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The Phenology of *Coffea arabica* var. Esperanza L4A5 Under Different Agroforestry Associations and Fertilization Conditions in the Caribbean Region of Costa Rica

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Abstract: This study focused on the phenology of *Coffea arabica* var. Esperanza L4A5, an F1 interspecific hybrid obtained by crossing commercial varieties with wild genotypes from Ethiopia and Sudan. Most phenological studies on *C. arabica* have been conducted in traditional high-altitude regions, leaving a gap in the understanding of its behavior in non-traditional areas such as the Caribbean region of Costa Rica. To establish a baseline on the phenological behavior of the Esperanza L4A5 hybrid in this region, we conducted a four-year study examining the effects of different agroforestry associations: (1) *Albizia saman*; (2) *Hymenaea courbaril* and *Erythrina poeppigiana*; (3) *Anacardium excelsum* and *Erythrina poeppigiana*; and coffee plots under full sun. Additionally, the phenology of the coffee plants was evaluated under differentiated fertilizations (physical, chemical, and without fertilization), considering meteorological factors such as temperature, humidity, and rainfall. The observed variables included the development of floral nodes, pre-anthesis, anthesis, and fruiting stages. To analyze the relationships between environmental factors, tree cover, fertilization, and the phenological stages, we employed multiple linear regression (MLR), which revealed that both tree cover and physical and chemical fertilizations had significant effects on the presence of developed floral nodes and, consequently, on fruit production. Furthermore, the random forest (RF) model was applied to capture complex interactions between variables and to rank the importance of meteorological factors, tree cover, and fertilization practices. These analyses demonstrated that the Esperanza L4A5 hybrid exhibited viable phenological development under the atypical conditions of the Caribbean region of Costa Rica, suggesting its potential to adapt and thrive in non-traditional coffee-growing areas.

Keywords: *Coffea arabica* var. Esperanza L4A5; hybrid; agroforestry systems; differentiated fertilization; phenology; regression analyses; Caribbean region of Costa Rica

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1. Introduction

The cultivation of *Coffea arabica* is fundamental to the economies of many tropical and subtropical countries, representing a significant source of income and employment for millions of people [1]. In Costa Rica, coffee has played a key role in socio-economic and cultural development since the 19th century, being globally recognized for the quality of its beans and sustainable production practices [2]. The mountainous regions of the country, at altitudes above 600 m above sea level, have provided optimal conditions for the traditional cultivation of high-quality coffee. However, the coffee sector faces significant challenges due to climate change, which affect traditional cultivation areas through variations in temperature, precipitation patterns, and an increased incidence of pests and diseases, such as coffee leaf rust [3]. These changes have prompted the search for new cultivation areas and the development of varieties that are more resistant and adaptable to different environmental conditions. Another key aspect is that global coffee research is advancing toward sustainability, product innovation, and the use of advanced technologies, largely driven by the consumer demand for ethical practices and healthier products. Factors such as climate change are pushing the industry to develop more resilient coffee varieties and sustainable practices to mitigate environmental impacts, especially given the crop's sensitivity to extreme weather conditions and the significant effect these have on global coffee production [4,5].

Based on the above, the Esperanza L4A5 hybrid emerges as a promising alternative for the expansion of coffee cultivation in non-conventional areas, thanks to its ability to adapt to less favorable climatic conditions and its resistance to diseases [6]. This F1 hybrid, resulting from the cross between commercial varieties and wild genotypes from Ethiopia and Sudan [7], has demonstrated resistance to leaf rust and tolerance to nematodes, while maintaining excellent cup quality. The introduction of F1 hybrids in coffee farming has shown benefits in terms of productivity and resilience against environmental adversities [8].

Despite the potential of Esperanza L4A5, there is a lack of information about its phenological behavior in regions with atypical climatic characteristics, such as the lowland areas of the Costa Rican Caribbean. In these zones, factors like elevated temperatures, high humidity, and abundant rainfall can significantly influence its development [9]. The climatic variability of the Caribbean region is characterized by high relative humidity (85–90%), average annual temperatures of 25 °C, and rainfall ranging from 3000 to 4000 mm, modulated by its proximity to the Caribbean Sea, mountainous terrain (Central Valley), and global events like El Niño and La Niña. These conditions directly affect local agriculture. During El Niño periods, the region experiences drier conditions, while La Niña tends to intensify rainfall, disrupting crop growth cycles and phenological synchronization, increasing the susceptibility to fungal diseases. Additionally, although solar radiation is high, it is limited during rainy months by cloud cover, influencing photosynthesis and crop productivity, particularly in shaded systems. However, the implementation of agroforestry systems and appropriate management practices could favor its adaptation to and productivity in these new environments [10].

Considering the above, it is proposed that the phenological development of the *Coffea arabica* hybrid Esperanza L4A5 may be influenced by agroforestry associations and differentiated fertilization and that these factors, together with local meteorological conditions (temperature, humidity, and rainfall), will significantly impact the growth stages, flowering synchrony, and fruiting of coffee plants under the atypical climatic conditions of the Caribbean region of Costa Rica. Through an experimental design that incorporates diverse agroforestry arrangements and differentiated fertilizations, this study aims to establish a baseline of the phenological behavior of this hybrid in a non-conventional coffee-growing area. To analyze the complex interactions between the experimental factors and the phenological stages of Esperanza L4A5, multiple linear regression (MLR) will be employed to identify and quantify relationships with key variables, such as temperature, humidity, and precipitation [11]. Additionally, random forest (RF), a machine learning algorithm known for its robustness in handling large datasets and nonlinear relationships [12], will be applied to model complex interactions and rank the importance of each variable [13,14].

The findings of this study will not only contribute to understanding the adaptability of the Esperanza L4A5 hybrid under lowland environmental conditions but will also provide valuable information for decision making regarding the expansion and management of coffee cultivation in the Caribbean region of Costa Rica.

2. Materials and Methods

2.1. Location of the Agroforestry Trial

The research area, previously described by [15], is in the canton of Guácimo, Limón province, Costa Rica, on the grounds of the EARTH University Forestry Farm at an altitude of 43 m above sea level, at the coordinates 10°13′00.0′′ N, 83°35′27.0′′ W (Figure 1).

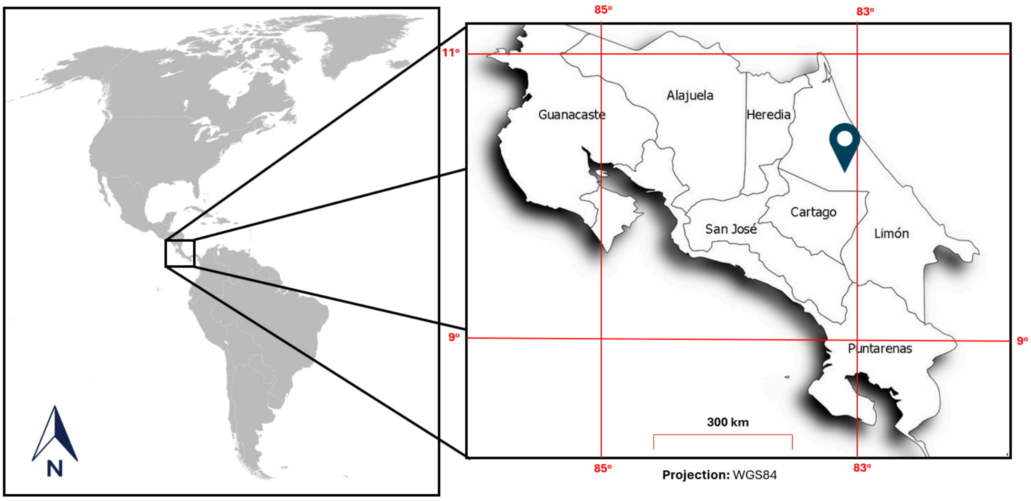

Figure 1. Location of agroforestry research area based on hybrids of *Coffea arabica* var. Esperanza L4A5, established in September 2019. The map base was used: https://paintmaps.com/blank-maps/52/samples.

2.2. Climate and Life Zone

The average temperature of the experimental area is 25 °C, fluctuating between 20 °C and 33 °C over the course of 24 h. The annual precipitation is 3701.99 mm, with an average relative humidity of 86% and a maximum solar radiation of 0.85 MJ/m^2-day [16]. According to historical meteorological data and the Holdridge life zone classification system, the project is situated in the heart of the Tropical Very Humid Forest (bmh-T) area of the Caribbean region of Costa Rica [17].

2.3. Soils

In the Caribe region, the soils are classified as Inceptisols, particularly within the Udepts suborder. These soils develop from the weathering of alluvial and colluvial sediments during prolonged periods without new sediment deposits. Inceptisols in this area often exhibit acidic pH levels, may contain amorphous clays, have high organic matter contents, and show clear differentiations in the subsurface horizons due to changes in the structure, color, or clay content [18]. The Inceptisols found in the Parismina River valley are noted for their significant agricultural potential in Costa Rica [19]. The terrain in the research area has slopes below 2%.

