

Article

Microclimatic Variability of Atmospheric and Soil Moisture in Andean *Juglans neotropica* Plantations

Juan P. Romero-Astudillo *, Luis H. Álvarez-Játiva, Paúl Tafur-Escanta and Juan Guamán-Tabango

Facultad de Ingeniería en Ciencias Agropecuarias y Ambientales, Universidad Técnica del Norte, Av. 17 de Julio 5-21 y Gral. José María Córdova, Ibarra 100105, Ecuador; lhalvarezj@utn.edu.ec (L.H.Á.-J.); pmtafur@utn.edu.ec (P.T.-E.); jfguaman@utn.edu.ec (J.G.-T.)

* Correspondence: jpromero@utn.edu.ec; Tel.: +593-992-546-504

Abstract

Understanding microclimatic variability at the land–atmosphere interface is essential for improving knowledge of atmospheric moisture dynamics in heterogeneous mountainous ecosystems. This study analyzes atmospheric relative humidity and soil moisture variability in an experimental *Juglans neotropica* Diels plantation located in the Ecuadorian Andes under real field conditions. An autonomous photovoltaic-powered monitoring system equipped with low-cost environmental sensors was deployed continuously for 60 days, generating more than 86,000 environmental measurements of atmospheric relative humidity above and below the canopy, together with soil moisture observations. The results revealed persistent vertical humidity stratification associated with canopy structure, characterized by systematically higher atmospheric humidity beneath the canopy compared to the upper atmospheric layer ($\Delta RH \approx -36\%$). Strong intersensor coherence was observed between canopy levels ($r = 0.8535$), indicating stable temporal consistency in atmospheric variability patterns throughout the monitoring period. Soil moisture exhibited comparatively more stable temporal dynamics than atmospheric humidity, suggesting partial microclimatic decoupling between atmospheric and edaphic layers. The observed humidity gradients remained temporally stable during both daytime and nighttime conditions, supporting the interpretation of canopy-mediated atmospheric buffering processes within the plantation environment. From an ecological perspective, the results indicate that vegetation structure contributes to localized moisture retention, attenuation of short-term atmospheric fluctuations, and regulation of near-surface microclimatic conditions under heterogeneous Andean environmental conditions. Rather than focusing on instrumentation performance, the study provides empirical evidence of persistent canopy-related atmospheric regulation and moisture stratification in a native Andean forest species under continuous field monitoring conditions. These findings contribute to the understanding of land–atmosphere interactions, ecohydrological dynamics, and vegetation-mediated microclimatic regulation in mountainous ecosystems.

Academic Editors: Lei Meng and Yaqian He

Received: 28 April 2026

Revised: 29 May 2026

Accepted: 3 June 2026

Published: 22 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: *Juglans-neotropica*-Diels microclimate; relative humidity; soil moisture; land–atmosphere interaction; canopy microclimate; andean ecosystems; environmental monitoring

1. Introduction

Ecuador's geographic diversity, shaped by the interaction of the Andes mountain range, oceanic currents, the Amazon basin, and pronounced edaphic heterogeneity, has led to the recognition of at least 91 ecosystems, positioning the country among the most biodiverse regions worldwide [1]. This environmental complexity, together with forest cover representing approximately 56% of the national territory, highlights the importance of forest ecosystems in regulating environmental processes and supporting sustainable development [2]. However, these ecosystems are increasingly threatened by deforestation rates ranging from 0.4% to 2.4% per year, resulting in significant biodiversity loss and degradation of ecosystem functionality [2].

Although forestry activities are primarily concentrated in coastal and Amazonian regions, Andean forests have experienced particularly severe degradation. By 2018, these ecosystems had lost nearly 52% of their original extent, mainly due to agricultural expansion and the introduction of exotic species such as *Eucalyptus globulus*, *Pinus radiata*, and *Pinus patula* [3–5]. Among the remaining inter-Andean montane forests—representing approximately 19.9% of Ecuador's forest cover—native species of high ecological and environmental relevance persist, including *Juglans neotropica* Diels [6,7].

Juglans neotropica Diels, commonly known as “nogal” or “tocte,” is distributed discontinuously along the Andean regions of Venezuela, Colombia, Ecuador, and Peru [8]. Due to habitat transformation, this species is currently classified as endangered and is more frequently found as isolated individuals in agroforestry systems or urban environments than in its original natural habitats [9].

Figure 1 illustrates a representative specimen located at the Yuyucocha Campus of the Universidad Técnica del Norte (Ibarra, Ecuador). Owing to its adaptability to degraded soils and its role in moisture retention and ecological restoration, this species is considered a priority for sustainable forest management in Andean environments [8].



Figure 1. *Juglans-neotropica*-Diels Plantation at the Yuyucocha Campus, Universidad Técnica del Norte (Ibarra, Ecuador).

From an environmental perspective, understanding microclimatic variability in native forest plantations is essential for analyzing land–atmosphere interactions, particularly in relation to atmospheric moisture dynamics, soil water behavior, and vegetation-mediated environmental regulation processes [10]. Variables such as relative humidity and soil moisture play a critical role in regulating near-surface atmospheric conditions and plant–water interactions [10].

Recent advances in environmental monitoring have enabled the acquisition of continuous high-resolution datasets capable of characterizing atmospheric variability under complex environmental conditions [11].

In particular, low-cost sensor networks have increasingly been used for microclimatic monitoring due to their accessibility, scalability, and suitability for deployment in remote ecosystems [12,13]. Previous studies have demonstrated the potential of distributed sensing systems for evaluating canopy-induced humidity gradients, vegetation buffering effects, and soil–atmosphere interactions in forested environments [14–16].

Recent international studies have highlighted the importance of continuous environmental monitoring for understanding microclimatic regulation in forested and mountainous ecosystems [17]. Several investigations conducted in tropical and temperate forests have reported that vegetation structure can significantly modify near-surface atmospheric conditions through canopy shading, moisture retention, and reductions in atmospheric turbulence [18]. Likewise, previous studies using autonomous environmental monitoring systems have demonstrated the usefulness of high-frequency humidity observations for evaluating vertical atmospheric stratification and microclimatic stability under forest canopies [19–21].

These studies indicate that continuous monitoring approaches can provide valuable information regarding land–atmosphere interactions and moisture variability under heterogeneous environmental conditions [22]. However, many previous investigations have been conducted either under controlled experimental conditions or using conventional meteorological stations with limited vertical resolution [23]. Consequently, simultaneous observations above and below the canopy under real field conditions remain relatively limited, particularly in tropical Andean ecosystems [24].

However, despite these advances, significant limitations remain in tropical and Andean mountainous ecosystems, where environmental heterogeneity, steep topography, and rapidly changing atmospheric conditions complicate continuous field observations [19]. Most previous studies have focused either on conventional meteorological stations or on short-term measurements, frequently lacking simultaneous monitoring above and below the canopy under real field conditions [21]. Furthermore, relatively few studies have explored the combined variability of atmospheric relative humidity and soil moisture in native Andean Forest species using autonomous low-cost monitoring systems [20].

In this context, the present study analyzes microclimatic variability in an experimental plantation of *Juglans neotropica* Diels located in the Andean region of Ecuador. The research focuses on the characterization of atmospheric relative humidity and soil moisture dynamics under real field conditions, with the objective of identifying patterns of temporal variability and evaluating their consistency across canopy levels. Particular attention is given to the persistence of vertical humidity gradients and to the role of canopy structure in regulating near-surface atmospheric moisture.

Unlike previous studies focused primarily on conventional meteorological observations or short-term environmental measurements, this research provides continuous high-resolution field evidence of microclimatic stratification in a native Andean forest species under real environmental conditions. The study emphasizes the empirical identification of persistent humidity differences between canopy strata, contributing to the understanding of canopy-induced atmospheric buffering processes and vegetation-mediated moisture regulation in heterogeneous mountainous ecosystems [25].

The study also examines the extent to which these variables can be interpreted as indicators of coupled processes within the soil–plant–atmosphere continuum, contributing to the understanding of land–atmosphere interactions in mountainous ecosystems. Rather than focusing on predictive environmental modeling, the study emphasizes empirical characterization of microclimatic dynamics through continuous autonomous monitoring under real field conditions. In this sense, the principal scientific contribution of this work lies in the characterization of persistent atmospheric moisture stratification and canopy-related microclimatic regulation in *Juglans neotropica* Diels plantations within the Ecuadorian Andes [26].

2. Materials and Methods

2.1. Study Area

The study was conducted in an experimental *Juglans neotropica* Diels plantation located at the Yuyucocha Campus of the Universidad Técnica del Norte (UTN), in Ibarra, Imbabura Province, Ecuador ($0^{\circ}21'24''$ N; $78^{\circ}07'18''$ W; 2256 m a.s.l.), as shown in Figure 2. The site is characterized by a temperate montane climate, with a mean annual temperature of 16 °C, an average relative humidity of 78%, and an atmospheric pressure of approximately 0.75 atm [27–29]. These environmental conditions are representative of Andean ecosystems where Andean walnut (*Juglans neotropica* Diels) is cultivated and provide a suitable setting for analyzing its hydric and energy balance dynamics [29,30].

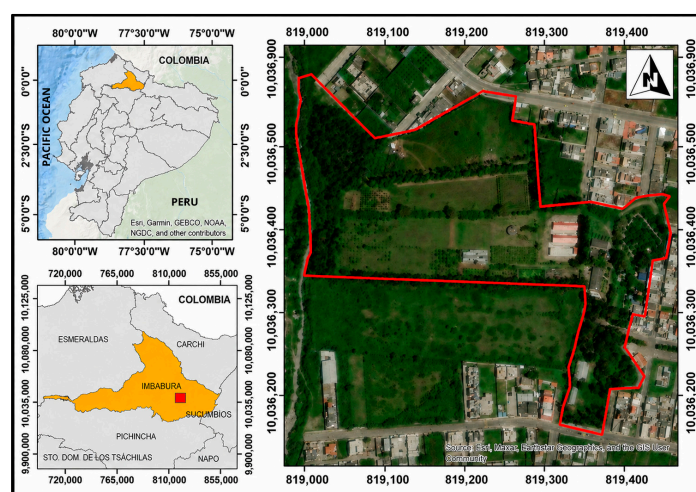


Figure 2. Plantation site at the Yuyucocha Campus, Universidad Técnica del Norte (Ibarra, Ecuador). The red polygon outlines the study plantation, and the red square indicates its location within Imbabura Province.

To provide an independent point of comparison for the measurements obtained from the developed system, a reference relative humidity sensor (RHref) was installed within the experimental plot. This sensor served as an operational reference for the local atmospheric conditions. It was positioned within the same study area as the photovoltaic monitoring device, at canopy height and under comparable exposure conditions, thereby ensuring spatial coherence between the datasets. The RHref sensor does not constitute a metrological ground-truth measurement; rather, its function is to serve as an independent operational benchmark for assessing the consistency, stability, and relative performance of the low-cost sensors integrated into the monitoring system under real field conditions.

The experimental area comprised 24 representative sampling points within the plot, where soil samples were collected at depths of 30 cm and 60 cm. All sampling tools and containers were previously sterilized to prevent cross-contamination. The samples were homogenized and submitted to the certified laboratory of the Agency for Phytosanitary and Zoosanitary Regulation and Control (AGROCALIDAD) for analysis of pH, texture, and macro- and micronutrient content. The results indicated pH values ranging from 7.24 to 8.16, corresponding to slightly alkaline to alkaline soils, with low organic matter content (1.31–1.52%) and nitrogen deficiency (0.07–0.08%). These characteristics may constrain water retention capacity and limit the availability of essential micronutrients such as iron and zinc [31].

According to the same analyses, the predominant soil textures were loam, sandy loam, and silty loam, which provide a balance between drainage and moisture retention. However, sandy loam soils exhibit greater susceptibility to nutrient leaching. The measured field capacity values (20–27%) and available water content (9–12%) are considered

suitable for the establishment of *Juglans neotropica* Diels, provided that appropriate water management practices and vegetative cover strategies are implemented [32–34]. For the climatic characterization of the study area, a database provided by INAMHI (2025) was used, corresponding precisely to the geographical coordinates of the experimental site.

To complement the environmental characterization of the study area, Figure 3 presents the temporal climatic profile recorded during the monitoring period based on the measured environmental variables available at the experimental site. The figure includes the variation in air temperature and relative humidity, which are key parameters influencing microclimatic behavior and land–atmosphere moisture interactions within the *Juglans neotropica* plantation. The observed conditions show relatively stable temperature values throughout the monitoring campaign, while relative humidity exhibited greater temporal variability associated with local atmospheric dynamics and diurnal environmental fluctuations.

