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Phenological Assessment of Hops (*Humulus lupulus* L.) Grown in Semi-Arid and Subtropical Climates Through BBCH Scale and a Thermal-Based Growth Model

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Abstract: Although usually studied as separate processes, plant growth and plant development are strictly interrelated. The BBCH scale ("Biologische Bundesanstalt, Bundessortenamt, and CHemical industry") has become one of the primary classification systems for documenting the growth and developmental stages of many plant species. Specifically, the BBCH scale for hops (*Humulus lupulus* L.) separately describes growth and development during the vegetative stage. This study aims to develop an integrated approach to better understand the interaction between vertical growth rates and vegetative development in hops. Growth rates and development patterns of the Cascade hop cultivar were assessed in semi-arid (Sicily, Italy) and subtropical (Florida, USA) climates. The Gompertz model accurately described vertical growth, while a modified Gaussian model effectively captured hop growth rates (HGRs). A strong correlation between growth and developmental stages was identified, allowing for the inference of growth dynamics from developmental observations during the vegetative phase. Growth and developmental stages showed a 71% match across both environments, with minor phase shifts influenced by growing conditions. From an applied perspective, understanding the growth characteristics associated with developmental stages is crucial for addressing challenges posed by pests and diseases in emerging hop-growing regions. This integrated approach offers valuable insights into optimizing cultivation practices for diverse environmental conditions.

Keywords: *Humulus lupulus*; growth dynamics; plant growth; thermal sums; vegetative stage

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1. Introduction

Plant growth can be defined as the increase in organ dimensions over time [1], whereas plant development refers to structural changes in plants [2]. Although usually examined as two separate processes, they are strictly interrelated [3,4]. Crops' economic yield is often considered as a function of growth rates expressed over time [5]. Time affects the potential yields of crops according to the duration of their growth cycle (planting to maturity), representing a measure of the resources used by crops in any specific growing environment [6]. It is well known that the phenology and growth of cultivated plants are influenced by environmental, genetic, and management factors [7,8]. Temperature regulates key processes such as germination and flowering, while photoperiod and light intensity affect photosynthesis and seasonal development [9,10]. Water availability is crucial for metabolism, with drought or excess water limiting growth [8,11,12]. Soil fertility and the availability of essential nutrients significantly impact vegetative vigor and yield [13,14]. Extreme conditions, such as frost or heatwaves, can disrupt phenological cycles, posing challenges to plant development and productivity [8,15].

Therefore, knowledge of growth and development patterns through phenological assessment plays a key role in developing crop management strategies, particularly when crops are grown in new production areas [16,17].

Hop (*Humulus lupulus* L.) is a perennial herbaceous plant cultivated for its female flowers, which are used as an essential ingredient in beer. Traditionally, hop production has been concentrated between latitudes 40° and 50° North or South [18]. However, driven by rapid growth in the global craft beer market, hop cultivation has recently expanded to new production regions worldwide, including Italy [19–23], Brazil [24,25], and Florida, United States [26,27]. Although the high phenological plasticity of hops to various climatic conditions (i.e., temperature, rainfall, and day length) has been indicated, there has been little research regarding the phenological classification for this crop in new production areas.

Growth patterns are characterized by cumulative increments of dimensions over time [28,29], whereas development consists of a series of events resulting in a qualitative or quantitative change in plant structure [30,31]. Today, the BBCH scale is a phenological classification system widely used for many plant species [32]. Specifically, considering the BBCH scale for hops [33], the growth and development during the vegetative stage are reported separately (i.e., stage 1: leaf development; and stage 3: elongation of bines), even though there is structural and functional evidence that these two processes are strongly related [34,35]. Moreover, this scale characterizes a growth stage without considering potential complementary relationships with the previous or subsequent phenological phases.

Therefore, a crucial research question is: can we identify integrative "developmental growth stages" that account for both growth and developmental characteristics? To answer this question, this study aims to develop a new approach to integrate growth rate and vegetative development in hops. For experimentation purposes, growth rates and development patterns of the Cascade cultivar were determined in two growing environments: a semi-arid climate in Sicily, Italy, and a subtropical climate in Florida, United States. We used thermal time to consider the effects of temperature on growth and development, building a multi-stage model based on the Hop Growth Rate (HGR) sequences and relating it to the vegetative development of the species [33]. From an applied point of view, the knowledge of the association between growth characteristics and development events is also crucial to better understand, and possibly act upon, the interactions between plant development and biotic or abiotic stressors.