2.4. Structure of the Experimental Design

The experiment considered two fundamental aspects: (1) the spatial arrangement of timber and service trees associated with the coffee hybrids and (2) fertilizations involving a minimal nutrient load in two differentiated forms—physical and chemical fertilization. Additionally, unfertilized sectors were included, serving as experimental controls. Based on these considerations, the arrangement of the components was organized according to a split-plot design with a completely randomized block structure.

2.4.1. Agroforestry Associations

For the tree–coffee interactions (agroforestry associations), the blocks included the following: *Albizia saman*, associated with coffee (C); *Hymenaea courbaril* and *Erythrina poeppigiana* with coffee (G + P); *Anacardium excelsum* and *Erythrina poeppigiana* with coffee (E + P); and Full sun 1 and Full sun 2, serving as experimental controls without tree associations.

In this study, the choice of tree species, like *A. saman*, *H. courbaril*, *A. excelsum*, and *E. poeppigiana,* was intentional, aimed at assessing their potential to boost coffee growth and productivity within agroforestry systems. These trees were selected not only for their native status and economic value in the region but also for their capacity to provide shade, enrich soil fertility, and foster a supportive microclimate for coffee hybrids [15].

2.4.2. Differentiated Fertilizations

"Formulation 1, termed physical fertilization (F1), consisted of the application of potassium chloride (KCl), which is the most common source of potassium in commercially available fertilizers in Costa Rica. This formulation, which includes chlorine as an accompanying ion, was applied at a dose of 13 g per plant. Additionally, MKP (0-52-34) was applied at 5 g per plant as the main source of phosphorus in the form of P_2O_5, providing 34% potassium (KCl). Finally, ammonium nitrate (33.5-0-0), a source of nitrogen NH_4NO_3, was used to meet the nitrogen needs of the plant, applied at a dose of 20 g per plant. The total dose per plant was calculated at 30.74 g/plant. Formulation 2, termed chemical (F2), comprised NPK (9-23-30) as the main source of phosphorus (P_2O_5) and potassium (KCl), applied at a dose of 57 g, copper sulfate at 0.12 g, and zinc sulfate at 0.29 g, all per plant. Urea (46-0-0) was used as a nitrogen source, applied at 42 g per plant. The total mixture was 79.53 g/plant. An area of 0.3 m^2 per plant was considered for the application of the nutritional amendment (Lime). This allowed for a reduction in the fertilization area and provided localized application, converting the need per hectare of 10.000 m^2 into a need per area/plant of 0.3 m^2 [15,20]". Soil and vegetative sampling were conducted annually to adjust the formulations accordingly.

Regarding fertilization treatments, F1 denoted physical fertilization, F2 represented chemical fertilization, and "Lime" indicated sectors that received only liming, which acted as control groups (Figure 2).

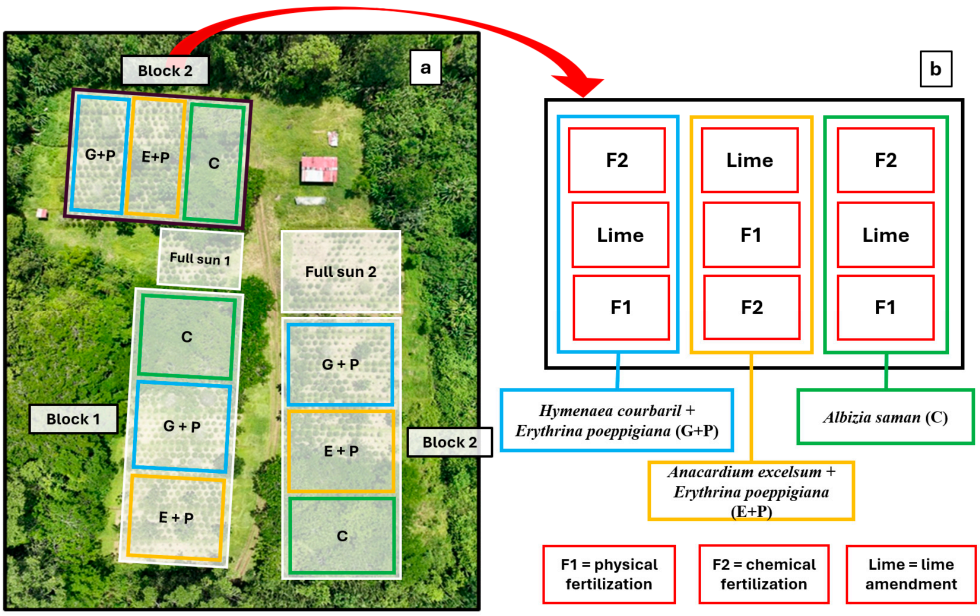

Figure 2. Spatial arrangement of the agroforestry trial: (**a**) The location of the agroforestry associations and full-sun sectors and (**b**) the spatial location of the plots under differentiated fertilization and with amendment only.

2.5. Data Logging

2.5.1. Characterization of the Aerial Vegetative Organs

Observations and data collection were conducted over a period of four years, considering all the coffee plants in the trial (1936 plants). Observations were conducted monthly to identify significant changes, which were promptly incorporated into the data. The analysis focused on the agroforestry associations, the coffee plants without interactions with trees (full-sun coffee plants), and the differentiated fertilizations.

During the first years of the study (2019–2021), we observed the developmental stages exhibited by the coffee plants. Initially, the records focused on the early phases of vegetative growth, their adaptability, and their development. As time progressed, crucial events in their reproductive development were noted, including early flowerings and the first cherry harvest, which took place at the end of 2020. The process was closely monitored, paying special attention to the morphology of the axillary and terminal buds, as well as the development of the floral nodes where the flowers form.

The nodes are of vital importance, as they determine the sites of future cherry production after successful flowering. A detailed characterization of the aerial vegetative organs was carried out, recording the development of the nodes, as well as the pre-anthesis and anthesis phases for each coffee plant (Figure 3). Additionally, the presence of ripe coffee fruits was documented to provide a comprehensive overview of the phenological stages (Figure 3). This detailed monitoring allowed for a deep understanding of the phenological processes of the coffee plant.

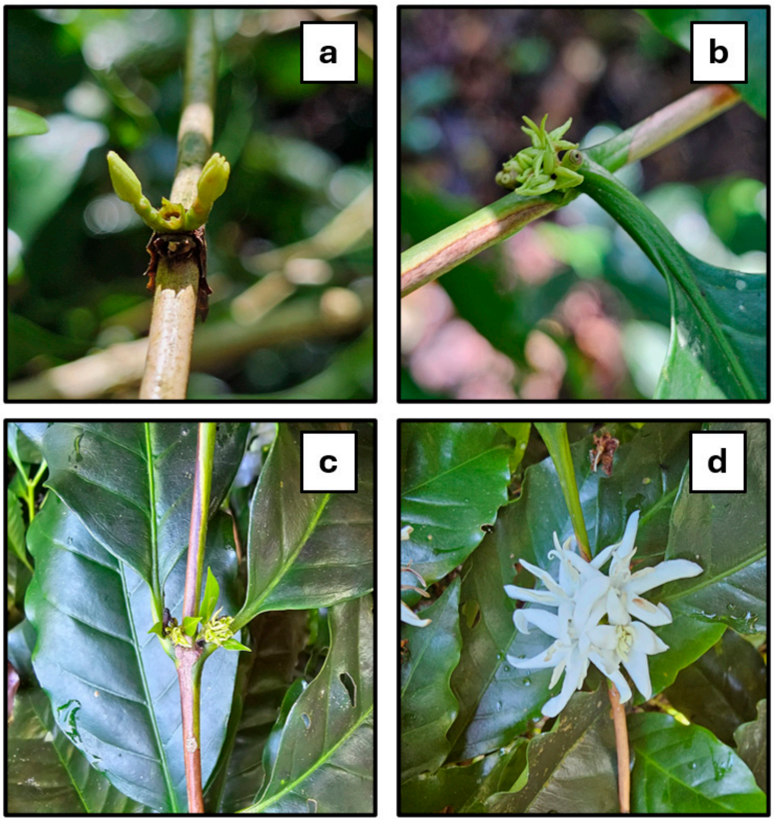

Figure 3. Characterization of the aerial vegetative organs: (**a**,**b**) floral nodes development, (**c**) pre-anthesis, and (**d**) floral anthesis.

2.5.2. Meteorological Variables

We considered meteorological variables such as temperature, humidity, and rainfall, as these significantly influence the phenology of coffee plants. Temperature affects the rate of physiological processes, impacting flowering initiation and fruit maturation, while humidity and rainfall play crucial roles in flower induction, synchronization, and fruit development [21,22]. Monitoring these variables was essential to understand their effects on the main development stages of the Esperanza L4A5 hybrid under different agroforestry arrangements and fertilization treatments.

