and organic production have opposite effects (increasing the probability of failure with low yields but decreasing it with high yields), indicating that their effectiveness may be mediated by integrated management of the production system; as well as, there is a small number of producers in the sample who use organic production, so the negative coefficient could be a consequence of a small subsample, weaker technical support or a transition period in production. Average altitude is consistently associated with a higher probability of lower yields, while varietal diversity shows a positive effect only at higher altitudes. Socioeconomic factors, such as income and experience, exhibit

complex relationships that could reflect diversification strategies or off-farm investments. For policy purposes, this underscores the need for differentiated technical recommendations and the design of intervention packages tailored to each producer profile, rather than applying uniform measures.

4. Discussion

4.1. Impact of Agronomic Practices on Yield

The overall results (Figure 2) indicate that the predominant agronomic practices in the Monzón Valley include: organic production, cultural, chemical, physical, and biological pest control, pruning, heavy bag management, integrated field management, shade management, cultivation at a specific altitudinal range, crop diversification, seed management, land and fertilizer use, and a high prevalence of the Catimor variety (Figure 3). This complex production system, analyzed from the perspective of sustainable development, has significant potential to contribute to SDG 2 (Zero Hunger)—through food security and increased productivity—and to SDG 12 (Responsible Consumption and Production), by promoting methods that can reduce environmental impact [33].

The probit model, identified as the best fit (Table 3), was used to measure the impact of these practices on coffee yield (Tables 4 and 5). Farmers were stratified into three production levels: low (43), medium (38), and high (71) (Figure 5). For low yield, the most relevant indicators were biological control, cultural control, crop altitude (850–1100 m a.s.l.), the presence of multiple coffee varieties on the farm, crop age, seed management techniques, organic production, monthly income, and farmer experience. At the medium level, the influencing factors were the same, with the exception of organic production, and the location of the crop between 750 and 850 m a.s.l. was added as a determining factor. For high yield, in addition to the indicators from the low level, the presence of crops in low-altitude areas was also relevant. This stratification reveals that the transition towards more resilient and sustainable systems (linked to SDG 9: Industry, Innovation and Infrastructure) is not homogeneous and depends on an integrated set of technical and socioeconomic factors [33].

One practice identified as influential by the model is shade-grown coffee (in associated or agroforestry systems). This aligns with the literature, which indicates that Peruvian coffee is predominantly grown in agroforestry systems, with only 13% under full sun conditions [48–50]. This preference is explained by the phenotypic plasticity of Arabica coffee, which optimizes its yield in these systems by finding favorable environmental conditions: lower solar radiation, limited heat stress, and uniform humidity—factors that promote larger bean size and weight [39,51]. Beyond productivity, these systems are pillars of SDG 15 (Life on Land), as they promote biodiversity, conserve soil, and sequester carbon, simultaneously contributing to climate change mitigation (SDG 13) [33].

Another critical practice is varietal selection. Of the 145 farmers surveyed, 95.39% (138) cultivate Catimor, a figure consistent with previous studies reporting a 90% dominance of this variety in Peru, mainly due to its tolerance to coffee rust [50]. However, Catimor presents contradictions: while some studies point to its susceptibility to other pests, low organoleptic quality, and limited yields [52], others argue that its final quality depends more on post-harvest processes than on the genetics itself [53]. A distinctive finding of our study is the positive effect of managing multiple varieties on the same farm, a benefit observed only in high-yield farmers. Although there are no previous studies addressing this specific practice in coffee, research in other crops (e.g., rice, maize) reports significant yield increases [54]. This suggests that genetic diversification can be a productive and sustainable strategy, especially for farmers with greater resources and management capabilities, thus contributing to food security and the resilience of livelihoods (SDGs 1 and 2) [33].