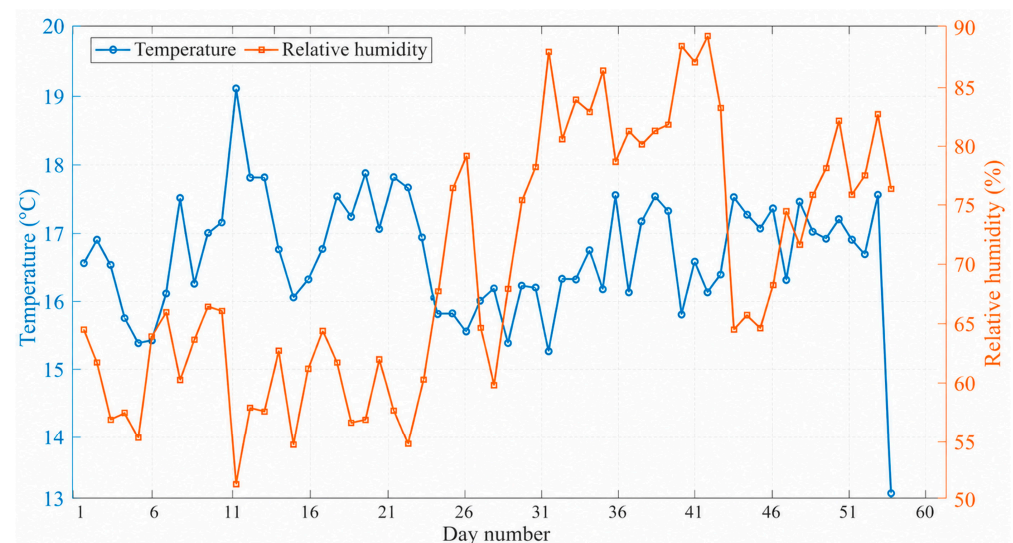


Figure 3. Climatic profile of the study area during the monitoring period based on measured air temperature and relative humidity.

2.2. Hybrid Measurement System

The developed measurement system consisted of an autonomous hybrid prototype powered by a 15 W photovoltaic panel and a 10,000 mAh battery, ensuring continuous operation even under low solar radiation conditions. The photovoltaic panel was covered with a transparent polyethylene sheet of 200 μm thickness to prevent damage from rain or dust accumulation.

The device incorporated two DHT11 sensors installed at heights of 20 cm and 75 cm above ground level to record the vertical gradient of air relative humidity. This configuration enabled simultaneous measurements of microclimatic conditions near the lower and upper canopy foliage, which may support future evapotranspiration-related analyses [12,13]. Additionally, a capacitive soil-moisture sensor was installed at a depth of 25 cm to monitor temporal variations in water content within the root zone.

Data were automatically stored on a microSD card through an SPI module controlled by an Arduino Nano microcontroller. An LCD display with an I²C interface was included for local data visualization, as shown in Figure 4.

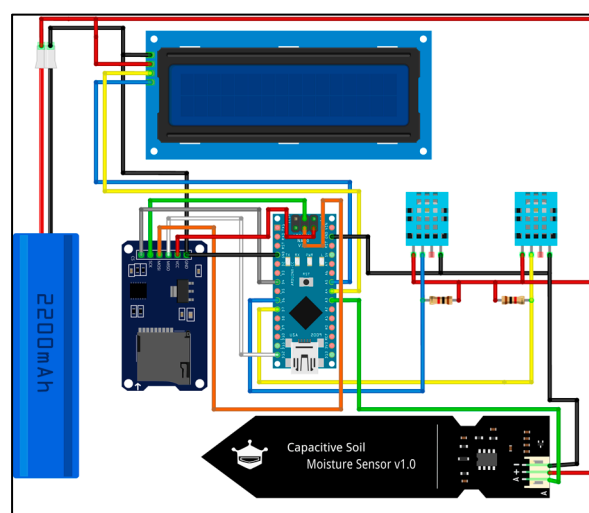


Figure 4. Monitoring system electronic diagram.

This device enabled the simultaneous acquisition of atmospheric and soil humidity data with a temporal resolution of one minute, establishing an observation framework that integrates atmospheric and edaphic dimensions through an autonomous photovoltaic power supply. The hybrid architecture of the system combines low-power electronics, distributed sensing, and renewable energy supply, enabling stable long-term monitoring under rural field conditions where electrical infrastructure is limited.

Sensor Calibration and Metrological Considerations

Calibration tests were conducted across a wide relative humidity range (15–95% RH) under ambient temperature conditions, evaluating the consistency of DHT11 readings relative to the reference instrument. The calibration procedure included repeated measurement cycles performed under quasi-stable environmental conditions in order to evaluate repeatability and intersensor consistency [35]. For each calibration stage, multiple observations were recorded to reduce random fluctuations and identify systematic deviations between sensor responses and the operational reference instrument [35,36].

The calibration analysis incorporated descriptive statistical indicators, including mean absolute error (MAE), root mean square error (RMSE), and average relative deviation between measured and reference humidity values [37]. According to the manufacturer's specifications, the DHT11 sensor provides a typical relative humidity measurement accuracy of $\pm 5\%$ RH within an operational range of 20–90% RH and a measurement resolution of 1% RH [35]. During repeated calibration and verification cycles, the observed intersensor deviations remained within the expected operational tolerance range of the sensor, demonstrating stable temporal behavior under quasi-stable environmental conditions. Systematic deviations identified during the calibration process were corrected through deterministic adjustment functions implemented in MATLAB, improving the temporal consistency of the recorded environmental signals [37].

This calibration procedure was performed prior to field deployment and complemented by periodic verification checks during the experimental phase. These verification procedures were preferentially conducted during nighttime periods, when atmospheric conditions exhibit greater thermal stability and reduced solar radiation influence. This strategy facilitated the detection of potential sensor drift and condensation-related effects, which are recognized operational limitations in low-cost capacitive humidity sensors under high-humidity conditions [38,39].

Rather than providing strict metrological ground-truth validation, the adopted calibration framework was intended to ensure operational consistency, temporal coherence,

and intersensor agreement under real field conditions. This approach is consistent with validation methodologies commonly employed in low-cost environmental sensing systems used for long-term field monitoring applications [37].

Soil moisture calibration was performed using an indirect gravimetric approach, correlating the TEROs 10 sensor voltage response with volumetric water content values obtained from controlled soil drying and wetting cycles [21]. A polynomial fitting function was applied between voltage output and gravimetrically derived volumetric water content values, improving sensor consistency under local soil conditions [40].

Although low-cost environmental sensors inherently present limitations in absolute metrological precision and sensitivity under rapidly changing environmental conditions, the combined calibration strategy adopted in this study ensured stable and reproducible measurements suitable for comparative microclimatic analysis and temporal variability assessment [37,41]. From a functional perspective, the implemented framework prioritizes operational stability, temporal consistency, and intersensor coherence, which are critical attributes for continuous environmental monitoring in rural agroforestry environments [41].

2.3. Data Processing and Microclimatic Analysis

The data were processed in MATLAB R2025b using a sequential scheme that included: (i) reading and temporal conversion of records, (ii) cleaning and removal of outliers, (iii) temporal smoothing using a moving average, (iv) derivation of microclimatic variables, and (v) classification into daytime and nighttime periods. To process the data at the electronic level, different mathematical methodologies were applied to reduce variations produced during data acquisition. The computational processing engine used in this research implemented a centered three-hour smoothing, expressed as:

$$x_{\text{smooth}}(t) = \frac{1}{3} [x_{(t-1)} + x_{(t)} + x_{(t+1)}] \quad (1)$$

From the smoothed signals, key indicators were derived:

- Humidity gradient between upper and lower sensors:

$$\Delta RH_{\text{canopy}} = S2H_{\text{smooth}} - S1H_{\text{smooth}} \quad (2)$$

- Moving average humidity of the device:

$$RH_{\text{mean}} = \frac{S1H_{\text{smooth}} + S2H_{\text{smooth}}}{2} \quad (3)$$

where RH (%) denotes the instantaneous relative humidity measured by each atmospheric sensor; $S1H_{\text{smooth}}$ (%) corresponds to the smoothed relative humidity recorded below the canopy; $S2H_{\text{smooth}}$ (%) represents the smoothed relative humidity measured above the canopy; $\Delta RH_{\text{canopy}}$ (%) is the vertical relative humidity gradient between canopy levels, defined as $\Delta RH_{\text{canopy}} = S2H_{\text{smooth}} - S1H_{\text{smooth}}$; RH_{mean} (%) is the mean relative humidity of the monitoring system computed from both atmospheric sensors; $x(t)$ denotes the raw sensor signal at a discrete time t ; $x_{\text{smooth}}(t)$ represents the temporally smoothed signal at time t ; t is the discrete time index of each measurement, and the temporal window refers to a centered moving window of three hours used for temporal smoothing.

The day/night classification was performed based on local solar time, defining the daytime period between 07:00 and 18:00 h, considering sunrise in the study area, and the nighttime period between 19:00 and 06:00 h. This separation allowed the evaluation of differences in the hygrothermal behavior of the canopy and its influence on transpiration and condensation processes.

3. Results

The data analysis was conducted on a total of 86,072 environmental measurements and 1506 calibration observations of atmospheric relative humidity below the canopy (S1H), above the canopy (S2H), and soil moisture (Hsoil), obtained through an autonomous monitoring system installed in an experimental *Juglans neotropica* Diels plantation. The monitoring framework was powered by photovoltaic energy, enabling continuous environmental observations under real field conditions throughout the experimental period.

The data processing workflow included the following stages: (i) physical cleaning of relative humidity records within the operational range (0–100%RH), (ii) computation of derived environmental indicators, (iii) robust regression fitting, (iv) classification of humid environmental conditions through threshold-based analysis ($RH_{ref} \geq 65\%$), and (v) generation of daytime and nighttime summaries of correlation coefficients, coefficients of determination (R^2), and root mean square error (RMSE) [42–44]. This analytical framework enabled the characterization of temporal variability patterns and humidity differences between canopy levels under variable environmental conditions.

The monitoring system operated continuously for 60 days, recording atmospheric humidity fluctuations above and below the canopy together with soil moisture variability throughout the experimental plantation. The primary objective of the monitoring process was to characterize microclimatic variability between canopy strata and evaluate temporal interactions between atmospheric and soil moisture conditions under real field environments.

To ensure traceability and reproducibility of the analysis, an automated processing framework was implemented in MATLAB, integrating data cleaning, feature extraction, regression analysis, and visualization of statistical indicators. This approach enabled systematic and transparent processing of the environmental dataset acquired during the monitoring campaign. The overall processing workflow is illustrated in Figure 5.

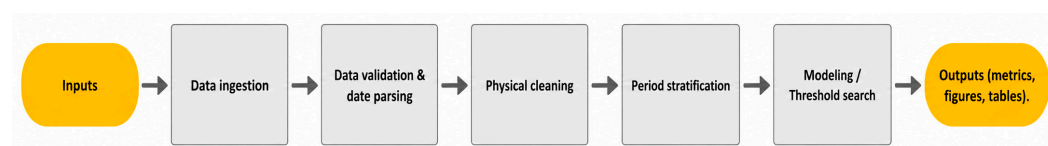


Figure 5. Flowchart of Data Ingestion, Cleaning, and Modeling Stages.

3.1. Descriptive Analysis of Atmospheric and Soil Humidity

The descriptive analysis revealed marked differences between atmospheric humidity conditions above and below the canopy, as well as between atmospheric and soil moisture dynamics throughout the monitoring period. These differences indicate the presence of persistent microclimatic gradients associated with canopy structure and near-surface environmental regulation within the *Juglans neotropica* Diels plantation. From an ecological perspective, the observed humidity stratification suggests that the vegetation layer actively modulates local atmospheric conditions by attenuating direct exposure to atmospheric mixing and promoting moisture retention beneath the canopy [14].

The S1H sensor (installed beneath the canopy) recorded a mean relative humidity of 38.28% and a median of 38.44%, with a standard deviation of 15.03, indicating moderate variability within a relatively humid and buffered microenvironment protected by the foliage. In contrast, the S2H sensor (positioned above the canopy) exhibited a lower mean value of 30.64% and a standard deviation of 13.53, together with slight positive skewness (0.09) and mildly platykurtic kurtosis (1.33). These statistical characteristics are consistent with upper canopy layers that are more exposed to atmospheric mixing, ventilation, and short-term environmental fluctuations. The relatively higher humidity conditions observed be-

neath the canopy support the interpretation of canopy-induced atmospheric buffering effects associated with vegetation-mediated microclimatic regulation processes [14].