2.6. Data Analysis

A multiple linear regression model was employed to examine the phenological development of the Esperanza L4A5 hybrid. This statistical approach allowed us to evaluate the relationships between multiple independent variables—specifically, meteorological factors such as temperature, humidity, and rainfall—and dependent variables representing different phenological stages, including the development of floral nodes, pre-anthesis, anthesis, and fruiting. Multiple regression was particularly suitable for phenological analyses where environmental variables interacted in complex ways to influence plant development [23,24]. The multiple linear regression analysis was performed using Equation (1):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots \beta_n X_n + \varepsilon \quad (1)$$

where Y is the dependent variable (different phenological stages, including the development of floral nodes, pre-anthesis, anthesis, and fruiting); β_0 is the intercept of the model (the value of Y when all independent variables are zero); and $\beta_1, \beta_2, \beta_3, \ldots, \beta_n$ are the regression coefficients corresponding to the independent variables $X_1, X_2, X_3, \ldots, X_n$ (temperature, humidity, and rainfall). These coefficients represent the expected change in Y, given a one-unit change in the corresponding independent variable, while holding the other independent variables constant; and ε is the error term or residual of the model (the difference between the observed values and the values predicted by the model).

By incorporating meteorological variables into the model, we quantified their individual and combined effects on the timing and progression of the phenological phases of the coffee hybrid under different agroforestry arrangements and fertilization treatments. This approach allowed us to identify which environmental factors had the most significant impact on phenological events, thereby providing a deeper understanding of the hybrid's adaptability to the atypical climatic conditions of the Costa Rican Caribbean region.

Due to the potential existence of nonlinear and complex relationships among the variables, the random forest (RF) algorithm was also employed as a complement. Random forest is an ensemble method that builds multiple decision trees from different subsets of the data, with the aim of improving the predictive capacity and handling nonlinear relationships [12]. The RF model averages the individual predictions ($\hat{y}$b) from each of the B trees to generate a final prediction ($\hat{y}$), according to Equation (2):

$$\hat{y} = \frac{1}{B}\sum_{b=1}^{B} \hat{y}b \quad (2)$$

This approach reduces model variance and is robust against outliers and noisy data [14]. In the context of this study, RF allowed for capturing complex interactions between the climatic and experimental variables, identifying the relative importance of each at different phenological stages.

The random forest model complements multiple linear regression by addressing nonlinear and complex relationships among variables. While multiple linear regression helps identify the linear effects of environmental factors on the phenological stages of coffee, random forest, as a machine learning technique, builds multiple decision trees that capture nonlinear interaction patterns, which are essential in ecological systems. This approach allows for greater predictive accuracy by accounting for complex interactions within the environmental conditions of Costa Rica's Caribbean region.

3. Results

3.1. Phenological Characterization of Esperanza L4A5

3.1.1. Adaptation and First Phenological Year (2019–2021)

During the first year of observation, both the biomass growth and the phenological development of the hybrid were noted. The coffee plants were established in the nursery in May 2019, where they underwent four months of adaptation. This period was crucial to ensure that the plants could survive and thrive in their natural environment once transplanted to the field. In the nursery, the final establishment conditions were carefully replicated, providing the coffee plants with an optimal environment for their initial development (Figure 4a).

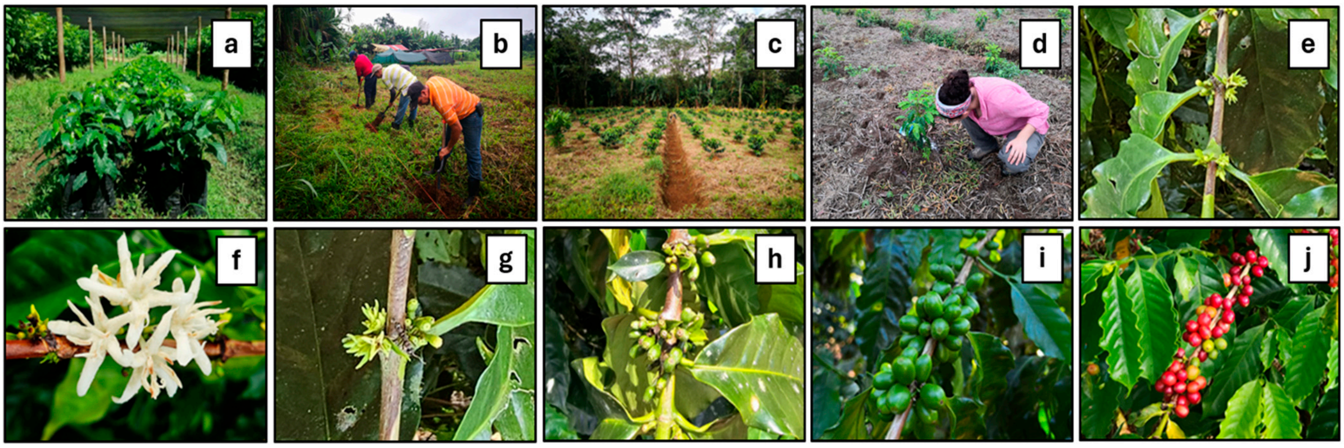

Figure 4. The phenological characterization of the first year: (**a**) the adaptability stage of the plant material in the nursery; (**b**) the establishment of the coffee plants in the trial area; (**c**) the maintenance of the trial area, focused on weed control; (**d**) the first fertilization of the coffee plants, considering differentiated fertilizations and experimental control areas with only liming; (**e**) the full development of floral buds; (**f**) flowering; (**g**) the start of the fruit-filling process; (**h**) the general development of the fruits; (**i**) the full development of the fruit; and (**j**) fruit maturity, initiating the harvesting process.

In September 2019, the coffee plants were transplanted to the field (Figure 4b). From that moment, plant care and general area maintenance began. Regular mechanical weed-control activities were implemented to ensure that the plants had a competition-free environment (Figure 4c). Simultaneously, the first fertilization application was carried out, following the experimental design established for the different sub-treatments (Figure 4d). This careful and planned approach ensured that each plant received the necessary nutrients for healthy growth, adapting to the specific conditions of the experiment. The combination of these efforts created an optimal environment to observe and document the development of the coffee plants from their earliest stages.

In January 2020, the observations were focused on floral development. It is in January that flowering induction begins in coffee plants, extending until the end of February, when the full development of floral buds is noted in most plants (Figure 4e). At this point, the characteristic "velón" shape can be observed, with closed, whitish-green petals. The flowering of the coffee plants occurred in two distinct periods (significant blooms in the number of plants at this stage). The first flowering happened in mid-March, when the plants began to exhibit open flowers. The second flowering took place in early May (Figure 4f). During the first year, uniform flowering was not observed, as is typical in the traditional coffee-growing areas of Costa Rica. This may be due to the conditions of the study site, the initial adaptation of the plants to their new environment, and climatic variability [25].

After the fall of the flowers from the first flowering in mid-March, the fruit-filling process began. The fruit sizes varied, considering the two recorded flowerings: the first in mid-March and the second in early May (Figure 4g). In July, the general initial development of the fruits was observed, with clear size differentiation (Figure 4h). This variation is due to the different flowering stages that were previously described. Until the end of August, the fruits continued their development, and some ripe cherries began to appear, albeit in limited but notable quantities. During this period, sporadic flowerings were also recorded, adding another layer of complexity to the phenological cycle of the coffee plant.

Full fruit development was observed from mid-August to September (Figure 4i). During this period, the fruit sizes began to become more uniform, although a significant number of small cherries and others that were still in the filling process were evident. This uneven development is typical in the early stages of coffee plants that are adapting to their environment. Additionally, sporadic flowerings were observed again, though in smaller quantities compared to those in August.

Finally, between October and November 2020, most fruits reached maturity (Figure 4j). At the beginning of October, the fruits began to show a red color, and by early November, many had acquired an intense crimson hue. In November, the first selective harvests were conducted, collecting only the fully ripe fruits. This harvesting process continued until the end of December, marking the end of the harvest season. Notably, at the end of December 2020, simultaneous with the harvests, floral developments were observed. In the first phenological year (2021), flowering induction was observed from December of the previous year and extended until the end of February. During this period, the coffee plants began to show the first signs of floral bud formation, which developed fully between April and mid-July—a phase that includes both pre-anthesis and anthesis. In July, the first indications of fruit filling were noted, and by October, full and homogeneous development was observed. The fruits reached maturity at the end of October, and selective harvests were carried out from that moment until the first weeks of January of the following year.

3.1.2. Second and Third Phenological Years (2022–2023)

In the second phenological year (2022), flowering induction in the coffee plants began in mid-January and extended until early March. Compared to the induction of flowering in the first phenological year (2021), a delay of approximately 11 days was noted. Nonetheless, greater uniformity was observed in plants with floral buds and the characteristic "velón", with closed, whitish-green petals. Flowering was slightly more abundant compared to the first year. A significant increase was noted in the number of coffee plants with open flowers, surpassing the synchrony of the first year. A significant increase was noted in the number of coffee plants with open flowers, with synchronization in approximately 43% of the trial plants, surpassing the synchrony of the first year.