The model also highlights cultivation altitude as a determining factor. The study area (700–1700 m a.s.l.) is located within the global coffee-growing belt [4], although the optimal range is usually cited as being between 1000 and 1600 m a.s.l. [17,49]. Altitude regulates the microclimate, temperature (critical for flowering), soil characteristics, and nutrient availability [8–11], while also limiting the proliferation of pests and diseases such as coffee rust [36]. Our results underscore the importance of optimizing land use according to its altitudinal suitability, a key practice for climate-smart agriculture (SDG 13) and the efficient use of resources (SDG 12). Furthermore, it is suggested that selecting varieties adapted to wider altitudinal ranges [12–15,40] could be a way to improve yields.

Furthermore, the model identifies integrated pest management (IPM) and cultural and biological controls as relevant agronomic practices for yield. These methods are crucial for mitigating direct damage to the fruit and preserving its quality [6]. Local evidence shows, for example, that the application of *B. bassiana* and the removal of residual berries significantly improve yields [34]. The adoption of IPM and biological control reduces dependence on synthetic chemical inputs, minimizing soil and water pollution, which aligns directly with SDG 3 (Good Health and Well-being) and SDG 6 (Clean Water and Sanitation) [33].

One finding that warrants analysis is that ecological management showed a negative correlation with yield in the current context of the Monzón Valley. This unexpected result underscores the need for future research that models the intervening variables of its adoption, such as the role of associations, agricultural extension, and government support policies [55]. Overcoming these barriers is essential for organic agriculture to become an engine of SDG 8 (Decent Work and Economic Growth), through access to specialized markets and premium prices, thus closing the circle of sustainability that this study helps to outline [33].

Although it may initially seem contradictory, the inverse relationship between organic coffee production and yield aligns with documented global evidence across multiple agricultural systems [56]. Studies by Valkila [57] and Lyngbaek et al. [58] demonstrate that organic yields are, on average, 22% lower than conventional yields. In the Monzón Valley, coffee farmers attribute this difference to insufficient fertilization and a high incidence of pests. However, the lower productivity does not negate the advantages of organic production, such as higher net income per unit area, differentiated prices [59], reduced exposure to agrochemicals, and preservation of biodiversity [60]. Consequently, the challenge lies in designing policies and strategies aimed at reducing the yield gap through specialized technical assistance, improved access to quality organic inputs, and the incorporation of shade systems with perennial species that do not interfere with coffee productivity.

The negative association between biological control and high yield contrasts with expectations. However, studies in the Peruvian Amazon region found that, although biological and cultural control methods achieved infestation reductions of up to 70%, no statistically significant differences were observed between treatments [61]. This suggests that the effectiveness of these practices depends critically on environmental conditions and pest pressure, and that their benefits may be realized in the long term rather than in the short term evaluated in this cross-sectional study.

4.2. Impact of Socioeconomic Factors on Yield

The main socioeconomic factors evaluated (Figures 3 and 4) were: technical assistance, farmer age, monthly monetary income, educational level, the price of coffee as an incentive, and access to financing. These factors not only determine productivity but also constitute pillars for sustainable development in coffee-growing communities, directly linking to

SDGs 1 (No Poverty), 2 (Zero Hunger), 4 (Quality Education), 8 (Decent Work), and 12 (Responsible Production) [33].

When applying the probit model to measure their impact, it was identified that monetary income and farmer experience are key indicators. Both showed a negative correlation with low and medium yield levels, but a positive correlation with high yield. This two-phase relationship emphasizes the importance of economic stability (SDG 1) and the accumulation of practical knowledge (SDG 4) as drivers of resilient agriculture [33].

The socioeconomic importance of coffee in Peru, where it is a pillar of exports and a source of livelihood for more than 223,000 families [1–3], gives these factors a critical dimension. In particular, the farmer's level of education and training emerges as a transformative element. This factor, regardless of income, has a positive effect on yields, especially when combined with ecological practices [29]. Education, enhanced by effective agricultural extension, empowers farmers to select adapted varieties [12–15], implement efficient farming systems [30], manage seeds technically [31], and prevent soil degradation and agricultural expansion into forests [32]. Thus, training stands as a crucial link between SDG 4, sustainable practices (SDG 12), and conservation (SDG 15) [33].