Complementarily, soil moisture (Hsoil) exhibited a mean value of 69.99%, a median of 69.45%, and a standard deviation of 11.57, with low skewness (0.10) and kurtosis values close to 2, indicating a comparatively stable hydric regime relative to atmospheric humidity variability, as illustrated in Figure 6. This behavior highlights the capacity of the soil layer to maintain sustained moisture conditions despite temporal fluctuations in the surrounding atmospheric environment, suggesting partial microclimatic decoupling between soil and atmospheric layers. From an environmental perspective, this decoupling behavior may reflect the influence of canopy structure in regulating atmospheric moisture exchange while simultaneously promoting soil water retention under heterogeneous field conditions.

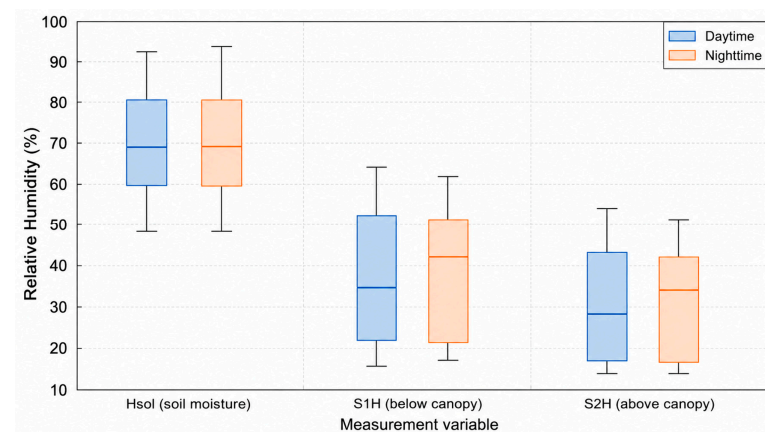


Figure 6. Boxplots of Atmospheric and Soil Humidity.

To complement the statistical analysis and provide a direct visualization of temporal environmental variability, Figure 7 presents the complete time series of atmospheric relative humidity recorded by sensors S1H and S2H together with soil moisture (Hsoil) throughout the monitoring period. The temporal representation highlights the persistence of humidity differences between canopy levels and reveals the contrasting temporal behavior between atmospheric and soil moisture dynamics.

Atmospheric humidity exhibited higher-frequency fluctuations associated with daily environmental variability, whereas soil moisture presented smoother and more attenuated temporal dynamics due to water retention processes within the soil profile. The time series also demonstrate the persistence of relatively higher humidity conditions beneath the canopy throughout most of the monitoring period, supporting the interpretation of canopy-induced atmospheric buffering effects and localized moisture retention associated with vegetation structure.

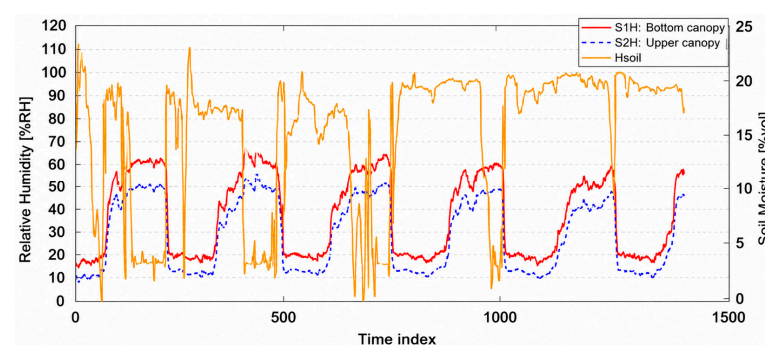


Figure 7. Time series of atmospheric relative humidity measured below the canopy (S1H), above the canopy (S2H), and soil moisture (Hsoil) during the monitoring period.

The integrated interpretation of these results suggests that the *Juglans neotropica* Diels plantation maintains differentiated microclimatic conditions between canopy layers, characterized by relatively higher humidity accumulation beneath the canopy and comparatively more variable atmospheric conditions above the foliage layer. These observations are consistent with the role of vegetation structure in regulating near-surface atmospheric moisture and reducing direct exposure to atmospheric mixing processes [14]. Furthermore, the persistence of these vertical humidity gradients throughout the monitoring period provides empirical evidence of vegetation-mediated atmospheric regulation and microclimatic stabilization within Andean forest environments.

3.2. Intersensor Relationship and Regression Analysis

To evaluate environmental coherence between canopy strata, several regression models were tested, as presented in Table 1. Among the evaluated formulations, the double inverse regression model provided the strongest empirical correspondence between the relative humidity measurements recorded beneath the canopy (S1H) and those obtained above the canopy (S2H). The objective of this analysis was not to establish a direct physical or causal relationship between variables, but rather to evaluate the degree of temporal coherence between atmospheric observations recorded at different canopy levels under real field conditions.

Table 1. Correlation test under statistical regression models.

Model	Correlation	R-Square
Double Inverse	0.8535	72.84%
Inverse-Y Log-X	−0.8512	72.45%
Inverse-Y Square Root-X	−0.8453	71.45%
S Curve	−0.8391	70.42%
Inverse of Y	−0.8360	69.90%
Multiplicative	0.8347	69.67%
Square Root-Y Inverse of X	−0.8278	68.53%
Logarithmic-Y Square Root-X	0.8277	68.50%
Square Root-Y Log-X	0.8222	67.61%
Exponential	0.8173	66.79%
Double Square Root	0.8146	66.36%
Inverse of X	−0.8143	66.30%
Inverse-Y Square-X	−0.8077	65.23%
Logarithm of X	0.8076	65.22%
Square Root of Y	0.8036	64.58%
Square Root of X	0.7994	63.90%
Linear	0.7878	62.06%
Log-Y Square-X	0.7866	61.87%
Square-Y Inverse of X	−0.7828	61.28%
Square-Y Log-X	0.7739	59.89%
Square Root-X Square-X	0.7718	59.56%
Square-Y Square Root-X	0.7645	58.45%
Square of X	0.7548	56.97%
Square of Y	0.7518	56.52%
Double Square	0.7165	51.34%

This empirical fitting yielded a correlation coefficient of $r = 0.8535$, indicating strong temporal coherence between atmospheric humidity observations recorded above and below the canopy. From an environmental perspective, this behavior suggests the existence of persistent microclimatic coupling between canopy strata despite the differences in atmospheric exposure and vegetation shielding effects [15]. The parameters estimated using the least squares method were: intercept = -0.00347 ($p < 0.0001$) and slope = 1.11028 ($p < 0.0001$), both statistically significant, as shown in Equation (4):

$$S1H(\%) = \frac{1}{-0.00347486 + \frac{1.11028}{S2H(\%)}} \quad (4)$$

The analysis of variance (ANOVA) confirmed the overall significance of the fit ($F = 4034.14$; $p < 0.0001$), with low residual variance ($MS_{\text{resid}} = 5.45 \times 10^{-6}$), indicating a stable empirical correspondence between atmospheric humidity measurements obtained at different canopy levels under variable environmental conditions. However, the lack-of-fit test ($F = 57.01$; $p < 0.0001$) suggests that the regression model does not fully capture the complexity of the monitored microclimatic system, which is expected in continuous environmental observations influenced by heterogeneous atmospheric processes.

Rather than representing a predictive environmental model, the fitted relationship should be interpreted as an empirical representation of atmospheric coherence between canopy strata. In this context, the observed statistical relationship supports the interpretation of persistent environmental variability patterns associated with vegetation structure and canopy-mediated atmospheric regulation processes [15].

The negative intercept is associated with minor calibration differences and sensor positioning effects, as illustrated in Figure 8, conditions commonly observed in vegetated canopy environments where local ventilation and atmospheric exposure may vary [16]. Nevertheless, these effects did not prevent the identification of consistent temporal patterns in atmospheric humidity variability between canopy levels.

The main statistical indicators supporting this environmental coherence are presented in Table 2, where the parameters of the fitted model are summarized. These results provide additional evidence of the persistence of differentiated atmospheric conditions between canopy strata throughout the monitoring period.

Table 2. Analysis of Coefficients for the Simple Regression Method.

Model	Intercept	Slope
Minimum Squares	-0.00347486	1.11028
Standard	0.000263181	0.0174807
Statistical	-13.2033	63.5149
<i>p</i> -Value	0.0000	0.0000
M.A.D.	-0.00441114	1.11076

The ANOVA analysis remained statistically significant ($F = 4034.14$; $p < 0.0001$), whereas the lack-of-fit test confirms that the regression should be interpreted strictly as a descriptive empirical fit of the correspondence between atmospheric observations rather than as a mechanistic environmental model of the system [15].

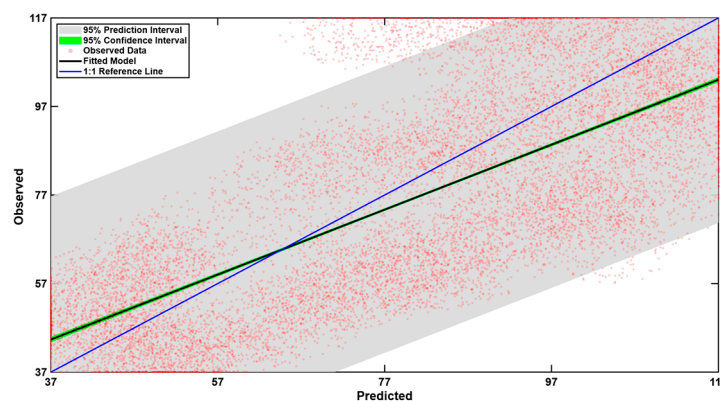


Figure 8. Prediction and Confidence Intervals for the Fitted Model.

3.3. Model Robustness and Residual Diagnostics

The residual diagnostics revealed positive temporal autocorrelation within the environmental monitoring series, indicating that atmospheric humidity conditions evolved continuously over time rather than as independent observations. The Durbin–Watson statistic ($DW = 0.0287$) reflects temporal dependence characteristic of continuous microclimatic processes and persistent environmental variability under field conditions [45].

Standardized residuals remained predominantly within the ± 2 interval, while 127 outliers and 119 influential observations were identified through influence and Cook’s distance analyses. Although these observations represented less than 10% of the total dataset, they are consistent with transient environmental fluctuations commonly observed in heterogeneous atmospheric environments, including short-term humidity transitions and localized atmospheric disturbances associated with natural microclimatic variability.

To reduce the influence of extreme observations while preserving the environmental structure of the dataset, a robust regression adjustment was applied. This approach facilitated a more stable interpretation of temporal humidity variability under heterogeneous atmospheric conditions [45].

The observed temporal autocorrelation is consistent with the continuous nature of soil–plant–atmosphere interactions and the persistence of environmental moisture dynamics in forested ecosystems. In this context, the statistical behavior identified in the monitoring series reflects the intrinsic continuity of microclimatic processes rather than anomalous behavior within the environmental observations.

From an environmental perspective, the results support the interpretation of persistent atmospheric variability and canopy-related microclimatic dynamics under real field conditions. The continuity observed in the monitoring series provides empirical evidence of temporally structured environmental behavior associated with vegetation-mediated atmospheric regulation processes.

3.4. Temporal Dynamics: Daytime and Nighttime Behavior

3.4.1. Coherence with Reference Humidity (RHref)

To evaluate the temporal coherence of the environmental observations obtained under field conditions, an additional relative humidity sensor (RHref) was incorporated within the same experimental plot under comparable environmental exposure conditions. This independent signal was used as an operational reference for comparative analysis of temporal atmospheric variability and intersensor coherence within the monitored microclimatic environment.

It is important to clarify that the RHref sensor was not intended to provide a metrological ground-truth reference. Instead, it was employed as an independent operational reference signal whose primary function was to evaluate temporal consistency and com-

parative environmental coherence under real field conditions. This approach is consistent with methodologies commonly applied in low-cost environmental monitoring studies, particularly in rural and heterogeneous environments where the deployment of high-precision meteorological instrumentation is often limited [46].

The analysis of daily variability, considering daytime ($n = 59$) and nighttime ($n = 60$) periods, revealed weak correlations between RH_{ref} and RH_{mean_disp} , defined in this study as the temporal average of the relative humidity measurements recorded by the monitoring device (S1H and S2H) for each analysis period. During daytime conditions, the correlation was $r = -0.094$ ($R^2 = 0.011$; $RMSE = 11.8$), whereas nighttime conditions showed a moderate improvement ($r = -0.219$; $R^2 = 0.044$; $RMSE = 12.9$), as shown in Figure 9.