In both the second and third physiological years, the effects of the 11-day delay in flowering induction continued to be evident. Additionally, a second wave of flowering was recorded, which extended until early July. Fruit filling began in August and continued until the end of October. During this time, fruits were also noted in the full development stage, and in other cases, they were ready to be harvested, allowing for the initiation of selective harvests. This process continued until early January 2023, when the harvests concluded.

In the third phenological year, the annual trend of the pattern characterized in previous years was observed, which, despite presenting variations in days, remained consistent in terms of stages. The general timeline of the phenological years explains how the stages unfold.

3.2. Quantitative Analysis of the Phenology of the Esperanza L4A5

The Esperanza L4A5 hybrid exhibited growing and stable development over the years. In 2020, only 23.09% of the coffee plants showed developing nodes. Regarding pre-anthesis and anthesis, they recorded 7.8% and 3.56%, respectively. In terms of fruiting, 10.33% of the coffee plants had ripe cherries ready for harvest. By 2023, 55.95% of the coffee plants simultaneously displayed developing nodes, with pre-anthesis and anthesis recorded at 48.55% and 34.81%, respectively. Additionally, 44.02% of the coffee plants had ripe cherries ready for harvest (Table 1). The results presented below are found in Table 1.

Table 1. Quantification of coffee plants by phenological stage, from 2020 to 2023.

Year	Plants with Developing Nodes	% of Plants with Developing Nodes	Plants with Pre-Anthesis	% of Plants with Pre-Anthesis	Plants with Anthesis	% of Plants with Anthesis	Plants with Ripe Fruits	% of Plants with Ripe Fruits
2020	447	23.09%	151	7.80%	69	3.56%	200	10.33%
2021	820	42.35%	1106	57.12%	481	24.85%	745	38.48%
2022	1035	53.47%	851	43.96%	841	43.44%	751	38.79%
2023	1083	55.95%	940	48.55%	674	34.81%	852	44.02%
Total number of coffee trees: 1936								

3.2.1. Floral Nodes Development

Over the four years, the number and percentage of coffee plants with floral nodes developing nodes showed a steady upward trend. In 2020, 447 coffee plants (23.09%) had developing nodes. This number increased to 820 plants (42.35%) in 2021, 1035 plants (53.47%) in 2022, and reached 1083 plants (55.95%) in 2023.

The increase in the number of developing nodes indicated a greater vegetative capacity and increasing reproductive potential, which is attributed to the maturity of the plant.

3.2.2. Pre-Anthesis

The pre-anthesis stage showed significant changes throughout the study. In 2020, only 151 coffee plants (7.80%) were in pre-anthesis. In 2021, this number notably increased to 1106 plants (57.12%), reflecting a substantial improvement in floral development. However, in 2022, there was a decrease to 851 plants (43.96%), followed by a slight increase in 2023 to 940 plants (48.55%).

3.2.3. Anthesis

The anthesis stage, characterized by the full opening of flowers, showed an upward trend until 2022, followed by a decrease in 2023. In 2020, only 69 coffee plants (3.56%) reached anthesis. This number rose to 481 plants (24.85%) in 2021 and to 841 plants (43.44%) in 2022. However, in 2023, a reduction to 674 plants (34.81%) was observed.

3.2.4. Ripe Fruits

The production of ripe fruits is a key indicator of crop productivity. In 2020, 200 coffee plants (10.33%) produced ripe fruits. This number significantly increased to 745 plants (38.48%) in 2021, remained stable in 2022 with 751 plants (38.79%), and rose to 852 plants (44.02%) in 2023.

3.3. Phenology of Esperanza L4A5 Considering Meteorological Factors

3.3.1. Temperature

The average monthly temperature varied notably between the years (Figure 5a). In December 2020, the lowest temperature was recorded, which remained similar until January 2021. This behavior is consistent with the typical seasonal variations of the Costa Rican Caribbean region, where late November, December, January, and even part of February are usually the coolest months of the year. The temperatures recorded during these months over the four years of the study have a direct relationship with the development of floral buds. Previous studies have demonstrated that lower temperatures can delay flowering, affecting its synchronization and quality, which explains the differences in the phenological timings compared to high-altitude areas [26–28]. Starting in March, temperatures gradually increase until reaching a peak in June–July, when the flowering period concludes and fruit filling begins. In September, temperatures decrease in magnitude, consolidating fruit filling and leading to the maturation of cherries for subsequent harvest. Generally, temperatures rise steadily from January, peaking in May, followed by a standardized decrease until October. From then on, temperatures decline towards the end of the year (November and December).

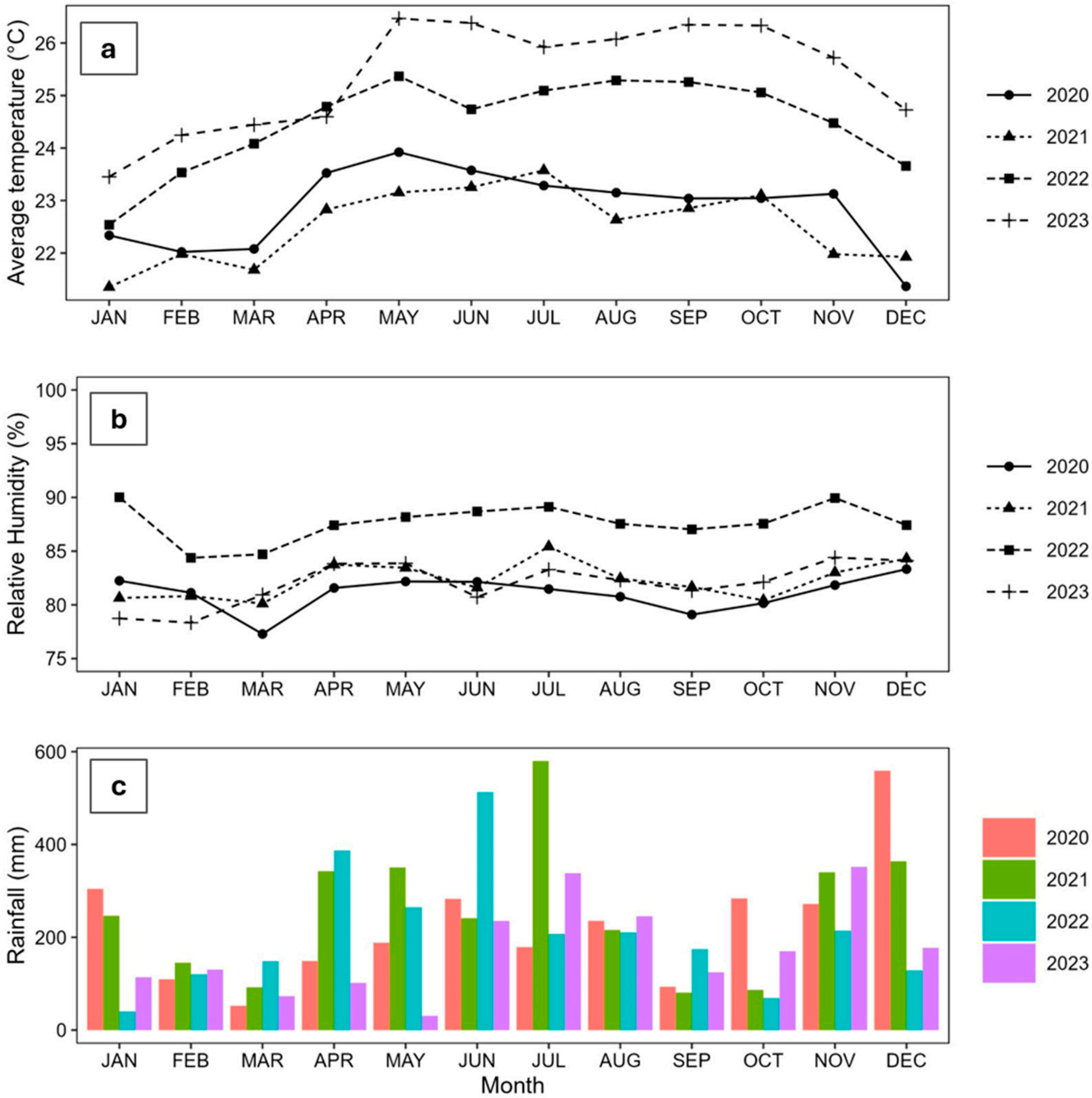

Figure 5. Monthly variations of meteorological variables (2020–2023): (**a**) average temperature (°C); (**b**) relative humidity (%); and (**c**) accumulated precipitation (mm).

During the warmer months (May to October), it was observed that temperatures favor fruit filling, promoting the accumulation of sugars and other beneficial compounds. On the other hand, excessively high temperatures can cause thermal stress, negatively impacting yield. The observations in the trial have been widely documented in studies by [26,29].