2. Materials and Methods

2.1. Experimental Sites and Crop Management

This study was performed in 2022 in two different climates: (i) semi-arid Mediterranean (Sicily, Italy) and (ii) subtropical (Wimauma, FL, USA). By employing the standard agronomic practices of these respective regions, the study aimed to understand the impact of these diverse climates on hop (cv. Cascade) cultivation.

Field observations were conducted throughout the vegetative growth stages of hops, corresponding to the BBCH scale ranging from 1.1 to 1.20. The observation period spanned from April to August in Sicily and from February to July in Florida, reflecting the distinct climatic conditions of each location. Daily values of rainfall and maximum and minimum temperatures at the study sites during the 2022 growing season (Figure 1) were obtained from the Agrometeorology Service Network of the Sicilian Region [36] and from the Florida Automated Weather Network [37]. In the Mediterranean semi-arid environment, total rainfall from April to August amounted to approximately 88.2 mm, significantly lower than the 492.8 mm recorded during the hop growth season (from February to July) in the subtropical region. The differences between minimum and maximum temperatures were relatively consistent across the two environments. In the semi-arid region, temperatures showed a marked upward trend from the beginning of the growing season, peaking in June and July before progressively declining toward the end of the cycle (Figure 1). In contrast, in the subtropics, there was a gradual but steady increase in both minimum and maximum temperatures, accompanied by widespread meteorological events that substantially increased relative humidity at the cultivation site.

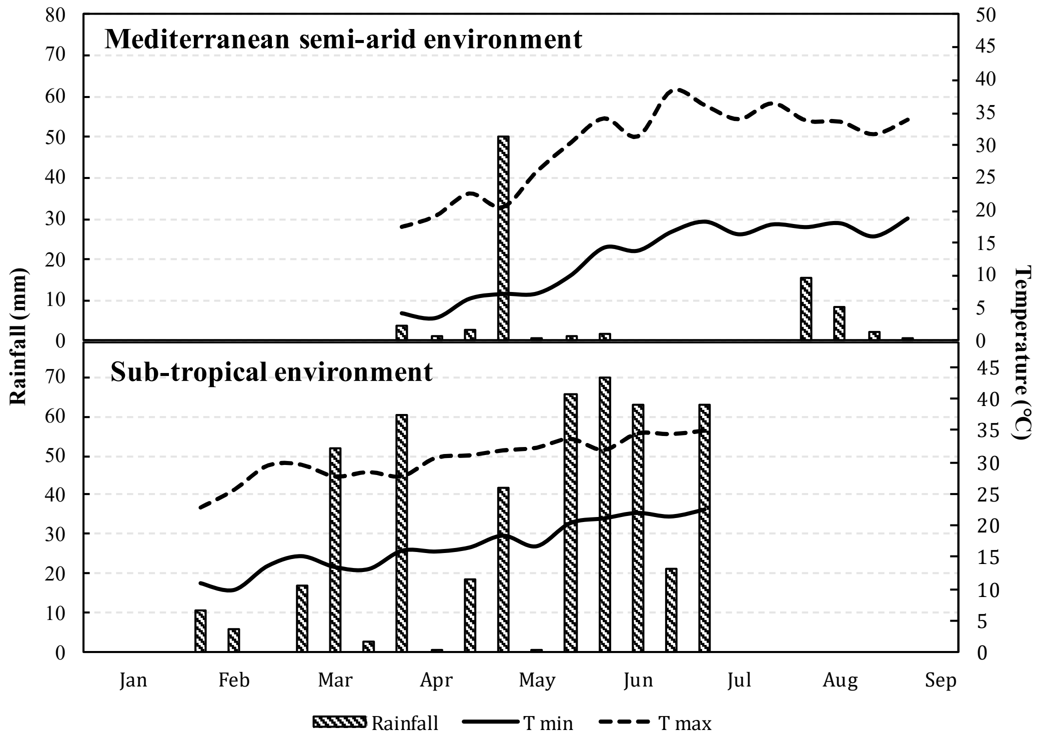

Figure 1. Rainfall and temperatures recorded at the "Sparacia" farm (Cammarata, AG, Sicily, Italy) (Mediterranean semi-arid environment) and at the Gulf Coast Research and Education Center (Wimauma, FL, USA) (subtropical environment) during the 2022 growing season.