Rather than indicating anomalous behavior within the monitoring framework, these low correlations likely reflect the strong spatial heterogeneity and dynamic atmospheric variability characteristic of microclimatic processes under real field conditions [47]. In heterogeneous canopy environments, localized atmospheric fluctuations, short-term turbulence, and differences in vegetation shielding may produce substantial variability even between sensors installed within the same experimental area.

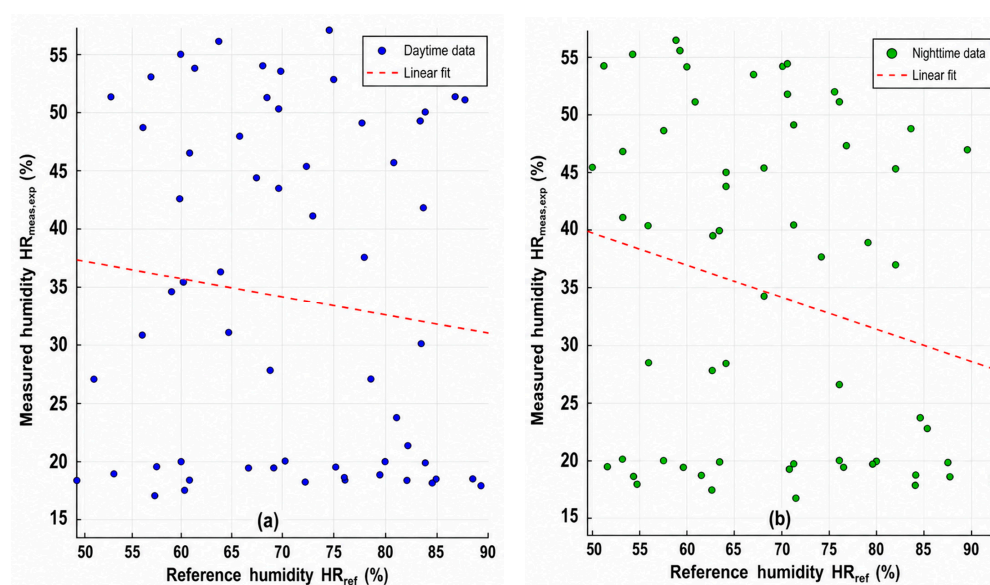


Figure 9. Relationship between measured humidity: (a) During day period; (b) During night period.

The greater coherence observed during nighttime conditions is consistent with enhanced thermal stability and the absence of direct solar radiation, conditions that reduce convective activity and attenuate short-term atmospheric fluctuations [35]. Under these conditions, atmospheric moisture dynamics tend to become more spatially homogeneous, facilitating stronger temporal consistency between environmental observations recorded at different locations within the plantation.

Within the intermediate relative humidity range (approximately 50–55%RH), increased measurement dispersion was observed, resulting in greater variability in the comparison between RH_{ref} and the variables derived from the monitoring system. This behavior is attributed primarily to the inherent sensitivity limitations of low-cost capacitive humidity sensors operating under rapidly changing atmospheric conditions. Similar behaviors have been reported in previous studies involving low-cost environmental sensing technologies deployed under heterogeneous field environments [36].

To reduce the influence of short-term atmospheric fluctuations, the data were subjected to temporal smoothing using a centered moving window, which attenuated high-frequency variability associated with transient atmospheric disturbances and electronic

acquisition noise. In this context, the larger dispersion observed within the 50–55%RH interval should be interpreted as an operational characteristic of low-cost environmental monitoring under dynamic atmospheric conditions rather than as a methodological deficiency [38]. Overall, the analysis supports the interpretation that the environmental observations obtained during the monitoring campaign reflect the high spatial and temporal variability characteristic of canopy-related atmospheric processes under real field conditions. From an environmental perspective, the observed behavior reinforces the importance of considering local atmospheric heterogeneity when interpreting microclimatic humidity dynamics in forest ecosystems.

3.4.2. Vertical Humidity Gradient ($\Delta RH = S2H - S1H$)

The relative humidity gradient (ΔRH) was consistently negative throughout the monitoring period, confirming systematically higher moisture retention beneath the tree canopy and demonstrating the presence of persistent vertical microclimatic stratification within the *Juglans neotropica* Diels plantation. It is important to clarify that the negative values of ΔRH ($\Delta RH \approx -36\%$) do not indicate negative relative humidity; rather, they represent the relative difference between the measurements recorded above the canopy (S2H) and those obtained beneath the canopy (S1H). Consequently, negative ΔRH values indicate that atmospheric humidity remained consistently higher within the microenvironment protected by the foliage than in the more exposed upper atmospheric layer.

From an ecological perspective, this persistent vertical humidity gradient provides empirical evidence of canopy-mediated atmospheric regulation processes under Andean field conditions [39]. The canopy appears to function as a buffering layer that attenuates direct atmospheric exchange, reduces short-term environmental fluctuations, and promotes localized moisture retention beneath the foliage [46]. This behavior is consistent with vegetation-mediated microclimatic regulation mechanisms commonly reported in forest ecosystems characterized by heterogeneous environmental conditions [47].

The mean recorded ΔRH values were $-36.0 \pm 19.1\%$ during the daytime and $-35.0 \pm 20.6\%$ at night, evidencing a stable pattern of vertical moisture stratification (Figure 10). The absence of statistically significant differences between daytime and nighttime conditions (t -test, $p = 0.7807$) suggests that the canopy-induced humidity buffering effect persists throughout the diurnal cycle despite thermal variability and changes in atmospheric radiation conditions.

During daylight hours, the correlation between ΔRH and air temperature was positive ($r = 0.35$), indicating that increasing temperature conditions intensified the atmospheric humidity gradient between canopy levels. In contrast, the relationship between ΔRH and solar radiation was negligible ($r = -0.01$), suggesting that direct radiative forcing was partially moderated by canopy coverage and vegetation shielding effects. During nighttime conditions, both correlations weakened ($r < 0.15$), reflecting the greater atmospheric stability associated with the absence of direct solar radiation.

The persistence of relatively higher humidity conditions beneath the canopy throughout both daytime and nighttime periods indicates that the vegetation layer contributes to maintaining localized atmospheric stability and moisture conservation within the plantation environment. These observations are particularly relevant in mountainous Andean ecosystems, where strong environmental heterogeneity and rapid atmospheric transitions frequently influence near-surface microclimatic behavior.

From a land–atmosphere interaction perspective, the observed humidity stratification suggests that *Juglans neotropica* Diels plantations may contribute to regulating near-surface atmospheric moisture through vegetation-mediated environmental buffering processes. This behavior may support soil moisture conservation and reduce direct exposure to atmospheric mixing within the understory microenvironment [39].

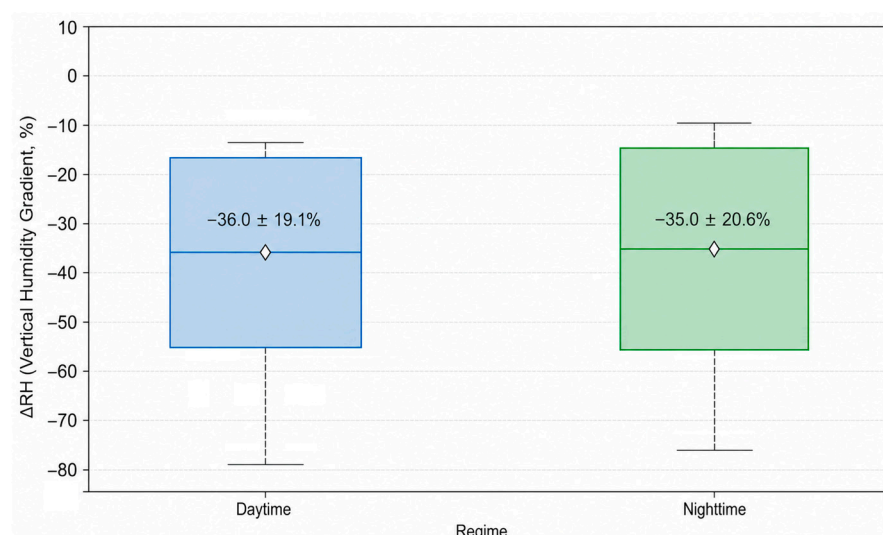


Figure 10. Boxplot of ΔRH by period. The rhombus marker indicates the mean value, and the associated label represents the mean $\pm$ standard deviation.

The continuous environmental dataset generated in this study, therefore, provides empirical evidence of persistent canopy-related atmospheric regulation under real field conditions. Rather than emphasizing the operational characteristics of the monitoring system itself, the results contribute to the understanding of microclimatic dynamics, vertical moisture stratification, and vegetation–atmosphere interactions within heterogeneous Andean forest environments.

3.4.3. Classification of Humid Days ($RH_{ref} \geq 65\%$)

The classification procedure identified that optimal relative humidity mean thresholds of 18.05% for the daytime period and 16.49% for the nighttime period to optimize the detection of high-humidity events. These thresholds were obtained through a grid-search procedure applied to the monitored dataset and should be interpreted as operational classification parameters derived from the observed measurements, rather than as climatic thresholds or environmental inference criteria.

During the daytime, the system achieved an accuracy of 96.6%, with perfect precision and a recall of 96.6%, resulting in an F1 score of 0.983. Out of a total of 59 daily observations, 57 true positives and 2 false negatives were recorded, demonstrating that the device successfully identified most high-humidity events detected by the operational reference sensor. During the nighttime period, the classification was completely accurate, with no false positives or false negatives, confirming the stability of the classification procedure under lower radiation and temperature conditions.

When analyzing overall interperiod behavior, the system maintained highly consistent performance, with an overall accuracy of 98.3%. The Kappa concordance coefficient ($Kappa = 0.000$) reflects the homogeneity of positive cases across the evaluated dataset and should be interpreted within the context of operational classification performance.

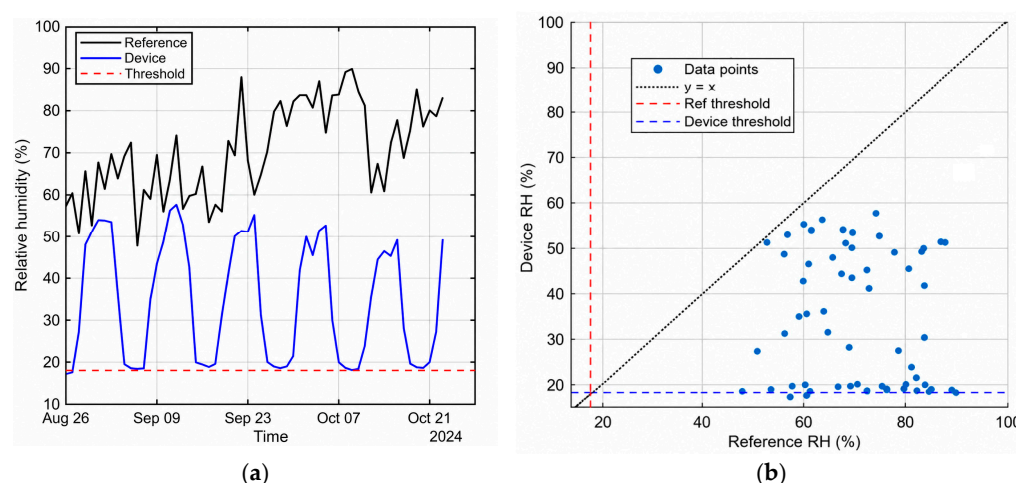
Collectively, the statistical metrics obtained (correlation coefficient, coefficient of determination, RMSE, accuracy, precision, recall, and F1-score) enable a comprehensive evaluation of the monitoring system's operational performance under real field conditions. These metrics quantify both intersensor coherence and the device's classification capability, providing quantitative evidence of its stability and reproducibility in situ. To facilitate the interpretation of the results, the main performance indicators are summarized in Table 3.

Table 3. Performance metrics of the classification system by period.

Period	Threshold (%RH)	RMSE	Accuracy	Precision	Recall	F1
Daytime	18.05	11.8	0.966	1.000	0.966	0.983
Nighttime	16.49	12.9	1.000	1.000	1.000	1.000
Overall	—	—	0.983	1.000	0.983	0.992

Taken together, these results indicate that the system operates consistently under both daytime and nighttime conditions, functioning as an operational humidity-event detection tool within the monitoring framework. In this context, the classification procedure should be understood as part of the device's signal interpretation workflow rather than as a predictive climatic model or environmental inference method.