3.3.2. Relative Humidity

The relative humidity remained comparatively stable over the years, with some variations (Figure 5b). The years 2020, 2021, and 2023 recorded lower and similar levels of humidity throughout the months compared to 2022, which showed the highest levels of relative humidity in several months, particularly in January and November. Relative humidity tends to increase during the months with higher precipitation (June to October) and decrease in the drier months (January to March). Relative humidity plays an important role in vegetative growth. Standardized humidity, dependent on rainfall, helps maintain cell turgor and favors photosynthesis. In the Caribbean region, the months with high humidity coincide with the rainy season, providing ideal conditions for the development of coffee plants. However, high relative humidity can also increase the susceptibility to fungal diseases such as coffee rust (*Hemileia vastatrix*) [30].

3.3.3. Rainfall

During the data collection years, the following annual precipitations were recorded: 2709.5 mm in 2020, 3054.15 mm in 2021, 2410.9 mm in 2022, and 2089.34 mm in 2023. These figures reflect the interannual variability of rainfall in the region, with a notable decrease in total precipitation in 2023 compared to previous years. This reduction in precipitation may have significantly influenced the phenological stages of the coffee, affecting everything from flowering to fruit filling and maturation. Variability in rainfall amounts not only affects the synchronization of these processes but can also impact productivity [31–34].

Rainfall occurred in greater volumes between the months of April and July, coinciding with the region's typical rainy season. However, over the four-year period, there were considerable variations between years in monthly magnitudes (Figure 5c). The year 2022 was the wettest, with the highest precipitation peaks, especially in July and September. In all of the years and on a monthly level, the periods with the least rainfall occurred between September–October and February–March.

Rainfall peaks are closely related to the flowering of coffee plants. When significant rainfall events occur, plants that have been experiencing a period of water stress reabsorb water, which induces flowering, a phenomenon known as rain-induced flowering. Physiologically, it is known that coffee plants in humid tropical habitats undergo this process. Active rehydration triggers a series of responses in the plants, culminating in flowering, thereby ensuring reproduction under favorable conditions [32–34]. Studies highlight how rainfall synchronizes coffee phenological cycles, providing an adaptive advantage in environments where water conditions can vary significantly [31]. In the context of the project, and considering the existence of periods with low precipitation, the different stages of floral development in the coffee plants can be observed throughout the year. The observations indicate that even during periods of scarce rainfall, coffee plants can experience sporadic flowering, which underscores the resilience and adaptability of these plants to climatic fluctuations [26,29].

3.4. Phenological Phases of C. arabica var Esperanza L4A5

During the observed phenological years, the magnitudes of temperature, precipitation, and relative humidity directly influence key developmental stages of the coffee plant: floral node development, flowering, and fruit maturation. Floral node development typically occurs when temperatures range between 22 °C and 24 °C, with high relative humidity levels of 80–90% and moderate rainfall. These conditions are consistent with observations in the Costa Rican Caribbean region, where lower temperatures during November to February influence floral bud formation and can delay flowering if temperatures are too low. The flowering phases (pre-anthesis and anthesis) are triggered after a significant increase in precipitation, reaching between 400 and 600 mm, which coincides with temperatures above 24 °C (daily averages) and relative humidity levels exceeding 80%. This combination of rain-induced flowering is well documented and ensures the transition into the reproductive phase, as the rehydration of coffee plants after water stress induces flowering.

Finally, fruit ripening is associated with higher temperatures, typically between 24 °C and 26 °C, coupled with reduced rainfall levels below 200 mm and relative humidity ranging from 70–80%. These warmer and drier conditions, particularly during May to October, favor sugar accumulation and fruit ripening while avoiding the risk of fungal diseases that can arise from excessive humidity. However, precipitation peaks in November and December may negatively affect the quality of mature cherries if they occur during harvest, which aligns with concerns about their increased susceptibility to stress factors under fluctuating rainfall conditions (Figure 6).

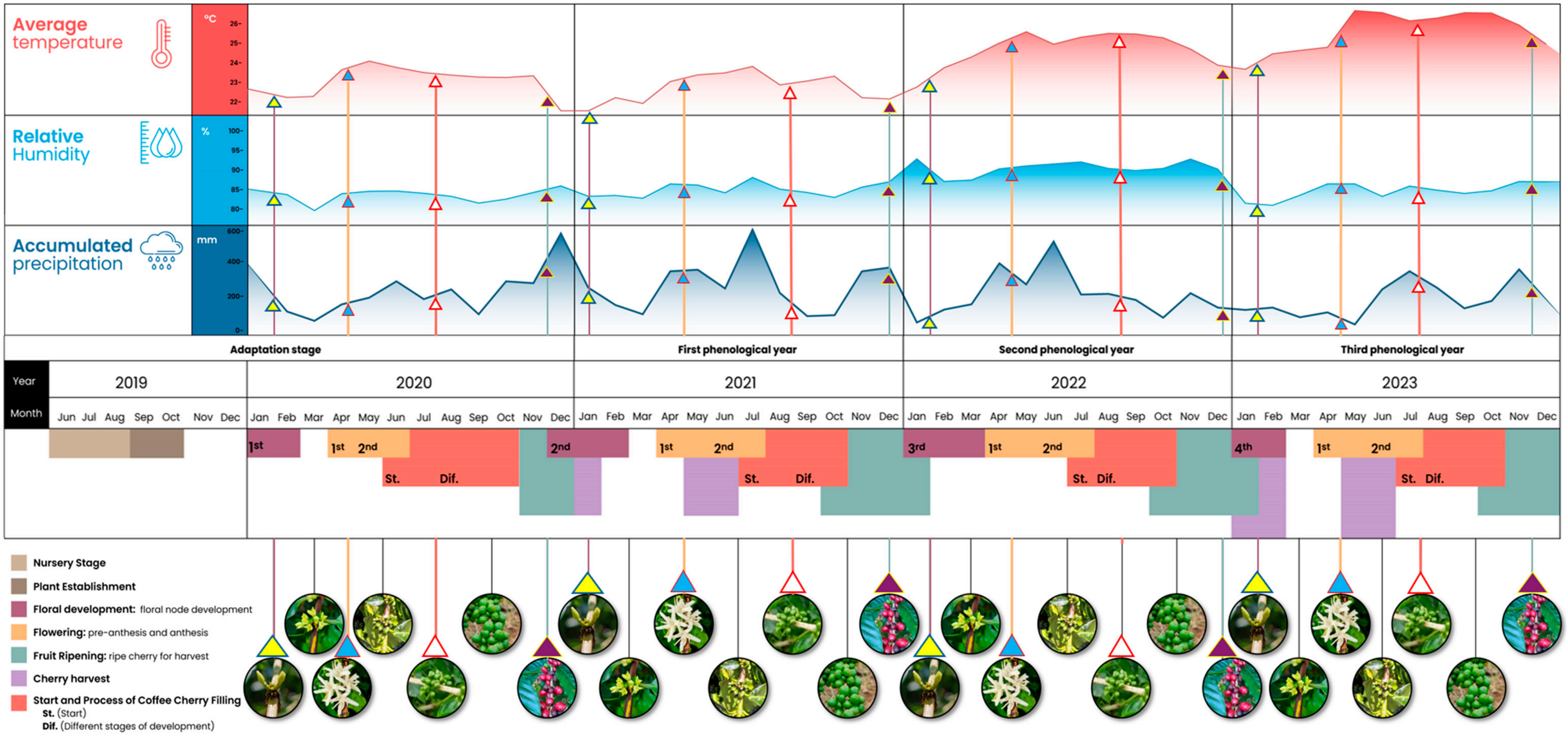

Figure 6. Phenological phases of Esperanza L4A5, established in the Caribbean region of Costa Rica.

3.5. Analysis of Phenological Stages: Effects of Agroforestry Associations, Differentiated Fertilizations, and Meteorological Variables (Average Temperature, Relative Humidity, and Rainfall)

3.5.1. Presence of Floral Nodes

The analysis of the multiple linear regression model revealed that several variables had significant effects on the presence of developing floral nodes. Temperature has a positive and highly significant effect ($p < 0.001$), with an increase in temperature associated with an average increase of 93.54 coffee plants with floral nodes, suggesting that warmer temperatures favor node development. Likewise, humidity also had a positive and significant effect ($p < 0.001$), with an average increase of 27.98 coffee plants with nodes for each additional unit of humidity. On the other hand, precipitation had a smaller but significant effect ($p < 0.05$), indicating an increase of 2.45 coffee plants with nodes for each unit increase in accumulated precipitation.

Among agroforestry associations, the only one showing a significant effect is Full sun 2, which had a negative effect ($p < 0.05$), suggesting a decrease in the number of nodes compared to other cover types. In terms of fertilization, coffee plants that did not receive fertilization (Lime) showed a considerable and highly significant negative effect ($p < 0.001$), reducing the number of coffee plants with nodes by an average of 17.37.