According to the probit model (Table 4), primary and secondary education levels were not statistically significant in explaining coffee crop yield. This finding contrasts with that reported by Afrianto et al. [29] and Wanzala et al. [30], who did identify formal education as a determining factor. This discrepancy suggests that, in the context of this valley, years of practical experience, a variable that did show robust statistical significance ($p < 0.01$), could be a more critical determinant of yield than formal education.

While accumulated experience allows for the refinement of management, harvesting, and post-harvest practices that contribute to sustainability [27], the probit model indicates that the availability of income and financing takes priority. Insufficient income and a lack of government support negatively impact yields [28,46]. In the region, access to credit is limited, and self-financing is the norm, a situation exacerbated by high interest rates [62–64]. Therefore, ensuring access to affordable financing is an urgent prerequisite (SDGs 1 and 8) for the widespread adoption of sustainable practices [33].

Finally, a notable contrast emerges when analyzing the age of the plantation. Unlike what has been reported in other regions, such as the Buru district in Indonesia, where aging without maintenance drastically reduces yields [65], in the Monzón Valley, plant age showed a positive effect. Average yields here (0.43–0.75 t/ha/year) are below the Peruvian national average (0.88 t/ha/year) [66], with this gap attributed to limitations in soil management, fertilization, and shade. However, high-yielding farmers achieve an average of 1.19 t/ha/year, surpassing regions such as Colombia (0.96 t/ha/year) [67] and approaching the yields of Brazil (1.57 t/ha/year) [68]. This disparity underscores the latent potential and the need to adopt integrated approaches that harmonize increased productivity (SDG 2) with sustainable land management (SDG 15), ensuring that intensification does not compromise resources for future generations [33].

4.3. Linking the Findings to the Sustainable Development Goals (SDGs)

Our results offer empirical evidence supporting the achievement of multiple SDGs in the context of coffee cultivation. Specifically:

- Regarding SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth), the study demonstrates that monthly income and farmer experience are key factors in achieving high yields ($p < 0.01$). This suggests that interventions aimed at improving productivity and technical training can directly translate into higher incomes and quality employment for farmers.

- For SDG 2 (Zero Hunger), identifying key factors such as seed management and farmer experience provides a roadmap for doubling the agricultural productivity of small-scale producers, a central objective of this SDG.
- Regarding SDG 12 (Responsible Consumption and Production), our findings on organic production, while showing a negative correlation with yield in the current context, underscore the critical need for supportive policies. Without technical assistance and access to adequate inputs, the transition to more sustainable systems may compromise productivity in the short term. This highlights the complexity of aligning production with the principles of responsible consumption.
- The results related to altitude (SDG 13, Climate Action) and variety diversity and biological control (SDG 15, Life on Land) provide valuable information for designing more climate-resilient and biodiversity-friendly farming systems. Promoting practices such as multi-variety cultivation and integrated pest management are strategies that can simultaneously contribute to productivity and ecosystem conservation.

4.4. Limitations of the Study: Environmental Factors Not Considered

We acknowledge that the manuscript did not incorporate key environmental variables such as precipitation, temperature, soil fertility [69,70], and fertilizer application, which, according to the specialized literature, are crucial for explaining coffee yield behavior [71,72]. Previous studies indicate that temperatures above 28 °C reduce yield, while the optimal range for maximizing it is between 23 and 27 °C [73]. Likewise, ambient temperature has a particular influence during the fruit formation stage, with significant losses starting at a maximum of 31.01 °C [74]. On the other hand, soil moisture, precipitation, and vapor pressure deficit are essential seasonal drivers for coffee production on a global scale [75].