In the semi-arid environment, the field experiment was carried out at the "Sparacia" experimental farm (Cammarata, AG, Italy, 37°38′07″ N; 13°45′47″ E; 450 m a.s.l.), belonging to the Department of Agricultural, Food, and Forest Sciences (D/SAAF) at the University of Palermo. The hopyard was built with a 3.60-meter-high V-trellis in 2021. Three replications on the row, each consisting of 10 hills, were set up. Distances of 0.7 m between plants in the row and 3 m between rows were adopted to allow mechanical weeding. Plastic mulch (2 mm polyethylene film) was also adopted to reduce the presence of weeds within the rows. During the growing season, two shallow mechanical interventions (about 10 cm in depth) were performed using a tractor-driven cultivator. The basal dressing was carried out by supplying 30 t ha^{-1} of mature bovine manure at planting. Annual fertilization was carried out in July 2022 (2.9 BBCH stage) using a foliar application of two products: Kelpstar® (Mugavero Teresa S.A.S., Termini Imerese, Italy) (seaweed extract with organic nitrogen, carbon, auxin, and cytokinin), and Siapton® (Sumitomo Chemical Italia s.r.l.; Milano, Italy) (organic nitrogen, carbon, and amino acids). The treatment was applied in a single foliar fertilization with a 20 L shoulder sprayer, by distributing 2 hl of fertilizer per ha, with doses of 150 mL hl^{-1} Kelpstar® and 150 mL hl^{-1} Siapton®. A localized irrigation system was set up with a single dripline per row. The system was equipped with a closing valve and a pressure gauge to control the working pressure. Irrigation was supplied according to crop requirements.

In the subtropical environment, the field experiment was carried out at the Gulf Coast Research and Education Center (Wimauma, FL, USA, 27°45′36″ N; 82°13′48″ W, 40 m a.s.l.), belonging to the University of Florida. The hopyard was built with a 4.57-meter-high V-trellis in 2019. The layout and configuration of the hopyard are as described by Agehara et al. [38]. Four replications on the row, each consisting of 10 hills, were set up. Distances of 0.9 m between plants in the row and 4.6 m between rows were adopted. Landscape fabric was also adopted as mulch for weed control within the rows, and bahiagrass (*Paspalum notatum*) was sown as a cover crop between the rows to prevent erosion and suppress weed growth. Weeds were chemically controlled only along the edges of landscape fabric. Insecticides and fungicides were sprayed to prevent or limit the spread of spider mites, aphid infestations, and fungal diseases. Fertigation was performed daily with a custom blend liquid fertilizer containing 5% N, 0.87% P, 6.64% K, 1.4% calcium, and 0.4% magnesium, as well as some micronutrients at <0.4%. Total inputs of N, P, K, and Ca were 306, 51, 386, and 81 kg ha^{-1}, respectively. Additional micronutrients were applied through fertigation of a micronutrient fertilizer (Microplex; Miller Chemical and Fertilizer, LLC., Hanover, PA, USA). Each row had two drip tapes with emitters spaced 30 cm apart, and the irrigation system was equipped with a closing valve and a pressure gauge to maintain constant working pressure. Irrigation was supplied according to crop requirements. To prevent immature flowering induced by insufficient photoperiod in subtropical environments [26], photoperiod extension was performed with supplemental lighting until adequate vegetative growth was achieved as described by Agehara [39].

2.2. Data Collection

Throughout the growing season, in both environments, we tracked the same set of plants (3 blocks of 10 plants each in the semi-arid environment and 4 blocks of 10 plants each in the subtropical one), recording their developmental stages weekly. This approach allowed us to monitor stage transitions while minimizing variability caused by individual differences. Developmental stages were determined in an expert way by using the BBCH scale [33]. Specifically, the study of the development of hop plants covered the phenological stage 1 of the BBCH, which corresponds to the development of the leaves along the bine, starting from phase 1.1 BBCH (1st pair of unfolded leaves), also corresponding to the beginning of twinning.