The interaction between temperature and humidity had a significant negative effect ($p < 0.001$), as did the interaction between temperature and precipitation ($p < 0.05$). This suggests that while high temperatures or humidity alone may favor node development, their combination can have adverse effects. The model explains approximately 56.8% of the variability in the presence of nodes, with an adjusted R^2 of 0.568, and the overall model is highly significant ($p < 0.001$), indicating that the selected variables are important for understanding the presence and number of floral nodes in coffee plants (Appendix A, Table A1).

The random forest (RF) analysis found that fertilization was the most influential variable, with a 25.88% increase in the mean squared error (%IncMSE) and a contribution to node purity (IncNodePurity) of 10,972.02. Humidity, precipitation, and temperature, along with their interactions, also stand out as important factors in node development. Agroforestry coverage, though less relevant, still had a considerable effect. The RF model, with an $R^2 = 0.777$, explains 77.7% of the variability in the data, outperforming the linear regression model and better capturing the complex relationships between climatic and management variables (Appendix A, Table A2).

3.5.2. Presence of Pre-Anthesis

The analysis of the multiple linear regression model showed that several variables had significant effects on the presence of pre-anthesis in the coffee plants. Precipitation had a positive and significant effect ($p < 0.01$), with an increase of 1.38 coffee plants with pre-anthesis for each additional unit of rainfall, suggesting that rainfall favors the development of this phenological phase. In contrast, the absence of shade (Full sun 2) had a significant negative effect ($p < 0.01$), indicating a negative impact on the presence of pre-anthesis in coffee plants.

The absence of fertilization (Lime) showed a highly significant negative effect ($p < 0.001$), reducing the number of coffee plants with pre-anthesis by an average of 19.02, suggesting that fertilization is crucial. The interaction between humidity and precipitation also showed a significant negative effect ($p < 0.01$), indicating that while these variables separately may favor the development of pre-anthesis, their combination appears to have a contrary effect. The model explains approximately 54.11% of the variability in the presence of pre-anthesis, with an adjusted R^2 of 0.4896, and the overall model is highly significant ($p < 0.001$) (Appendix A, Table A3).

The random forest (RF) model analysis showed that fertilization was the most influential factor, with a 24.04% increase in the mean squared error (%IncMSE) and a significant contribution to node purity of 13,043.14, indicating that fertilization has a predominant impact on pre-anthesis development. Among the climatic variables, humidity had the greatest impact, with an 8.73% increase in the mean squared error and a contribution to node purity of 3199.95, suggesting that high humidity levels are important for this phenological stage. Precipitation and temperature were also relevant, though with less impact, while interactions between these variables, such as humidity and precipitation, had moderate effects. Additionally, agroforestry associations played an important role, with a 2.63% increase in the mean squared error and a high contribution to node purity (4334.41), indicating that the type of coverage affects pre-anthesis development. The R^2 = 0.822 value indicates that the random forest model explains approximately 82.23% of the variability in the data (Appendix A, Table A4).

3.5.3. Presence of Anthesis

The coffee plants without coverage (Full sun 2) and without fertilization (Lime) ($p < 0.001$) were associated with a substantial decrease in the flower count, reducing the number of flowers by an average of 12.51 and 20.95, respectively. In contrast, the interaction between humidity and rainfall had a significant positive effect ($p = 0.0156$), slightly increasing flower production by 0.01 flowers for each unit increase in the combined humidity conditions. Additionally, the interaction between temperature and rainfall approached significance ($p \approx 0.096$), suggesting a possible slight negative impact on flower count. The individual effects of temperature, humidity, rainfall, and agroforestry coverages were not statistically significant. The model explained approximately 70.68% of the variability in the flower count (adjusted R^2 = 0.7068) and was highly significant overall ($p < 2.2 \times 10^{-16}$) (Appendix A, Table A5).

The analysis of the random forest (RF) model revealed that fertilization is the most influential factor in the presence of anthesis in coffee plants, with an 18.87% increase in the mean squared error (%IncMSE) and a significant contribution to node purity of 8353.87. This indicates that fertilization plays a crucial role in this phenological phase.

Among the climatic variables, humidity stands out as the most important, with a 4.85% increase in the mean squared error and a contribution to node purity of 1557.58, suggesting that adequate humidity levels are essential for the development of anthesis. Temperature and precipitation also have an impact, although to a lesser extent compared to fertilization and humidity. The interactions between variables, especially temperature and humidity (8.62% increase in the mean squared error and high node purity of 3568.44), show that these combinations also significantly influence the presence of anthesis.

Additionally, agroforestry associations play an important role, with an 8.19% increase in the mean squared error and a notable contribution to node purity (4001.25), indicating that the type of coverage influences this developmental phase. The model achieved an R^2 = 0.816, indicating that random forest explains approximately 81.63% of the variability in the data (Appendix A, Table A6).

3.5.4. Presence of Ripe Fruits

According to the analysis of the multiple linear regression model, temperature has a positive and significant effect ($p < 0.01$), with an increase in temperature associated with an increase of 74.39 ripe fruits for each additional unit of temperature. Similarly, humidity also presents a positive and significant effect ($p < 0.01$), suggesting that an increase in humidity favors the maturation of fruits, with an average increase of 25.04 ripe fruits for each additional unit of humidity.

The interaction between temperature and rainfall has a significantly positive effect ($p < 0.001$), indicating that these variables in combination promote fruit maturation. On the other hand, the interaction between humidity and rainfall shows a significantly negative effect ($p < 0.01$), suggesting that although these variables may be beneficial individually, their combination could have an adverse effect.

Regarding agroforestry coverages, full-sun coffee plants (Full sun 2) have a highly significant negative effect ($p < 0.001$), decreasing the number of ripe fruits by an average of

13.48. This indicates that coffee cultivation without agroforestry association may not be favorable for fruit maturation compared to coffee plants under coverages. Likewise, the absence of fertilization (Lime) shows a very significant negative effect ($p < 0.001$), with an average reduction of 16.84 ripe fruits, underscoring the importance of fertilization.

The model explains approximately 68.75% of the variability in the presence of ripe fruits, with an adjusted R^2 of 0.6524, and is highly significant overall ($p < 0.001$). This indicates that climatic variables, along with coverage and fertilization, are important determinants in the fruit maturation process of coffee plants (Appendix A, Table A7).

The analysis of the random forest (RF) model shows that fertilization was the most influential variable in the presence of ripe fruits in the coffee plants, with a 24.96% increase in the mean squared error (%IncMSE) and a significant contribution to node purity of 7113.79. This indicates that fertilization is the key factor in promoting fruit maturation.

Agroforestry coverages also had a relevant impact, with a 9.95% increase in the mean squared error and an important contribution to node purity (3996.62), suggesting that the type of coverage significantly affects the number of ripe fruits.

Among the climatic variables, precipitation had a considerable effect, with a 4.76% increase in the mean squared error and an increase in node purity of 901.05, indicating that rainfall plays a significant role in the maturation process. Humidity and the interaction between humidity and precipitation also had notable effects, contributing moderately to the model. The R^2 value of 0.697 indicates that the random forest model explains approximately 69.74% of the variability in the data (Appendix A, Table A8).

4. Discussion

The phenological characterization and quantitative analyses of the Esperanza L4A5 hybrid during the four-year study period (2019–2023) provide unprecedented and detailed information on the development stages and the factors influencing both the vegetative growth and the reproductive success of coffee plants in the Costa Rican Caribbean context. The integration of multiple linear regression and random forest (RF) models elucidated the relative importance of the experiment, based on climatic variables and the phenological expression of the Esperanza L4A5 hybrid.

4.1. Adaptation and Early Phenological Development

During the initial phenological year (2019–2021), the Esperanza L4A5 hybrid demonstrated robust adaptability and vegetative growth following its transplantation from the nursery to the field. Replicating the nursery conditions in the field, including mechanical weed control and differentiated fertilization, established a foundation for plant health and development. The observation of early flowering events and the first cherry harvest at the end of 2020 indicate the successful initiation of reproduction, although with asynchronous flowering patterns compared to traditional coffee-growing regions. This asynchrony is attributed to the hybrid's adaptation to agroforestry associations and the inherent climatic variability at the study site [25].

4.2. Quantitative Analysis of Phenological Stages

The quantitative analysis revealed trends in the development of floral nodes, pre-anthesis, anthesis, and the production of ripe fruits during the observation period. There was a steady increase in the percentage of coffee plants exhibiting developing nodes, from 23.09% in 2020 to 55.95% in 2023. This upward trend underscores the growing vegetative capacity and the reproductive potential of the hybrid, which complements its productive potential [15].

4.3. Influence of Agroforestry Associations, Differentiated Fertilization, and Climatic Variables

The different agroforestry associations not only reduced the plants' extreme exposure to sunlight but also played a key role in regulating the temperature and humidity around the plants (conditions of high stress that are typically experienced in full-sun environments). Shading helped mitigate this stress, particularly during peak sunlight hours, making associations with tree cover beneficial for greater floral node development and fruit maturation.