Figure 11a shows the time series of relative humidity recorded by the device and the reference sensor, along with the classification threshold. It can be observed that the humidity peaks largely coincide between signals, demonstrating the system's capability to identify high-humidity conditions within the monitored dataset. Likewise, Figure 11b presents the scatter plot between the values measured by the device and those obtained from the reference sensor, where the points follow a consistent trend. The threshold lines delineate the operational alert zones defined for the monitoring system.

**Figure 11.** Plots of device versus reference relative humidity during daytime period. (a) Time-series plot; (b) scatter plot.

During the nighttime period, an increase in classification stability was also observed, indicating that this timeframe is suitable for verification and calibration procedures, as shown in Figure 12a,b. The absence of false positives and the minimal number of false negatives indicate stable classification behavior within the monitored dataset, supporting the system's use as an operational monitoring tool rather than as a predictive environmental model.

The comparative analysis of ΔRH revealed high consistency between the evaluated periods. During the daytime, the average value was $-36.04 \pm 19.06\%$, while at night it was $-35.03 \pm 20.56\%$, with no statistically significant differences (t -test, $p = 0.7807$). Cohen's effect size ($d = -0.051$) indicated a practically negligible difference between both periods, confirming that the system's measurement behavior remains uniform under both daytime and nighttime environmental conditions, as shown in Figure 13.

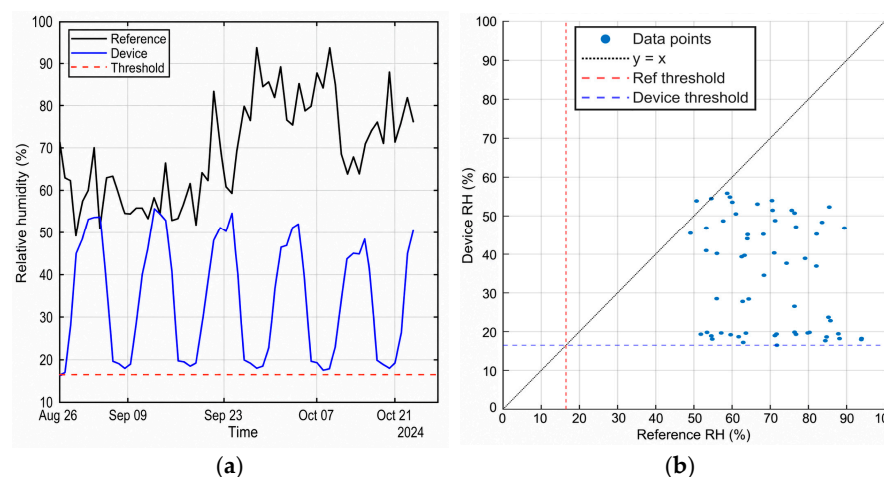


Figure 12. Plots of device versus reference relative humidity during nighttime period. (a) Time-series plot; (b) scatter plot.

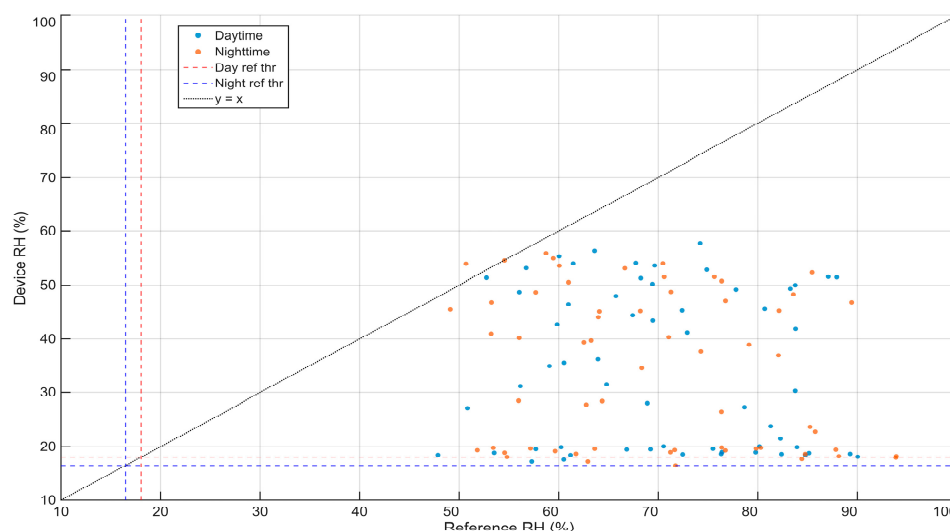


Figure 13. Inter-period comparison of relative humidity measured by the device and the reference sensor, using daytime and nighttime thresholds.

The graphical and metric results demonstrate that the system satisfies operational reliability criteria for continuous environmental monitoring [37]. The classification procedure provides a consistent mechanism for identifying high-humidity events within the monitored dataset, supporting the interpretation of environmental signals obtained from the photovoltaic monitoring device.

Rather than functioning as a predictive climatic model, the implemented methodology operates as an observational and classification framework that enables the detection of humidity variations under real field conditions. This distinction is important to avoid overinterpretation of the classification results while preserving the practical value of the monitoring system for agroforestry applications.

3.4.4. Time Under Saturation

The indicator Pct, representing the daily percentage of time with relative humidity (RH) $\geq 65\%$, recorded averages of 41.1% during the daytime and 38.5% at night, with variability of $\pm 23.3\%$ and $\pm 25.4\%$, respectively. These results indicate that the air remained moderately humid for a significant proportion of time, suggesting favorable conditions for reduced transpiration. The corresponding frequency distributions are shown in Figure 14, where daytime and nighttime periods are compared.

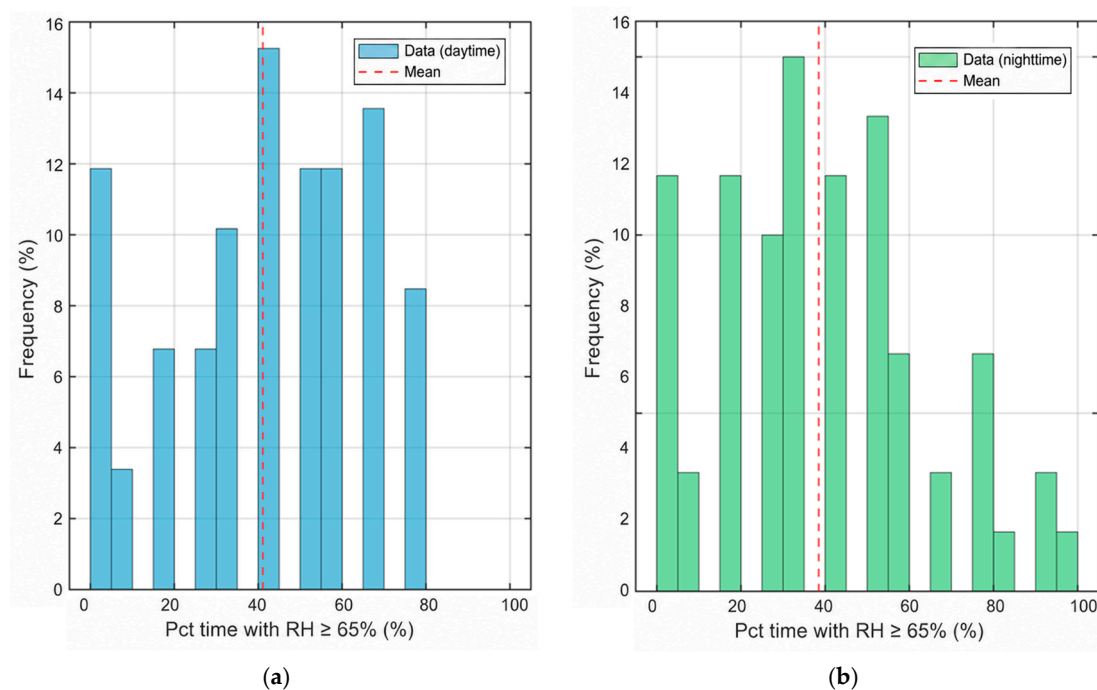


Figure 14. Histograms of Pct_time with RH $\geq$ 65% by period; (a) daytime; (b) nighttime.

This indicator complements the microclimatic analysis of the monitoring system and can be integrated into water balance models or irrigation management strategies, leveraging the continuous recording capability of the photovoltaic system, which enables precise identification of critical ambient humidity conditions in real time.

3.5. Scientific Contribution and Applicability

The integrated analysis demonstrated that the autonomous instrumentation system is capable of performing precise, stable, and continuous measurements under field conditions. Over 60 days of operation, the device recorded 86,072 measurements of relative and soil humidity, maintaining operational stability thanks to continuous photovoltaic power supply and automatic battery management.

The high intersensor correlation between measurements taken below and above the canopy ($r = 0.8535$) confirms the system's reliability and validity. This performance is complemented by the accuracy achieved in the classification of humid days ($RH_{ref} \geq 65\%$), where accuracies exceeded 96% during the day and 100% at night, with an average F1 coefficient of 0.992.

The vertical humidity gradient (ΔRH) was consistently negative ($-36.04 \pm 19.06\%$ daytime and $-35.03 \pm 20.56\%$ nighttime; $p = 0.7807$; $d = -0.051$), confirming that the tree canopy retains moisture and generates a more humid internal microclimate, in agreement with previous studies on microclimatic regulation in neotropical ecosystems [21]. Complementarily, the daily percentage of time with $RH \geq 65\%$ averaged 41.1% during the day and 38.5% at night, indicating that the air remained moderately humid for approximately 40% of the time—reducing transpiration losses but increasing condensation risk [40].

These observations confirm the system's sensitivity and stability for capturing hydric gradients and detecting critical humidity conditions under scenarios of thermal variability. From an engineering perspective, the system integrates a deterministic and computationally efficient methodology that combines statistical automation with the physical robustness of the instrumentation, ensuring traceability, reproducibility, and minimal human intervention. This approach provides a foundation for the development of adaptive

algorithms capable of automatically adjusting humidity thresholds based on real-time climatic conditions.

Furthermore, the dataset obtained represents a valuable resource for modeling evapotranspiration processes, water balance, and irrigation scheduling, particularly in low-cost agricultural and forestry systems. Its application is especially relevant for *Juglans neotropica* Diels plantations, where microclimatic monitoring can optimize water management and improve local productivity, promoting economic and technological development in rural areas [41].

The device's energy autonomy and modular design facilitate its replication in rural environments and restoration ecosystems, promoting the adoption of sustainable sensing technologies and advancing the transition toward precision forestry in Ecuador. Finally, this research lays the groundwork for establishing a comprehensive database for integrating machine learning techniques into environmental monitoring, leveraging the system's high temporal resolution and statistical consistency.

4. Discussion

4.1. Microclimatic Variability and Atmospheric Moisture Dynamics

The continuous monitoring campaign conducted at the Yuyucocha Experimental Farm of the Universidad Técnica del Norte (UTN), located in Imbabura Province, enabled the characterization of atmospheric and soil moisture variability under real field conditions. Over the 60-day observation period, more than 86,000 environmental measurements were collected, revealing persistent temporal variability patterns associated with canopy structure and near-surface atmospheric regulation processes [48].

The environmental observations demonstrated consistent differences between atmospheric conditions measured beneath and above the canopy, indicating the presence of stable microclimatic gradients throughout the monitoring period. In particular, relatively higher humidity levels beneath the canopy suggest the existence of canopy-induced buffering effects associated with reduced atmospheric mixing, moisture retention, and attenuation of short-term atmospheric fluctuations [19,49].

The intersensor correlation ($r = 0.8535$) obtained from the double inverse regression fit reflects strong temporal coherence between atmospheric observations recorded at different canopy levels. Rather than representing a direct physical model of atmospheric moisture transport, this relationship provides empirical evidence of consistent environmental variability patterns across the monitored microclimatic strata. Similar ranges of environmental coherence have been reported in previous field-based atmospheric monitoring studies conducted under heterogeneous climatic conditions [48,50,51].

The temporal persistence observed in the humidity series indicates that the canopy layer exerts a significant influence on near-surface atmospheric conditions, contributing to the regulation of local moisture dynamics. From an environmental perspective, the observed differences between canopy levels are consistent with vegetation-mediated microclimatic regulation processes commonly reported in forest ecosystems [52].

Systematic data processing and temporal smoothing procedures contributed to reducing high-frequency atmospheric noise while preserving the dominant environmental variability patterns within the dataset [53]. This approach facilitated the interpretation of temporal humidity dynamics and supported the identification of persistent atmospheric behavior throughout the monitoring campaign.