Hop Growth Rates (HGR) were calculated during the vegetative growing phase from objective measurements, according to the following formula, as shown in a recent study by Carrubba et al. [19]:

$$\mathrm{HGR} = H_t / \sum_{i=1}^{k} \left(T_{avg} - T_{base}\right)_i \quad (1)$$

where Ht is the height value at a measurement time, t, $\sum_{i=1}^{k} \left(T_{avg} - T_{base}\right)_i$ represents the cumulative growing degree-days (GDDs) within surveys, with i and k indicating the first and last days of measurement, respectively, T_{avg} is daily average temperature, and T_{base} is the base temperature (i.e., the temperature value below which plant growth is assumed to be zero). T_{base} = 0 °C was adopted in the vegetative phases according to what is shown in recent works dealing with hop phenological studies [19,40].

2.3. Growth Stage Identification and Evaluation

With the purpose of developing a method that is both practical and readily implementable in diverse agricultural settings, the new growth stages proposed were based solely on a single parameter: the Hop Growth Rates (HGR). The partition into four growth stages was based on the mathematical shape of a peak function, reflecting the observed trend of HGRs in two distinct growing environments. Therefore, these stages were defined to simplify the analysis and were fewer in number than the developmental stages (Table 1). Stage I represents the initial slow growth phase, characterized by HGR values below 3 mm GDD^{-1}. This is followed by Stage II, the rapid growth phase, culminating in the growth rate peak. Stage III corresponds to the post-peak slow growth phase, while Stage IV marks the late phase, where growth declines sharply and eventually ceases (Figure 2).

Our objective was to provide farmers with an additional feasible tool for crop management, particularly in regions where hops are being introduced as a novel crop, without introducing unnecessary complexity to field measurements and assessments. By focusing exclusively on growth rates—a parameter that is both straightforward to measure and highly indicative of vegetative dynamics—we aimed to create a reference scale that balances precision with practicality. It is well established that plant phenological development and growth are influenced by numerous factors, including environmental conditions and physiological variables. However, focusing solely on the most evident outcomes of these combined factors (i.e., HGRs) allows us to avoid the need to consider each variable in isolation. Introducing all factors individually could unnecessarily complicate the methodology and hinder its practical application.

Table 1. Growth stage identification according to HGRs' ranges detected during BBCH stage 1 (Leaf development) in a Mediterranean and subtropical environment.

Location	Growth Stages	HGR Values Range (mm GDDs^{-1})
Mediterranean environment	I	0.59→2.57
	II	3.09→5.96
	III	4.03→1.19
	IV	0.93→0.00
Subtropical environment	I	0.00→1.96
	II	2.99→11.2
	III	8.36→5.50
	IV	2.88→0.00

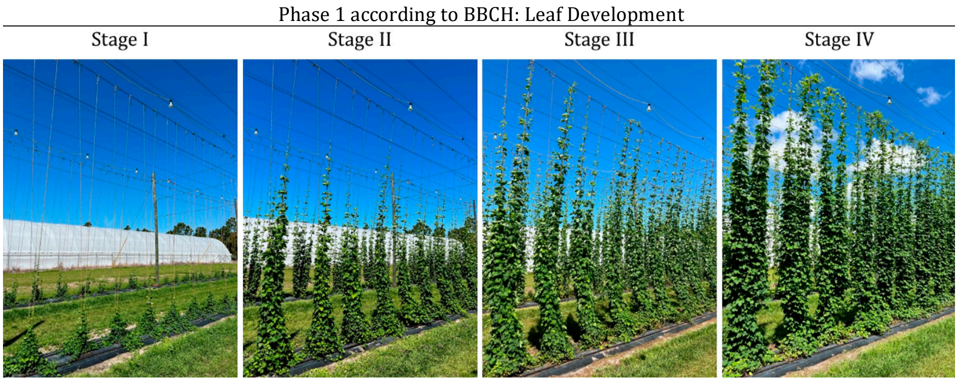

Figure 2. The four growth stages identified from the joint evaluation of developmental stages, determined from morphological observations in an expert way (BBCH), and HGRs during the vegetative growing phase. Stage I is the initial slow growth phase with HGR values below 3 mm GDDs–1; Stage II is the rapid growth phase until reaching the peak; Stage III is the slow growth phase following the peak; Stage IV is the late growth phase when growth declines rapidly and finally ceases. Photographs were taken at the Gulf Coast Research and Education Center (Wimauma, FL, USA) during the 2022 growing season (photo credits: Shinsuke Agehara).