In the Peruvian context, the work of Maita et al. [76] in the Peruvian Amazon demonstrates the influence of soil properties, crop age, and altitude on coffee yield. These authors indicate that organic matter and cation exchange capacity explain 32.41% of the variance, while available phosphorus (P) and potassium (K) contribute the remaining 17.88%. The same research maintains that soils with high K (>150 mg/kg) and P (>20 mg/kg) content are associated with yields exceeding 1.5 t/ha, highlighting the importance of soil fertility for achieving high yields [76].

Consequently, the exclusion of these variables from the modeling constitutes a limitation of the present research. However, this decision stems primarily from the lack of a meteorological station to collect the data necessary for retrospective studies such as ours. Secondly, because this is a cross-sectional design, these variables would have constant values, preventing adequate observation of their temporal influence. For future research, it is recommended that these variables be incorporated through direct measurements and the design of time series models to explain the dynamics of coffee yield.

5. Conclusions

Various agricultural management methods were identified in the coffee plantations of the Monzón Valley. Chemical and cultural control were predominant, followed by physical and, to a lesser extent, biological control. The implemented practices such as pruning, shade management, and crop rotation are applied at altitudes ranging from 700 to 1700 m above sea level, which influences yields and determines a varied distribution of plots. Most farmers prefer to cultivate the Catimor variety, although some opt for combinations and complementary crops to diversify their production. Producers receive agricultural extension services, especially in seed and fertilizer management, and benefit from support programs for transitioning from coca cultivation, in which 83 farmers participate. However, despite the influence of socioeconomic factors, varieties, practices, and location, the pre-

dominant farmer profile shows an average age of 46 years, limited monthly income, and restricted access to financing. This situation is reflected in the existence of three distinct yield levels: low, medium, and high.

Using probit models, it was determined that several variables influence coffee yields: agricultural practices, location, varieties, technical assistance services, educational level, and farmer experience. Analyzing the marginal effects of these variables allowed for an understanding of their relative impact on productivity. This study provides a detailed and up-to-date overview of agronomic practices and socioeconomic factors that influence coffee productivity in the Monzón Valley, highlighting relevant information on diversification, preferred varieties, available services, and financial constraints. It also employs statistical models to analyze the multivariable relationship with yields, offering crucial information for the formulation of policies and support programs in the region.

A significant limitation of this work lies in its cross-sectional design and the use of self-reported data, which may affect causal inference and the temporal generalizability of the findings. Future research could benefit from longitudinal designs and the incorporation of objective measurements to validate and expand upon these results.

In this context, the limited availability of external financing highlights the need for the Peruvian government to implement an expanded agricultural credit program. This policy could facilitate the transition of producers from low yields to significantly higher yields, alleviating one of the main constraints identified and thus enhancing the effect of the other production variables analyzed. A combined approach to agronomic and socioeconomic aspects emerges as key to improving coffee production and promoting sustainable development in the region.

Author Contributions: Conceptualization, A.R.R. and N.F.R.; methodology, A.R.R.; software, A.R.R.; validation, L.A.M.y.C. and B.A.H.B.; formal analysis, A.R.R.; investigation, A.R.R. and L.V.J.; resources, L.V.J. and J.E.H.V.; data curation, J.A.R.E.; writing—original draft preparation, A.R.R.; writing—review and editing, N.F.R.; visualization, A.R.R.; supervision, N.F.R. and L.A.M.y.C.; project administration, A.R.R.; funding acquisition, J.E.H.V. and J.A.R.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Informed consent for participation was obtained from all subjects involved in the study.

Data Availability Statement: The datasets generated and analyzed during this study are available at the following permanent web link: <https://github.com/AlexRengifo20/dryad-app/blob/main/Data.xlsx>. All correspondence should be addressed to Nelino Florida Rofner [N.F.R.], while requests for materials should be sent to Alex Rengifo Rojas [A.R.R.]. Accessed on 14 December 2025.

Conflicts of Interest: There are no conflicts of interest, financial or non-financial, on the part of the authors. All the authors have contributed equally to the development of this manuscript. The authors are aware of the submission to the journal. Similarly, the authors have not received any financial support from any institution other than the one indicated.

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