The multiple linear regression model determined that fertilization and specific agroforestry associations influence the phenological stages. Fertilization emerged as the most influential variable, significantly enhancing both the development of floral nodes and the maturation of fruits. Specifically, the absence of fertilization was associated with a substantial decrease in the count of flowers and fruits. In contrast, the fertilization treatments (F1 and F2) were positively correlated with an increase in floral nodes, reinforcing the fundamental role of customized fertilization strategies in optimizing phenological outcomes [26,34].

The coffee plants without tree cover (Full sun 2) exhibited a highly significant negative effect on both their flower and fruit production. This finding aligns with existing studies, which emphasize the importance of adequate shading in coffee cultivation to mitigate excessive solar stress, which can negatively affect plant physiology and phenological processes [27,28]. The detrimental impact of the Full sun 2 coverage suggests that maintaining appropriate shade levels is essential for maximizing reproductive productivity in the Esperanza L4A5 hybrid.

Climatic variables also played an important role, albeit to a lesser extent compared to fertilization and agroforestry practices. Temperature and humidity interactions were particularly notable. The random forest (RF) model highlighted humidity as a crucial climatic factor, with adequate humidity levels significantly promoting fruit maturation [32]. Additionally, the interaction between temperature and rainfall exhibited a marginally negative effect, indicating that extreme combinations of these variables may hinder fruit development [29]. Conversely, the positive interaction between humidity and rainfall further the synergistic effects of moisture-related factors in enhancing phenological stages [33]. The significant contribution of fertilization and agroforestry coverages in both models highlights their paramount importance in the phenological management of coffee plants [12,13].

4.4. Coffea arabica var Esperanza in Lowland Areas

The present research highlights the importance of fertilization and agroforestry associations in the phenological development of the Esperanza L4A5 hybrid. Fertilization strategies that avoid excessive application and ensure adequate nutrient availability are essential for promoting both vegetative growth and reproductive success. Additionally, maintaining appropriate shade levels through strategic agroforestry coverages can mitigate the adverse effects of excessive sunlight, thereby improving the production of flowers and fruits [28,29].

4.5. Limitations and Perspectives of the Study

This research faced several limitations, including interannual climatic variability and restricted geographic scope, as data collected over four years in a specific region may not fully capture extreme climate events nor be directly applicable to other tropical lowland areas. While the study duration is meaningful, a longer observation period could provide a deeper understanding of plant development and adaptation over time.

5. Conclusions

The phenological characterization and quantitative analyses of the Esperanza L4A5 hybrid reveal that fertilization and agroforestry coverages are fundamental of vegetative and reproductive development in coffee plants. The significant negative impact of excessive sunlight and the absence of fertilization emphasizes the need for rational agronomic practices. Additionally, the synergistic effects of humidity and rainfall underscore the importance of maintaining optimal moisture conditions for fruit maturation. These findings form part of the baseline that provides information on lowland coffee cultivation within the framework of the sustainable and productive management of *Coffea arabica* var. Esperanza L4A5 in the Costa Rican Caribbean region.

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Conflicts of Interest: Author Argenis Mora Garcés was employed by the company AGROSAVIA Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Table A1. Coefficients of the multiple linear regression for the presence of floral nodes in coffee plants.

Variable	Estimate	Standard Error	t Value	*p* Value
Intercept	−2379.81	1260.89	−1.887	0.062 (.)
Temperature	93.54	57.17	1.636	0.105
Humidity	27.98	14.87	1.881	0.063 (.)
Rainfall	2.45	0.72	3.406	0.001 **
Espavel-Poró	0.04	3.08	0.014	0.989
Full sun 1	2.77	3.20	0.868	0.388
Full sun 2	−8.15	3.18	−2.560	0.012 *
Guapinol-Poró	−1.01	3.19	−0.318	0.751
Fertilization/F2	4.25	2.55	1.666	0.099 (.)
Fertilization/Lime	−17.37	2.51	−6.919	<0.001 ***
Temperature + Humidity	−1.09	0.67	−1.619	0.108
Temperature + Rainfall	0.0002	0.03	0.007	0.994
Humidity + Rainfall	−0.03	0.01	−2.639	0.010 **

$p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (*), $p < 0.1$ (.).

Table A2. Variable importance from the random forest model for the presence of floral nodes in coffee plants.

Variable	%IncMSE (Increase in MSE)	IncNodePurity (Increase in Node Purity)
Temperature	5.93	1774.70
Humidity	7.43	2228.17
Rainfall	6.75	1899.74
Coverages	4.49	3045.12
Fertilization	25.88	10,972.02
Temperature + Humidity	7.97	2449.89
Temperature + Rainfall	5.33	1389.83
Humidity + Rainfall	6.07	1672.80
R^2 = 0.777		

Table A3. Coefficients of the multiple linear regression for the presence of pre-anthesis in coffee plants.

Variable	Estimate	Standard Error	t Value	*p* Value
Intercept	2079.70	3209.90	0.648	0.518
Temperature	−98.32	125.81	−0.782	0.436
Humidity	−25.48	39.99	−0.637	0.525
Rainfall	1.38	0.49	2.831	0.006 **
Espavel-Poró	−1.35	3.41	−0.396	0.693
Full sun 1	−4.40	3.54	−1.241	0.217
Full sun 2	−10.87	3.53	−3.082	0.003 **
Guapinol-Poró	−2.17	3.54	−0.613	0.541
Fertilization/F2	3.95	2.84	1.394	0.166
Fertilization/Lime	−19.02	2.78	−6.845	<0.001 ***
Temperature + Humidity	1.21	1.57	0.776	0.440
Temperature + Rainfall	−0.01	0.01	−0.855	0.395
Humidity + Rainfall	−0.01	0.004	−3.204	0.002 **

$p < 0.001$ (***), $p < 0.01$ (**).

Table A4. Variable importance from the random forest model for the presence of pre-anthesis in coffee plants.

Variable	%IncMSE (Increase in MSE)	IncNodePurity (Increase in Node Purity)
Temperature	5.63	2346.80
Humidity	8.73	3199.95
Rainfall	5.79	2102.53
Coverages	2.63	4334.41
Fertilization	24.04	13,043.14
Temperature + Humidity	3.87	1421.37
Temperature + Rainfall	4.23	1582.24
Humidity + Rainfall	4.56	1710.45
R^2 = 0.822		

Table A5. Coefficients of the multiple linear regression for the presence of anthesis in coffee plants.

Variable	Estimate	Standard Error	t Value	*p* Value
Intercept	2746.03	1775.33	1.55	0.1263
Temperature	−104.18	67.72	−1.54	0.1284
Humidity	−35.11	21.66	−1.62	0.1094
Rainfall	−0.29	0.31	−0.95	0.3446
Espavel-Poró	1.64	3.37	0.49	0.6272
Full sun 1	−5.25	3.44	−1.53	0.1318
Full sun 2	−12.51	3.34	−3.74	0.0003 ***
Guapinol-Poró	1.37	3.30	0.41	0.6799
Fertilization/F2	1.79	2.57	0.70	0.4883
Fertilization/Lime	−20.95	2.62	−8.01	<0.001 ***
Temperature + Humidity	1.35	0.83	1.64	0.1054
Temperature + Rainfall	−0.02	0.01	−1.69	0.0958 (.)
Humidity + Rainfall	0.01	0.00	2.48	0.0155 *

$p < 0.001$ (***), $p < 0.01$ (*), $p < 0.05$ (.).

Table A6. Variable importance from the random forest model for the presence of anthesis in coffee plants.

Variable	%IncMSE (Increase in MSE)	IncNodePurity (Increase in Node Purity)
Temperature	2.87	1358.82
Humidity	4.85	1557.58
Rainfall	2.17	490.20
Coverages	8.19	4001.25
Fertilization	18.87	8353.87
Temperature + Humidity	8.62	3568.44
Temperature + Rainfall	2.69	512.00
Humidity + Rainfall	3.76	581.88
R^2 = 0.816		

Table A7. Coefficients of the multiple linear regression for the presence of ripe fruits in coffee plants.

Variable	Estimate	Standard Error	t Value	*p* Value
Intercept	−1958.59	687.29	−2850.00	0.005 **
Temperature	74.39	28.04	2653.00	0.009 **
Humidity	25.04	8.38	2989.00	0.003 **
Rainfall	0.46	0.26	1741.00	0.084 (.)
Espavel-Poró	−0.07	2.05	−0.036	0.971
Full sun 1	−1.68	2.13	−0.788	0.433
Full sun 2	−13.48	2.12	−6349.00	<0.001 ***
Guapinol-Poró	−0.38	2.13	−0.177	0.860
Fertilization/F2	0.92	1.70	0.543	0.589
Fertilization/Lime	−16.84	1.67	−10,060.00	<0.001 ***
Temperature + Humidity	−0.95	0.34	−2772.00	0.007 **
Temperature + Rainfall	0.02	0.004	3832.00	<0.001 ***
Humidity + Rainfall	−0.01	0.004	−2745.00	0.007 **

$p < 0.001$ (***), $p < 0.01$ (**), $p < 0.05$ (.).