After defining the four growth stages, we validated them by comparing the stages derived from thermal time and HGR with the developmental stages outlined in the BBCH scale. The 1.1 to 1.20 steps were grouped into four categories corresponding to the leaf development stage 1 [33]. To validate and assess classification accuracy, we used confusion matrices to compare observed growth rate classes at each vegetative step with their predicted counterparts. This method, widely utilized in the literature [41–44], confirmed the reliability of growth rates as indicators of specific developmental phases.

2.4. Statistical Analysis

All the statistical analyses were performed using the statistical packages Minitab® (version 19.2.0.0; Minitab LLC., State College, PA, USA), and Sigmaplot® (version 12.0; Grafiti LLC., Palo Alto, CA, USA). Plant height data and growth rates were related to the duration expressed in Julian calendar days. Considering the nonlinear relations between the introduced parameters, we compared different nonlinear regression models studied extensively in the literature [45,46].

Linear regression analysis was also performed to study any possible asynchronism between axis growth and leaf emission, by calculating the coefficient of determination between relative axis length and vegetative development completion (i.e., 1 BBCH stage) for each of the two growing environments.

Finally, confusion matrices were used. The analysis gave us a classification accuracy for each growing environment (i.e., semi-arid and subtropical environments), calculated as the ratio of correctly classified observations (diagonal values) to the total number of observations, underscoring the robustness of the proposed method for linking growth rates with developmental progression. The data represent the number of observations classified at each developmental and growth stage. Rows correspond to actual developmental stages based on "principal growth stage 1: Leaf Development" of the BBCH scale [32,33], while columns represent predicted growth stages.

Also, we calculated four metrics to evaluate the performance of the new growth stages classification: accuracy, precision, recall, and the F1 score. The first three metrics are based on predictions being classified into four categories: true positive (*TP*), false positive (*FP*), true negative (*TN*), and false negative (*FN*). Accuracy is the number of sampled plants correctly classified out of all the plants present in the test set. Precision is the probability that a sampled plant is actually in growth stage I, given that the model classified it as growth stage I. Recall is the probability that a sampled plant will be classified into growth stage I, given that the plant is actually in that growth stage. The F1 score is the harmonic mean of precision and recall. All three metrics have a range of 0–1, where 1 is a perfect classification.

$$\text{Accuracy} = \frac{TP + TN}{TP + FP + TN + FN} \tag{2}$$

$$Precision = \frac{TP}{TP + FP} \tag{3}$$

$$Recall = \frac{TP}{TP + FN} \tag{4}$$

$$F1 - \text{score} = \frac{2 \times Precision \times Recall}{Precision + Recall} \tag{5}$$

where *TP*, *FP*, *FN*, and *TN* are the number of true-positive, false-positive, false-negative, and true-negative classifications, respectively.

3. Results

3.1. NonLinear Regression Models for Hop Development and Growth Analysis

The height growth of hop plants was best described by the Gompertz model (Equation (6e); Table 2), which showed the highest goodness-of-fit among all tested models based on AIC (Akaike information criterion) values [47] (Table 2). For both cultivation environments (Figure 3), after a first phase of initial stasis, or slow growth, a substantial increase in height between the 30th and 60th day of cultivation was recorded, then followed by a slow growth phase until reaching the top of the trellises.

Table 2. Nonlinear regression models tested in the study.