Overall, the results indicate that the dataset generated in this study provides a robust empirical representation of atmospheric moisture variability and soil-atmosphere interactions under Andean field conditions. In this context, the principal contribution of the study lies in the characterization of microclimatic dynamics associated with canopy structure and environmental heterogeneity rather than in the monitoring system itself.

4.2. Microclimatic Dynamics and Ecological Interpretation

The vertical humidity gradient ($\Delta RH \approx -36\%$) consistently observed between canopy strata represents a key indicator of persistent microclimatic stratification associated with vegetation structure. This gradient reflects the capacity of the canopy to retain moisture and regulate near-surface atmospheric conditions, contributing to the formation of a more humid and environmentally buffered microenvironment beneath the foliage. The absence of statistically significant differences between daytime and nighttime periods ($p = 0.7807$) indicates temporal stability in this microclimatic pattern, consistent with observations reported in neotropical ecosystems where vegetation cover contributes to atmospheric buffering processes [54,55].

From an ecological perspective, the observed humidity stratification provides empirical evidence of canopy–atmosphere interactions within *Juglans neotropica* Diels plantations. The canopy layer appears to influence local atmospheric moisture conditions by attenuating short-term environmental fluctuations, reducing direct atmospheric mixing, and promoting relatively stable humidity accumulation beneath the foliage. These observations are consistent with vegetation-mediated microclimatic regulation processes commonly reported in forest ecosystems [56]. In particular, the persistence of higher humidity beneath the canopy suggests that the vegetation structure contributes to modifying local vapor exchange dynamics and reducing atmospheric exposure within the understory environment.

The persistence of relatively higher humidity conditions beneath the canopy throughout the monitoring period suggests the existence of localized atmospheric buffering effects associated with canopy structure and reduced atmospheric turbulence. This behavior may contribute to the maintenance of favorable microenvironmental conditions for soil moisture conservation, near-surface hydric stability, and mitigation of rapid atmospheric fluctuations under heterogeneous environmental conditions [57]. In this context, the canopy may function as a regulating interface within the soil–plant–atmosphere continuum, modulating local moisture dynamics under Andean field conditions. The observed buffering behavior may also contribute to reducing evaporative stress within the understory microenvironment by maintaining more stable atmospheric moisture conditions beneath the foliage layer.

From an ecohydrological perspective, the coexistence of relatively stable soil moisture conditions and persistent atmospheric humidity stratification suggests the presence of coupled moisture-regulation processes operating between the soil, vegetation, and atmosphere. The canopy-mediated attenuation of atmospheric variability may facilitate localized moisture conservation and contribute to stabilizing near-surface hydric conditions despite external environmental fluctuations [46]. These interactions are particularly relevant in mountainous Andean ecosystems, where steep topography and heterogeneous environmental conditions frequently intensify short-term atmospheric variability and water exchange dynamics [58].

These findings are particularly relevant in the context of forest degradation in Ecuador's Andean region, where vegetation loss has affected ecosystem functionality and environmental regulation processes, with estimated deforestation rates of approximately 1.16% annually [59].

In this context, *Juglans neotropica* Diels may contribute to the maintenance of local microclimatic stability and soil moisture conservation, supporting ecological restoration processes and environmental resilience in degraded mountainous ecosystems [60]. The observed atmospheric buffering behavior therefore highlights the ecological importance of native canopy structure for maintaining localized environmental stability in heterogeneous mountainous landscapes.

The continuous dataset generated in this study provides a useful basis for interpreting moisture-retention dynamics and microclimatic variability under real field conditions.

Rather than emphasizing the characteristics of the monitoring system itself, the results contribute to the understanding of atmospheric variability influenced by vegetation structure and canopy stratification, providing relevant information for ecological monitoring and agroforestry management under Andean environmental conditions [61]. Furthermore, the persistent humidity gradients identified throughout the monitoring period provide empirical evidence of canopy-mediated atmospheric regulation processes operating within native Andean forest environments.

4.3. Scalability in Environmental Monitoring Contexts

The analytical framework implemented in this study enabled the processing of large environmental datasets while maintaining computational efficiency under continuous monitoring conditions [61]. The adopted methodology facilitated the systematic analysis of atmospheric and soil moisture variability, supporting the characterization of temporal microclimatic dynamics under real field environments.

From an environmental perspective, the methodology supports the generation of continuous datasets capable of representing atmospheric variability and humidity dynamics across different canopy levels. Although the present study focused on *Juglans neotropica* Diels plantations, the monitoring approach may be adaptable to other environmental conditions and forest ecosystems characterized by heterogeneous microclimatic behavior [62].

The continuous observations obtained during the monitoring campaign demonstrate the feasibility of implementing long-term environmental monitoring strategies in rural and mountainous regions using autonomous low-cost instrumentation. In particular, the acquisition of high-resolution temporal datasets may contribute to improving the understanding of canopy-related atmospheric regulation processes and soil–atmosphere interactions under field conditions [63]. In the context of Andean ecosystems, where environmental heterogeneity and limited meteorological infrastructure frequently restrict long-term field observations, continuous microclimatic monitoring approaches may provide useful information for ecological characterization and environmental variability assessment. From a practical perspective, the ability to generate stable environmental datasets under real field conditions represents an important contribution for future ecological monitoring efforts in rural environments.

4.4. Integration with Environmental Modeling Frameworks

The dataset generated in this study provides a useful basis for interpreting microclimatic variability and moisture dynamics under real field conditions. The temporal resolution and consistency of the observations enable the characterization of atmospheric humidity patterns associated with canopy structure and soil moisture behavior in heterogeneous mountainous environments [64]. The implemented monitoring framework demonstrated the feasibility of continuous environmental sensing using autonomous low-cost instrumentation under field conditions. In particular, the results revealed persistent vertical humidity gradients and stable temporal patterns, supporting the interpretation of canopy-induced microclimatic regulation processes and near-surface atmospheric variability [51].

Rather than functioning as a predictive environmental modeling platform, the proposed methodology was designed as an observational framework focused on the empirical characterization of atmospheric and soil moisture variability. This distinction is important because the present study did not directly measure additional environmental variables commonly required for complete evapotranspiration or surface energy balance modeling, such as net radiation, wind speed, or turbulent heat fluxes [65,66].

Nevertheless, the continuous dataset generated in this study may support future environmental analyses related to moisture transport, atmospheric variability, and canopy-scale microclimatic processes in Andean ecosystems. From an environmental perspective,

the results contribute to the understanding of vegetation-mediated atmospheric regulation and moisture dynamics under heterogeneous mountainous conditions.

The approach adopted in this research emphasizes operational stability, temporal coherence, and environmental interpretability rather than advanced predictive capabilities or speculative technological expansion. In this sense, the principal contribution of the study lies in the empirical characterization of near-surface atmospheric variability and soil moisture dynamics under real field conditions, contributing to the understanding of land–atmosphere interactions in heterogeneous mountainous ecosystems.

4.5. Environmental and Socioeconomic Implications

The generation of continuous microclimatic datasets contributes to addressing information gaps in environmental monitoring, particularly in rural areas where climatic variability plays a key role in agricultural productivity [67]. Access to detailed environmental data may support improved understanding of local atmospheric variability and facilitate more informed water resource management strategies under heterogeneous environmental conditions.

The focus on *Juglans neotropica* Diels highlights the importance of monitoring native species within Andean ecosystems, particularly in the context of conservation and ecological restoration efforts [68]. Continuous environmental observations provide valuable information for understanding ecosystem dynamics, canopy-related atmospheric regulation, and vegetation-mediated moisture retention processes under real field conditions [69].

Additionally, the use of energy-autonomous monitoring approaches aligns with sustainable development strategies, promoting the implementation of accessible environmental monitoring methodologies in rural and agroforestry contexts [70].

4.6. Technological Development Perspectives

The prototype demonstrated stable operation for continuous monitoring of soil and atmospheric humidity under real field conditions. The implemented autonomous framework enabled the acquisition of high-resolution environmental datasets, facilitating the characterization of temporal microclimatic variability and canopy-related humidity gradients throughout the monitoring period.

Although the present study focused on empirical environmental characterization rather than predictive environmental modeling, the generated dataset may support future investigations related to atmospheric variability, moisture transport processes, and soil–plant–atmosphere interactions in Andean ecosystems. In particular, the continuous observations obtained under field conditions provide useful information for comparative microclimatic analysis in heterogeneous mountainous environments.

From a practical perspective, the methodology demonstrated the applicability of low-cost autonomous monitoring systems for long-term environmental observations in rural and agroforestry contexts. The operational stability and temporal coherence observed throughout the experimental period support the feasibility of implementing continuous environmental monitoring strategies in regions where access to conventional meteorological infrastructure is limited.

5. Conclusions

The present study provides empirical evidence of persistent microclimatic stratification within an Andean *Juglans neotropica* Diels plantation under real field conditions. Based on more than 86,000 environmental measurements collected over a continuous 60-day monitoring period, the results revealed stable and reproducible patterns of atmospheric humidity variability associated with vegetation structure and canopy-related environmental regulation.

The principal scientific contributions of this research lies in the identification and characterization of persistent vertical humidity gradients between canopy strata ($\Delta RH \approx -36\%$), demonstrating systematically higher atmospheric moisture conditions beneath the canopy compared to the upper atmospheric layer. This behavior provides empirical evidence of canopy-mediated atmospheric buffering processes operating within heterogeneous Andean environments, where vegetation structure contributes to moisture retention, attenuation of atmospheric fluctuations, and regulation of near-surface environmental conditions.

The temporal stability of the observed humidity gradients under both daytime and nighttime conditions indicates that the canopy functions as a regulating interface within the soil–plant–atmosphere continuum. The persistence of relatively higher humidity conditions beneath the foliage suggests that vegetation structure plays an important ecological role in reducing direct atmospheric mixing and promoting localized microclimatic stability under variable mountainous environmental conditions.

The combined analysis of atmospheric humidity and soil moisture variability also revealed the existence of coupled environmental dynamics between atmospheric and edaphic layers. While atmospheric humidity exhibited higher-frequency fluctuations associated with short-term environmental variability, soil moisture maintained comparatively more stable temporal behavior, suggesting partial microclimatic decoupling between soil and atmospheric layers mediated by canopy structure.

The strong intersensor coherence obtained between canopy levels ($r = 0.8535$) supports the temporal consistency of the environmental observations and confirms the persistence of differentiated atmospheric conditions within the plantation environment. Rather than representing a mechanistic atmospheric model, the regression analysis provided an empirical representation of environmental coherence between canopy strata under continuous field monitoring conditions.

Although the operational reference humidity signal (RH_{ref}) showed limited direct correlation with the monitored variables, the environmental dataset demonstrated strong internal temporal consistency and stable atmospheric variability patterns throughout the monitoring campaign. These results reinforce the importance of intersensor coherence and continuous environmental observations for interpreting microclimatic dynamics in heterogeneous ecosystems where direct metrological ground-truth validation may be limited.

From an ecological and atmospheric perspective, the findings contribute to the understanding of land–atmosphere interactions in native Andean forest ecosystems. The observed canopy buffering behavior and persistent atmospheric moisture stratification highlight the ecological importance of vegetation structure in regulating near-surface humidity dynamics and maintaining localized environmental stability in mountainous landscapes affected by environmental heterogeneity and forest degradation.

Overall, this study contributes new high-resolution field evidence regarding canopy-mediated atmospheric regulation and persistent microclimatic moisture stratification in *Juglans neotropica* Diels plantations. The generated dataset therefore represents a valuable empirical basis for future research focused on microclimatic dynamics, ecohydrological interactions, and environmental variability in heterogeneous Andean ecosystems.

Author Contributions: Conceptualization, J.G.-T. and J.P.R.-A.; methodology, J.G.-T., J.P.R.-A. and P.T.-E.; software, J.G.-T.; validation, J.G.-T., P.T.-E. and L.H.Á.-J.; formal analysis, J.G.-T. and J.P.R.-A.; investigation, J.G.-T., J.P.R.-A. and L.H.Á.-J.; resources, P.T.-E. and L.H.Á.-J.; data curation, J.G.-T.; writing—original draft preparation, J.G.-T. and J.P.R.-A.; writing—review and editing, J.G.-T., J.P.R.-A., P.T.-E. and L.H.Á.-J.; visualization, J.G.-T.; supervision, P.T.-E.; project administration, J.G.-T. and P.T.-E.; funding acquisition, P.T.-E. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by InvestigaUTN-2024-1427 project, receiving funding from Universidad Técnica del Norte.