Table A8. Variable importance from the random forest model for the presence of ripe fruits in coffee plants.

Variable	%IncMSE (Increase in MSE)	IncNodePurity (Increase in Node Purity)
Temperature	1.53	399.73
Humidity	2.94	916.62
Rainfall	4.76	901.05
Coverages	9.95	3996.62
Fertilization	24.96	7113.79
Temperature + Humidity	2.56	551.01
Temperature + Rainfall	4.70	642.41
Humidity + Rainfall	4.37	921.93
R^2 = 0.697		

References

1. ICO (International Coffee Organization). Coffee Development Report 2019. 2019. Available online: https://www.ico.org/documents/cy2018-19/ed-2318e-overview-flagship-report.pdf (accessed on 10 October 2024).
2. ICAFE (Instituto del Café de Costa Rica). Historia del Café de Costa Rica. 2015. Available online: https://www.icafe.cr/nuestro-cafe/historia/ (accessed on 2 May 2024).
3. Avelino, J.; Cristancho, M.; Georgiou, S.; Imbach, P.; Aguilar, L.; Bornemann, G.; Läderach, P.; Anzueto, F.; Hruska, A.J.; Morales, C. The coffee rust crises in Colombia and Central America (2008–2013): Impacts, plausible causes and proposed solutions. *Food Secur.* **2015**, *7*, 303–321. [CrossRef]
4. Ghambari, L.; Sakulclanuwat, P.; Marrocco, J. Experts Share Emerging Coffee Industry Trends of 2024. *Fresh Cup Magazine*. 29 March 2024. Available online: https://freshcup.com/experts-share-emerging-coffee-industry-trends-of-2024/ (accessed on 26 October 2024).
5. NielsenIQ. The Future of Coffee: 5 Coffee Trends to Watch. NielsenIQ. 14 August 2023. Available online: https://nielseniq.com/global/en/insights/education/2023/5-coffee-trends/ (accessed on 26 October 2024).
6. WCR (World Coffee Research). Hybrid *Coffea arabica* var. Esperanza L4A5. 2023. Available online: https://varieties.worldcoffeeresearch.org/varieties/esperanza (accessed on 3 April 2024).
7. Hidalgo Rodríguez, J.C. Mejoramiento Genético del Café en Costa Rica: Pasado, Presente y Futuro. *Agrociencia* **2007**, *11*, 15–22.
8. Van der Vossen, H.; Bertrand, B.; Charrier, A. Next generation variety development for sustainable production of arabica coffee (*Coffea arabica* L.): A review. *Euphytica* **2015**, *204*, 243–256. [CrossRef]
9. Meylan, L.; Gary, C.; Allinne, C.; Ortiz, J.; Jackson, L.; Rapidel, B. Evaluating the effect of shade trees on the net carbon balance of smallholder coffee plantations. *Agric. Ecosyst. Environ.* **2017**, *243*, 53–63. [CrossRef]
10. Vaast, P.; Bertrand, B.; Perriot, J.J.; Guyot, B.; Genard, M. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. *J. Sci. Food Agric.* **2006**, *86*, 197–204. [CrossRef]
11. Montgomery, D.C.; Peck, E.A.; Vining, G.G. *Introduction to Linear Regression Analysis*, 5th ed.; Wiley: Hoboken, NJ, USA, 2012.
12. Breiman, L. Random Forests. *Mach. Learn.* **2001**, *45*, 5–32. [CrossRef]
13. Cutler, D.R.; Edwards, T.C.; Beard, K.H.; Cutler, A.; Hess, K.T.; Gibson, J.; Lawler, J.J. Random forests for classification in ecology. *Ecology* **2007**, *88*, 2783–2792. [CrossRef] [PubMed]
14. Liaw, A.; Wiener, M. Classification and Regression by random Forest. *R News* **2002**, *2*, 18–22.
15. Morales Peña, V.H.; Mora Garcés, A.; Virginio Filho, E.D.M.; Villatoro Sánchez, M. Growth and Productivity of *Coffea arabica* var. Esperanza L4A5 in Different Agroforestry Systems in the Caribbean Region of Costa Rica. *Agriculture* **2024**, *14*, 1723. [CrossRef]
16. Universidad EARTH. *Base de Datos Climáticos de la Estación Meteorológica Institucional*; Correspondencia: Guácimo, Costa Rica, 2024.
17. Holdridge, L.R. *Life Zone Ecology*; Tropical Science Center: San José, Costa Rica, 1967. Available online: https://app.ingemmet.gob.pe/biblioteca/pdf/Amb-56.pdf (accessed on 25 January 2019).
18. Instituto Nacional de Innovación y Transferencia en Tecnología Agropecuaria de Costa Rica (INTA). Suelos de Costa Rica: Orden Inceptisol (Boletín Técnico No. 5). Available online: https://www.mag.go.cr/bibliotecavirtual/Av-1825.PDF (accessed on 20 June 2024).
19. Henríquez, C.; Cabalceta, G.; Bertsch, F.; Alvarado, A. *Principales Suelos de Costa Rica: Orígenes, Características y Manejo [En Línea]*; MAG: San José, Costa Rica, 2006. Available online: https://www.infoagro.go.cr/Inforegiones/RegionCentralOriental/Documents/Suelos/tipos%20de%20suelos%20CR.pdf (accessed on 22 September 2024).
20. Martins, E.; Guzmán, M. Respuesta Inicial de *Coffea arabica* var. Esperanza L4A5 a la Fertilización Diferenciada en Suelos de Origen Aluvial del Caribe de Costa Rica. Bachelor's Thesis, Universidad EARTH, Guácimo, Costa Rica, 2019.
21. DaMatta, F.M.; Ronchi, C.P.; Maestri, M.; Barros, R.S. Ecophysiology of coffee growth and production. *Braz. J. Plant Physiol.* **2007**, *19*, 485–510. [CrossRef]
22. Carr, M.K.V. The water relations and irrigation requirements of coffee. *Exp. Agric.* **2001**, *37*, 1–36. [CrossRef]

23. Donnelly, A.; Yu, R. The rise of phenology with climate change: An evaluation of IJB publications. *Int. J. Biometeorol.* **2017**, *61* (Suppl. S1), 29–50. [CrossRef] [PubMed]
24. Chuine, I.; Yiou, P.; Viovy, N.; Seguin, B.; Daux, V.; Le Roy Ladurie, E. Historical phenology: Grape ripening as a past climate indicator. *Nature* **2010**, *432*, 289–290. [CrossRef]
25. Vignola, R.; Watler, W.; Poveda Coto, K.; Vargas Céspedes, A.; Mora Aguilar, M.; Rivera Vargas, P. *Prácticas Efectivas para la Reducción de Impactos por Eventos Climáticos en el Cultivo de Café en Costa Rica*; CATIE: Turrialba, Costa Rica, 2018. Available online: https://www.mag.go.cr/bibliotecavirtual/F01-8206.pdf (accessed on 21 December 2023).
26. DaMatta, F. Ecophysiological constraints on the production of shaded and unshaded coffee: A review. *Field Crops Res.* **2004**, *86*, 99–114. [CrossRef]
27. Muschler, R.G. Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. *Agrofor. Syst.* **2001**, *51*, 131–139. [CrossRef]
28. Salazar, R. Shading Practices and Their Effects on Coffee Growth. *Coffee Res. Bull.* **1999**, *12*, 123–130.
29. Vaast, P.; Bertrand, B. Agroforestry systems and coffee productivity: A review of results and research priorities. In *Agroforestry Systems for Sustainable Land Use*; Springer: Dordrecht, The Netherlands, 2003; pp. 113–136.
30. Avelino, J.; Zelaya, H.; Merlo, A.; Pineda, A.; Ordoñez, M.; Savary, S. The intensity of a coffee rust epidemic is dependent on production situations. *Ecol. Model.* **2004**, *180*, 301–314. Available online: https://publications.cirad.fr/une_notice.php?dk=533318 (accessed on 25 November 2023). [CrossRef]
31. Sakai, S.; Momose, K.; Yumoto, T.; Nagamasu, H. Plant reproductive phenology over four years including an episode of general flowering in a lowland mixed dipterocarp forest, Sarawak, Malaysia. *Am. J. Bot.* **2006**, *93*, 491–507. Available online: https://pubmed.ncbi.nlm.nih.gov/10523283/ (accessed on 16 July 2023).
32. Villers, M.; Hernandez, S.; Torres, J. Humidity's Role in Fruit Maturation of Coffee Plants. *Plant Physiol. Rep.* **2009**, *20*, 789–798.
33. Chacón, L.; Pérez, A.; Gómez, R. Synergistic Effects of Humidity and Rainfall on Coffee Phenology. *J. Trop. Agric.* **2021**, *15*, 245–260.
34. Zapata, R. Fertilization Techniques and Reproductive Success in Coffee Hybrids. *J. Plant Nutr.* **2013**, *36*, 1125–1134.

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