Variables	Model	Formula	AICs Values	
Equation	**Height vs. Time**		**SA**	**ST**
6a	Sigmoidal function	$y = y_{asym}/\{1 + \exp[-(t - t_0)/b]\}$	1294.2	1365.1
6b	Modified sigmoidal function	$y = y_0 + y_{asym}/\{1 + \exp[-(t - t_0)/b]\}$	1293.7	1371.7
6c	Logistic function	$y = y_{asym}/[1 + (t/t_0)^b]$	1295.5	1363.5
6d	Modified logistic function	$y = y_0 + y_{asym}/[1 + (t/t_0)^b]$	1303.3	1365.5
6e	Gompertz	$y = y_{asym} \exp\{-\exp[-(t - t_0)/b]\}$	1293.6	1363.3
6f	Modified Gompertz	$y = y_0 + y_{asym} \exp\{-\exp[-(t - t_0)/b]\}$	1294.8	1364.9

Table 2. *Cont*.

Variables	Model	Formula	AICs Values	
Equation	**Height vs. Time**		**SA**	**ST**
	HGR vs. Time			
6g	Gaussian function	$y = y_{asym} \exp\{-0.5[(t - t_0)/b]^2\}$	150.7	308.3
6h	Modified Gaussian function	$y = y_0 + y_{asym} \exp\{-0.5[(t - t_0)/b]^2\}$	148.9	269.0
6i	Modified Gaussian function	$y = y_{asym} \exp\{-k[(t - t_0)/b]^c\}$	150.6	297.5
6j	Modified Gaussian function	$y = y_0 + y_{asym} \exp\{-k[(t - t_0)/b]^c\}$	152.7	271.1
6k	Lorentzian peak function	$y = y_{asym}/\{1 + [(t - t_0)/b]^2\}$	154.0	346.7
6l	Modified Lorentzian peak function	$y = y_0 + y_{asym}/\{1 + [(t - t_0)/b]^2\}$	151.0	300.4

Note. For the "Height vs. Time" nonlinear models tested, y is the response variable (e.g., height), t is the explanatory variable (e.g., time), y_{asym} is the asymptotic y value, t_0 is the inflection point of the curve, b controls the steepness and the shape of the curve; whereas, for the "HGR vs. Time" nonlinear models y is the response variable (e.g., HGR), t is the explanatory variable (e.g., time), y_{asym} is the asymptotic maximum y value, t_0 is the inflection point at which the growth rate is maximized, a (default = 0.5 for the Gaussian function), b, c, and k are coefficients controlling the height and the width of the skew of the "bell". **Abbreviation**: SA stands for the semi-arid environment (Sicily, Italy), whereas ST stands for the subtropical environment (Florida, USA).