Institutional Review Board Statement: Not applicable. The study did not involve humans or animals.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Universidad Técnica del Norte was the institution that contributed to funding this study by providing all the technological tools to achieve the objectives.

Acknowledgments: The authors express their gratitude to the Universidad Técnica del Norte (UTN) for supporting this research. In addition, the authors gratefully acknowledge the valuable contributions of Jorge-Luis Ramírez-López from Universidad Técnica del Norte to the development of the theoretical framework related to *Juglans neotropica* Diels, particularly concerning its ecological and forestry importance in Andean ecosystems. During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-5, 2025) for grammar correction, language editing, and improving the clarity of sentences. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

UTN	Universidad Técnica del Norte
FICAYA	Facultad de Ingeniería en Ciencias Agropecuarias y Ambientales
S1H	Relative humidity sensor placed below the canopy
S2H	Relative humidity sensor placed above the canopy
Hsoil	Soil humidity measured at 25 cm depth
RHref	Reference relative humidity sensor
ΔRH	Difference in relative humidity between the device and reference
%RH	Relative humidity percentage
PET	Potential Evapotranspiration
Ra	Extraterrestrial radiation
DOY	Day of Year
DW	Durbin–Watson statistic
RMSE	Root Mean Square Error
Acc	Accuracy of classification
F1	F1-score or harmonic mean between Precision and Recall
Prec	Precision
Rec	Recall or Sensitivity
Kappa	Cohen’s Kappa coefficient of agreement
TP	True Positives
FP	False Positives
TN	True Negatives
FN	False Negatives
N	Total number of analyzed observations
Thr	Classification threshold
p	p -value or probability value in statistical tests
d	Cohen’s effect size (Cohen’s d)
SPI	Serial Peripheral Interface
IoT	Internet of Things
AI	Artificial Intelligence
ML	Machine Learning

References

1. Del Barrio, L. Potencialidades Ecológicas y Socioculturales para el Desarrollo de un Modelo de Producción Agroecológico en la Interfase Urbano Rural Lunlunta, Maipú–Mendoza. Ph.D. Thesis, Universidad Nacional de La Plata, Buenos Aires, Argentina, 2023.
2. Sierra, R.; Calva, O.; Guevara, A. *La Deforestación en el Ecuador, 1990–2018: Factores Promotores y Tendencias Recientes*; Ministerio de Ambiente y Agua del Ecuador: Quito, Ecuador, 2021.
3. Günter, S.; Weber, M.; Erreis, R.; Aguirre, N. Influence of Distance to Forest Edges on Natural Regeneration of Abandoned Pastures: A Case Study in the Tropical Mountain Rain Forest of Southern Ecuador. *Eur. J. For. Res.* **2006**, *126*, 67–75. <https://doi.org/10.1007/s10342-006-0156-0>.
4. Villacís, B.; Carrillo, D. *Estadística Demográfica en el Ecuador: Diagnóstico y Propuesta*; INEC: Quito, Ecuador, 2012.
5. Ministerio del Ambiente del Ecuador. *Evaluación Nacional Forestal: Sistematización de la Experiencia*; Ministerio del Ambiente del Ecuador: Quito, Ecuador, 2014.
6. Kvist, L.P.; Aguirre, Z.; Sánchez, O. Bosques Montanos Bajos Occidentales en Ecuador y Sus Plantas Útiles. In *Botánica Económica de los Andes Centrales*; Universidad Mayor de San Andrés: La Paz, Bolivia, 2006; pp. 205–223.
7. Aguirre Mendoza, Z. Composición Florística, Estructura y Endemismo del Componente Leñoso de un Bosque Montano en el Sur del Ecuador. *Arnaldia* **2017**, *24*, 543–556. <https://doi.org/10.22497/arnaldia.242.24207>.
8. Toro Vanegas, E.; Roldan Rojas, I.C. Estado del Arte, Propagación y Conservación de *Juglans neotropica* Diels., en Zonas Andinas. *Madera Bosques* **2018**, *24*. <https://doi.org/10.21829/myb.2018.2411560>.
9. Stone, D.E.; Oh, S.-H.; Tripp, E.A.; Ríos, G.L.E.; Manos, P.S. Natural History, Distribution, Phylogenetic Relationships, and Conservation of Central American Black Walnuts (*Juglans* Sect. *Rhysocaryon*). *J. Torrey Bot. Soc.* **2009**, *136*, 1–25. <https://doi.org/10.3159/08-RA-036R.1>.
10. Elsayed, A.; Rixon, S.; Levison, J.; Binns, A.; Goel, P. Application of Classification Machine Learning Algorithms for Characterizing Nutrient Transport in a Clay Plain Agricultural Watershed. *J. Environ. Manag.* **2023**, *345*, 118924. <https://doi.org/10.1016/j.jenvman.2023.118924>.
11. Peña-Arancibia, J.L.; Mahboob, M.G.; Islam, A.T.; Mainuddin, M.; Yu, Y.; Ahmad, M.D.; Ibn Murad, K.F.; Saha, K.K.; Hossain, A.; Moniruzzaman, M.; et al. The Green Revolution from Space: Mapping the Historic Dynamics of Main Rice Types in One of the World's Food Bowls. *Remote Sens. Appl.* **2021**, *21*, 100460. <https://doi.org/10.1016/j.rsase.2020.100460>.
12. Fritschen, L.J.; Gay, L.W. An Exchange System for Precise Measurements of Temperature and Humidity Gradients in the Air Near the Ground. *Hydrol. Water Resour. Ariz. Southwest* **1979**, *9*, 37–43.
13. Lindroth, A.; Norén, B. Evapotranspiration Measurements in Järdrås, Instrumentation, Data Gathering and Processing. In *Developments in Agricultural and Managed Forest Ecology*; Elsevier: Amsterdam, The Netherlands, 1979; pp. 15–26.
14. Jiménez-Pérez, A.; Cach-Pérez, M.J.; Valdez-Hernández, M.; De la Rosa-Manzano, E. Effect of Canopy Management in the Water Status of Cacao (*Theobroma Cacao*) and the Microclimate within the Crop Area. *Bot. Sci.* **2019**, *97*, 701–710. <https://doi.org/10.17129/botsci.2256>.
15. Fyllas, N.M.; Bentley, L.P.; Shenkin, A.; Asner, G.P.; Atkin, O.K.; Díaz, S.; Enquist, B.J.; Farfan-Rios, W.; Gloor, E.; Guerrieri, R.; et al. Solar Radiation and Functional Traits Explain the Decline of Forest Primary Productivity along a Tropical Elevation Gradient. *Ecol. Lett.* **2017**, *20*, 730–740. <https://doi.org/10.1111/ele.12771>.
16. Lee, S.-W.; Lee, Y.-S.; Choi, B.I.; Kim, Y.-G.; Kim, S. Relative Humidity Measurements of a Thin-Film Humidity Sensor in Condensing Conditions in the Temperature Range from −40 °C to 5 °C. *Meas. Sci. Technol.* **2024**, *35*, 075801. <https://doi.org/10.1088/1361-6501/ad3c62>.
17. von Büren, R.S.; Zehnder, M.; von Oppen, J.; Rossi, C.; Wipf, S.; Rumpf, S. A Novel Method for Monitoring Above- and Below-ground Microclimates in Mountain Ecosystems Year-Round. *J. Veg. Sci.* **2025**, *36*, e70063. <https://doi.org/10.1111/jvs.70063>.
18. Makar, P.A.; Staebler, R.M.; Akingunola, A.; Zhang, J.; McLinden, C.; Kharol, S.K.; Pabla, B.; Cheung, P.; Zheng, Q. The Effects of Forest Canopy Shading and Turbulence on Boundary Layer Ozone. *Nat. Commun.* **2017**, *8*, 15243. <https://doi.org/10.1038/ncomms15243>.
19. Zhang, Y.; Hogan, J.A.; Sun, H. Janzen's Mountain Passes Hypothesis in a Changing World: Pitfalls and Opportunities. *New Phytol.* **2025**, *248*, 1126–1131. <https://doi.org/10.1111/nph.70433>.
20. Werner, C.; Wallrabe, U.; Christen, A.; Comella, L.; Dormann, C.; Göritz, A.; Grote, R.; Haberstroh, S.; Jouda, M.; Kiese, R.; et al. ECOSENSE—Multi-Scale Quantification and Modelling of Spatio-Temporal Dynamics of Ecosystem Processes by Smart Autonomous Sensor Networks. *Res. Ideas Outcomes* **2024**, *10*, e129357. <https://doi.org/10.3897/rio.10.e129357>.

21. Murakami, M.; Nunes Ramos, F.; Durand, M.; Ashton, R.; Batke, S.P. Quantification and Variation of Microclimatic Variables Within Tree Canopies—Considerations for Epiphyte Research. *Front. For. Glob. Change* **2022**, *5*, 828725. <https://doi.org/10.3389/ffgc.2022.828725>.
22. Xie, Z.; Ma, Y.; Hu, Z.; Ma, W.; Chen, X.; Wang, B.; Han, C. The Integrated Observation Network of Land-Atmosphere Interactions over Heterogeneous Landscapes of the Tibetan Plateau. In Proceedings of the 25th EGU General Assembly, Vienna, Austria and Online, 23–28 April 2023.
23. Hu, X.; Wu, X.; Shao, S.; Yan, C. Effects of Vertical Spatial Resolution of Sounding Data on Meteorological Parameters. In *Proceedings of the Sixth Conference on Frontiers in Optical Imaging and Technology: Novel Technologies in Optical Systems*; Wang, P., Xue, D., Eds.; SPIE: Bellingham, WA, USA, 2024; p. 20.
24. Asner, G.P. Mesoscale Exploration and Conservation of Tropical Canopies in a Changing Climate. In *Treetops at Risk*; Springer: New York, NY, USA, 2013; pp. 177–193.
25. Fierke, J.; Putzenlechner, B.; Simon, A.; Gowda, J.H.; Reiter, E.J.; Walentowski, H.; Kappas, M. Modelling Microclimatic Variability in Andean Forests of Northern Patagonia. *Int. J. Biometeorol.* **2025**, *69*, 1279–1295. <https://doi.org/10.1007/s00484-025-02891-x>.
26. Rekwar, R.K.; Patra, A.; Jatav, H.S.; Singh, S.K.; Mohapatra, K.K.; Kundu, A.; Dutta, A.; Trivedi, A.; Sharma, L.D.; Anjum, M.; et al. Ecological Aspects of the Soil-Water-Plant-Atmosphere System. In *Plant Perspectives to Global Climate Changes*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 279–302.
27. Parry, M.L.; Carter, T.R.; Konijn, N.T. The Effects of Variations in Mean Temperature and Frost Risk. In *The Impact of Climatic Variations on Agriculture*; Springer: Dordrecht, The Netherlands, 1988; pp. 443–459.
28. Arias-Muñoz, P.; Cabrera-García, S.; Jácome-Aguirre, G. A Multicriteria Geographic Information System Analysis of Wildfire Susceptibility in the Andean Region: A Case Study in Ibarra, Ecuador. *Fire* **2024**, *7*, 81. <https://doi.org/10.3390/fire7030081>.
29. Montilla Pacheco, A.d.J.; Mora Pisco, C.I.; Durán Vasco, M.E.; Pastrán Calles, F.R. Contribución al estudio de la geografía climática del Ecuador continental. *Cienc. Unemi* **2024**, *17*, 237–248. <https://doi.org/10.29076/issn.2528-7737vol17iss44.2024pp237-248p>.
30. Vanegas Zabala, G.; Samaniego, F.; Urquiza-Alvarez, C.E. Multivariate Nonlinear Analysis of Climatological Variables and Its Effect on Local Temperature. *EASI Ing. Cienc. Apl. Ind.* **2024**, *3*, 1–7. <https://doi.org/10.53591/easi.v3i1.0532>.
31. Hou, N.; Li, B.; Tong, Y. Study on the effects of nitrogen deficiency on grain iron and zinc concentrations of landrace and bred wheat varieties in China. *J. Plant Nutr.* **2011**, *34*, 830–838. <https://doi.org/10.1080/01904167.2011.544352>.
32. Unger, P.W. *Soil and Water Conservation Handbook*; CRC Press: Boca Raton, FL, USA, 2006; ISBN 9781482277876.
33. Mendoza Moreno, S.F.; Inzunza Ibarra, M.A.; Román López, A.; Villa Castorena, M.M.; Catalán Valencia, E.A.; Lagarda Murrieta, Á. Patrón de Distribución de Humedad Óptimo en Nogal con Riego por Microaspersión. *Agrofaz Publicación Semest. Investig. Científica* **2005**, *5*, 725–732.
34. Ramírez-López, J.-L.; Añazco, M.; Vallejos, H.; Arcos, C.; Estrada, K. Assessment of Three Provenances of *Juglans Neotropica* Diels to Identify Optimal Seed Sources in the Northern Ecuadorian Andes. *Int. J. Plant Biol.* **2025**, *16*, 87. <https://doi.org/10.3390/ijpb16030087>.
35. Majewski, J. Low Humidity Characteristics of Polymer-Based Capacitive Humidity Sensors. *Metrol. Meas. Syst.* **2017**, *24*, 607–616. <https://doi.org/10.1515/mms-2017-0048>.
36. Ortiz Diaz, H.A.; Escobar Amado, C.D.; Sepúlveda Mora, S.B. Análisis Estadístico de Variables Climatológicas en la Ciudad de Cúcuta. *Respuestas* **2018**, *23*, 39–44. <https://doi.org/10.22463/0122820X.1328>.
37. Pavanello, M.; Bordonni, M.; Vivaldi, V.; Reguzzoni, M.; Tamburini, A.; Villa, F.; Meisina, C. Low-Cost Sensors for the Measurement of Soil Water Content for Rainfall-Induced Shallow Landslide Early Warning Systems. *Water* **2024**, *16*, 3244. <https://doi.org/10.3390/w16223244>.
38. Ságová, Z.; Kuznetsov, P.; Evstigneev, V.; Krenický, T.; Voronin, D.; Kotelnikov, D.; Yakimovich, B. Improving the Accuracy of Air Temperature Monitoring for Automated Tasks in Agriculture Using Affordable Meteorological Equipment. *Acta Technol. Agric.* **2025**, *28*, 176–182. <https://doi.org/10.2478/ata-2025-0022>.
39. Behera, S.; Chavan, S.B.; Deshmukh, P.P. Microclimate Modification Through Agroforestry Influences Crop Yield Under Extreme Weather Conditions. *Clim. Change Environ. Sustain.* **2024**, *12*, 12–20. <https://doi.org/10.5958/2320-642X.2024.00002.1>.
40. Watson, P.; Otani, H.; Maughan, R.J. Influence of Relative Humidity on Prolonged Exercise Capacity in a Warm Environment. *Br. J. Sports Med.* **2011**, *45*, A3.3–A4. <https://doi.org/10.1136/bjsports-2011-090606.10>.