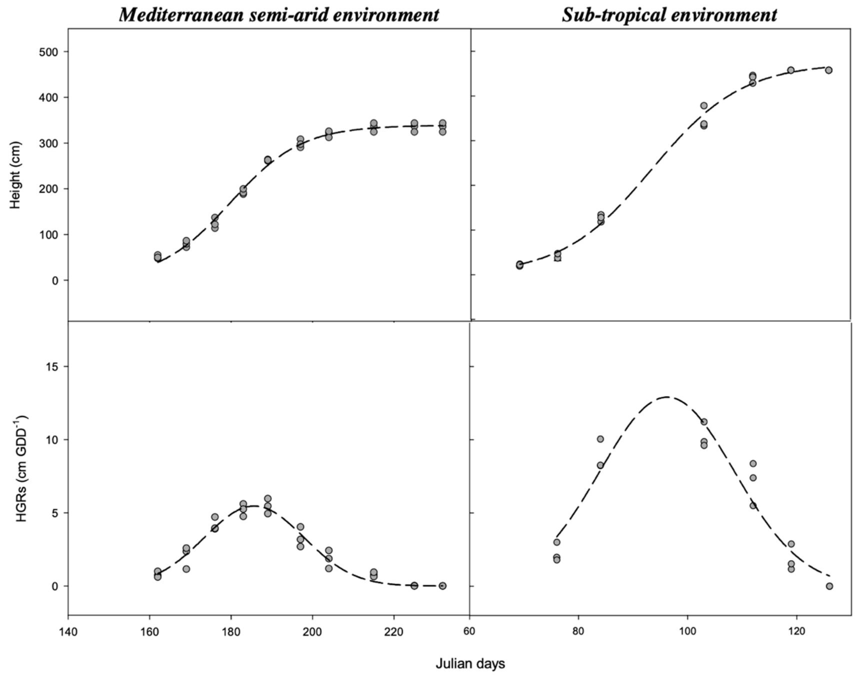

Figure 3. Height vs. Time (Julian calendar days) and HGR vs. Time (Julian calendar days) nonlinear regressions during the 2022 growing season for Mediterranean semi-arid and subtropical environments. Regression models for semi-arid Mediterranean environment: Height vs. Time (n = 170), $y = 349.07 \exp(-\exp(-(x - 174.4)/13.6))$; HGR vs. Time (n = 170) $y = 0.12 + 5.3 \exp(-0.5((x - 185.6)/11.9)^2)$. Regression models for subtropical environment: Height vs. Time (n = 210) $y = 499.9 \times \exp(-\exp(-(x - 87.8)/13.7))$; HGR vs. Time (n = 180) $y = -3.6 + 15.6 \exp(-0.5((x - 96.5)/16.5)^2)$.

HGR trends were best fitted by a modified Gaussian function (Equation (6h); Table 2), because of the lowest AIC value obtained among all tested functions and considering the high goodness-of-fit with the empirical data (Table 2). Crop growth rate dynamics were similar between the two environments, although the values recorded in the subtropical environment were on average greater than those in the Mediterranean environment (Figure 3).

Nevertheless, in both environments, HGRs increased to a maximum value approximately 3 to 4 weeks following the initiation of growth and subsequently declined throughout the remaining growing season. The maximum HGR value achieved by plants in the subtropical environment was consistently greater than that achieved in the Mediterranean environment (i.e., 13.8 and 8.8 mm GDD^{-1}, respectively) (Figure 3).

3.2. Evaluating Predictions: Linear Regressions and Confusion Matrices

To deepen the association between the leaf emission process (1 BBCH stage) and vertical elongation of bines, a regression analysis was carried out. The results indicated that in both environments, the length of the plant's vertical axis increased gradually following certain advancements in the leaf development process (Figure 4).

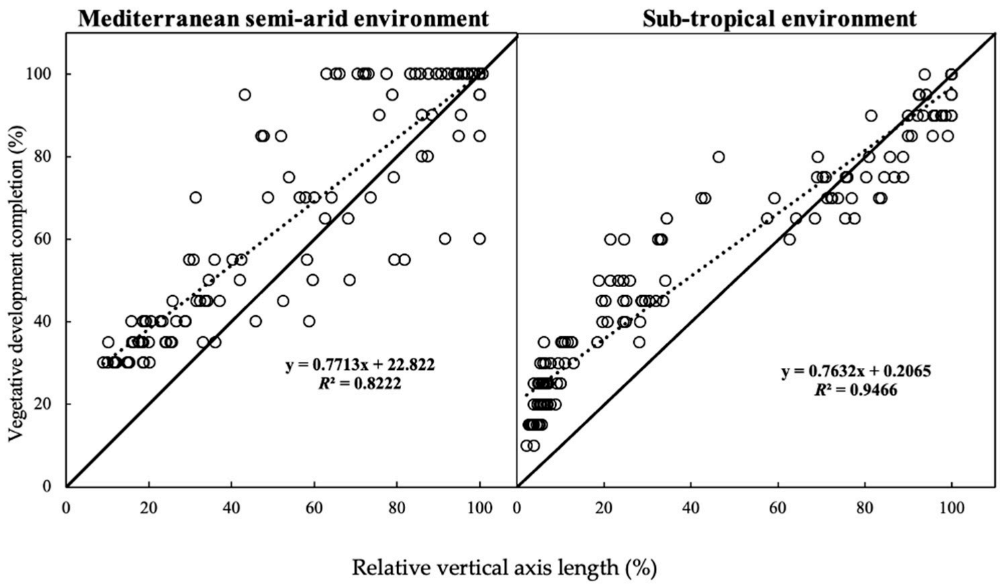

Figure 4. Relative vegetative development completion in relation to relative vertical axis length during cultivation in two growing environments, Mediterranean semi-arid and subtropical. Percentages are calculated as the length of the axis divided by the final length at the completion of the 1st stage according to the BBCH scale, respectively. The solid line on each graph represents x = y.