41. Chaudhary, N.; Singh, G.; Ather, D.; Kler, R.; Bhandwal, M. Arduino-Based Monitoring of Microclimatic Variables for Precision Agriculture in Sugarcane Cultivation. In *Proceedings of the 2023 4th International Conference on Computation, Automation and Knowledge Management (ICCAKM)*; IEEE: New York, NY, USA, 2023; pp. 1–6.
42. Gonzalez Mera, E.A.; Paredes Anchatipan, A.D.; Vásquez Carrera, P.J. Predicción de Estrés Hídrico Mediante Machine Learning Utilizando Sensores LoT de Monitoreo Ambiental: Caso de Estudio En Cultivos de Café de Centro Experimental Sacha Wiwa. *ImmDev* **2025**, *4*, 14–28. <https://doi.org/10.69583/inndev.v4n1.2025.153>.
43. Rousseeuw, P.J.; Hubert, M. Anomaly Detection by Robust Statistics. *WIREs Data Min. Knowl. Discov.* **2018**, *8*. <https://doi.org/10.1002/widm.1236>.
44. Suriano, D.; Abulude, F.O. Monitoring Gas Emissions in Agricultural Productions through Low-Cost Technologies: The POREM (Poultry-Manure-Based Bio-Activator for Better Soil Management through Bioremediation) Project Experience. *Earth* **2024**, *5*, 564–582. <https://doi.org/10.3390/earth5040029>.
45. Morozov, O.G.; Shagvaliev, R.M.; Grabovetcky, D.S.; Shagvaliev, T.R.; Sarvarova, L.M. Reference Sensor of Addressable Type for Qualitative and Quantitative Air Monitoring: Physical Principles of Design and Mathematical Analysis. In *Proceedings of the 2024 Systems of Signal Synchronization, Generating and Processing in Telecommunications (SYNCHROINFO)*; IEEE: New York, NY, USA 2024; pp. 1–4.
46. Davis, K.T.; Dobrowski, S.Z.; Holden, Z.A.; Higuera, P.E.; Abatzoglou, J.T. Microclimatic Buffering in Forests of the Future: The Role of Local Water Balance. *Ecography* **2019**, *42*, 1–11. <https://doi.org/10.1111/ecog.03836>.
47. Unsworth, M.H. Climate and Air Pollution as Determinants of Forest Ecosystem Processes. In *Responses of Forest Ecosystems to Environmental Changes*; Springer: Dordrecht, Netherlands, 1992; pp. 63–75.
48. Ali, S.; Glass, T.; Parr, B.; Potgieter, J.; Alam, F. Low Cost Sensor With IoT LoRaWAN Connectivity and Machine Learning-Based Calibration for Air Pollution Monitoring. *IEEE Trans. Instrum. Meas.* **2021**, *70*, 1–11. <https://doi.org/10.1109/TIM.2020.3034109>.
49. Tinoco-Jaramillo, L.; Vargas-Tierras, Y.; Habibi, N.; Caicedo, C.; Chanaluiza, A.; Paredes-Arcos, F.; Viera, W.; Almeida, M.; Vásquez-Castillo, W. Agroforestry Systems of Cocoa (*Theobroma Cacao* L.) in the Ecuadorian Amazon. *Forests* **2024**, *15*, 195. <https://doi.org/10.3390/f15010195>.
50. Lee, H.; Kang, J.; Kim, S.; Im, Y.; Yoo, S.; Lee, D. Long-Term Evaluation and Calibration of Low-Cost Particulate Matter (PM) Sensor. *Sensors* **2020**, *20*, 3617. <https://doi.org/10.3390/s20133617>.
51. Kunić, Z.; Mršić, L.; Đambić, G.; Ražov, T. Innovative Air-Preconditioning Method for Accurate Particulate Matter Sensing in Humid Environments. *Sensors* **2024**, *24*, 5477. <https://doi.org/10.3390/s24175477>.
52. de Souza, K.M.; Candido, L.A.; Corrêa, P.B.; de Melo Monte, M.J.; Ramos, W.M.P.; Timoteo, G.G. Análise do Efeito de Amortecimento do Microclima da Floresta de Sub-Bosque da Reserva Florestal Adolpho Ducke na Amazônia Central. *Rev. Bras. Climatol.* **2025**, *37*, 330–359. <https://doi.org/10.55761/abclima.v37i21.19670>.
53. Shynkarenko, V.I.; Makarov, O.V. Study of the Efficiency of Some Deterministic Preprocessing Methods for Sorting Algorithms. *Probl. Program.* **2023**, 3–14. <https://doi.org/10.15407/pp2023.04.003>.
54. Klamerus-Iwan, A.; Link, T.E.; Keim, R.F.; Van Stan, J.T., II. Storage and Routing of Precipitation Through Canopies. In *Precipitation Partitioning by Vegetation*; Springer International Publishing: Cham, Switzerland, 2020; pp. 17–34.
55. Deng, Y.; Dong, J.; Zhang, W.; Yuan, S.; Tan, Z.; Song, Q.; Deng, X.; Cao, M. Quantifying the Vertical Microclimate Profile within a Tropical Seasonal Rainforest, Based on Both Ground- and Canopy-Referenced Approaches. *iForest* **2022**, *15*, 24–32. <https://doi.org/10.3832/ifor3780-014>.
56. Bouwen, K.; Domec, J.-C.; Charru, M.; Ogée, J. The Impact of Forest Canopy Structure on the Understory Microclimate: A Physics-Based Approach and Sensitivity Analysis. In *Proceedings of the European Geosciences Union General Assembly 2024 (EGU24)*, Vienna, Austria, 14–19 April 2024.
57. Xie, Y.; Wang, Y.; Huang, D.; Chen, X.; Deng, H. Vegetation Transpiration Drives Root-Zone Soil Moisture Depletion in Subtropical Humid Regions: Evidence from GLDAS Catchment Simulations in Fujian Province. *Atmosphere* **2025**, *16*, 1180. <https://doi.org/10.3390/atmos16101180>.
58. Pérez-Giraldo, L.C.; Cerda-Paredes, J.M.; Craven, D.; Lopatin, J. Environmental Heterogeneity and Spatial Variation Mediates Plant Diversity and Ecosystem Stability in Mountain Ecosystems of the Mediterranean Andes *EcoEvoRxiv* **2025**. <https://doi.org/10.1002/ecog.08305>.
59. Torracchi Carrasco, J.E. Deforestación y Pérdida de Hábitat en Bosques de Montaña en la Cuenca Alta del Río Zamora (Loja, Ecuador). Ph.D. Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2015. <https://doi.org/10.20868/UPM.THESIS.39446>.

60. Palacios-Herrera, B.; Pereira-Lorenzo, S.; Pucha-Cofrep, D. Influence of Climate, Soil, and Topography on the Phenotypic Traits of *Juglans neotropica* Diels Matrix Trees in Natural and Artificial Populations of the Loja and Zamora-Chinchi provinces of Ecuador. *Preprints* **2025**. <https://doi.org/10.20944/preprints202501.1434.v1>.
61. Mestre, G.; Ruano, A.; Duarte, H.; Silva, S.; Khosravani, H.; Pesteh, S.; Ferreira, P.; Horta, R. An Intelligent Weather Station. *Sensors* **2015**, *15*, 31005–31022. <https://doi.org/10.3390/s151229841>.
62. Cariou, C.; Moiroux-Arvis, L.; Pinet, F.; Chanut, J.-P. Internet of Underground Things in Agriculture 4.0: Challenges, Applications and Perspectives. *Sensors* **2023**, *23*, 4058. <https://doi.org/10.3390/s23084058>.
63. Cevallos Suarez, M.; Urdaneta, F.; Jaimes, E.; Rodríguez Balza, M. Transición Agroecológica de los Sistemas de Producción Agrícola de la Provincia de Imbabura Ecuador. *Rev. Fac. Agron. Univ. Zulia* **2020**, *37*, 69–94.
64. Niu, H.; Hollenbeck, D.; Zhao, T.; Wang, D.; Chen, Y. Evapotranspiration Estimation with Small UAVs in Precision Agriculture. *Sensors* **2020**, *20*, 6427. <https://doi.org/10.3390/S20226427>.
65. Alfieri, J.G.; Blanken, P.D.; Yates, D.N.; Steffen, K. Variability in the Environmental Factors Driving Evapotranspiration from a Grazed Rangeland during Severe Drought Conditions. *J. Hydrometeorol.* **2007**, *8*, 207–220. <https://doi.org/10.1175/JHM569.1>.
66. Alfieri, J.G.; Niyogi, D.; Zhang, H.; LeMone, M.A.; Chen, F. Quantifying the Spatial Variability of Surface Fluxes Using Data from the 2002 International H2O Project. *Bound.-Layer Meteorol.* **2009**, *133*, 323–341. <https://doi.org/10.1007/s10546-009-9406-2>.
67. Rivera Guzmán, E.F.; Mañay Chochos, E.D.; Chiliquinga Malliquinga, M.D.; Baldeón Egas, P.F.; Toasa Guachi, R.M. LoRa Network-Based System for Monitoring the Agricultural Sector in Andean Areas: Case Study Ecuador. *Sensors* **2022**, *22*, 6743. <https://doi.org/10.3390/s22186743>.
68. Ramos, C.; Zagal, E.; Timmusk, S.; Dube, F.; Paulino, L.; Ortiz, J.; Intriago, J.; Fuentes, J.P. Soil Carbon Sequestration in “Nothofagus Obliqua” Forests with Different Canopy Cover Levels under Silvopastoral Management. *Agronomy* **2025**, *15*, 855.
69. Vaca Llivigañay, J.A.; Palacios Herrera, B.G. Estructura, Productividad de Madera y Regeneración Natural de *Juglans Neotropica* Diels en la Hacienda la Florencia del Cantón y Provincia de Loja. *Cienc. Lat. Rev. Científica Multidiscip.* **2023**, *7*, 1640–1655. https://doi.org/10.37811/cl_rcm.v7i2.5430.
70. Daniel, I.; Cabrera, J.B.; Arias, P. Solar Energy Supply for the Rural Parish GAD's of Ecuador. In *Proceedings of the 2018 IEEE ANDESCON*; IEEE: New York, NY, USA, 2018; pp. 1–6.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.