Specifically, a more marked asynchronism between the plant's axis length and vegetative development completion for the Mediterranean environment was recorded. Conversely, in the subtropical environment, the use of a supplemental lighting system prevented premature flowering, which otherwise is a common phenological phenomenon under insufficient day length conditions in subtropical and tropical climates [26,27,38], allowing adequate vegetative growth before transitioning into the reproductive phase.

The last step in our research was to explore the relationship between growth and developmental stages. The four growth stages identified for the vegetative phase, according to the HGR distributions, were related to the developmental stages and determined based on morphological observations (1 BBCH phase) (Tables 3 and 4).

In detail, within the Mediterranean environment, the agreement between the predicted and observed classes was 69%, with strong initial alignment between the BBCH-based stages and Growth Stages I and II. This alignment was supported by highly positive precision, recall, and F1-Score values. Conversely, for Stage III, a notably low recall value (0.44) was recorded, indicating a high rate of false negatives, which reduced the corresponding F1-Score to 0.33. In the final stage (Stage IV), the classification was again validated, as reflected by positive validation parameters. However, a significant number of false negatives were still observed, albeit with acceptable recall (0.66) and F1-Score (0.79) values (Table 3).

Table 3. Confusion matrix between growth stages and developmental stages determined from morphological observations in an expert way during the vegetative growing phase in a Mediterranean semi-arid environment.

Development Stages (Observed)	Mediterranean Semi-Arid Environment				
	Growth Stages (Predicted)				
	Stage I	Stage II	Stage III	Stage IV	Total
From 1.1 to 1.5 BBCH	24	0	0	0	24
From 1.6 to 1.10 BBCH	10	18	0	0	28
From 1.11 to 1.15 BBCH	0	9	8	1	18
From 1.16 to 1.20 BBCH	0	5	23	55	83
Total	34	32	31	56	153
Validation parameters:					
Accuracy	0.93	0.84	0.78	0.81	
Precision	0.71	0.56	0.26	0.98	
Recall	1.00	0.64	0.44	0.66	
F1-Score	0.83	0.60	0.33	0.79	
				Match:	69%
				Mismatch:	31%

Table 4. Confusion matrix between growth stages and developmental stages determined from morphological observations in an expert way during the vegetative growing phase in a subtropical environment.

Development Stages (Observed)	Subtropical Environment				
	Growth Stages (Predicted)				
	Stage I	Stage II	Stage III	Stage IV	Total
From 1.1 to 1.5 BBCH	35	5	0	0	40
From 1.6 to 1.10 BBCH	12	21	5	0	38
From 1.11 to 1.15 BBCH	2	8	24	2	36
From 1.16 to 1.20 BBCH	0	1	18	47	66
Total	49	35	47	49	180
Validation parameters:					
Accuracy	0.89	0.82	0.80	0.88	
Precision	0.71	0.60	0.51	0.96	
Recall	0.87	0.55	0.67	0.71	
F1-Score	0.79	0.57	0.58	0.82	
				Match:	71%
				Mismatch:	29%

In the subtropical environment, a better overall fit was observed across all expected and predicted phases. F1-Score values consistently exceeded 0.50, with a reduced incidence of false positives (FP) and false negatives (FN). This positively influenced the precision and recall metrics for each growth stage proposed in the classification study (Table 4).

Overall, when considering both environments, Growth Stages II and III exhibited slight shifts in developmental phases depending on the growing environment, though these deviations were minor (Tables 3 and 4). Growth Stage IV (growth arrest), characterized by reduced HGR values (approaching or equal to zero), was synchronous across both environments and closely matched the developmental stages 1.16–1.20 with high accuracy.

4. Discussion

As far as we are aware, there is still little knowledge about the vegetative growth rate dynamics of hop plants. Our results suggest that the height growth function of hops is similar to that recorded for the genus *Cannabis* [48,49], which may not be surprising as both species belong to the same botanical family of the Cannabinaceae.

The Gompertz model appeared to be the best-fitting model with the height growth data of hop plants in the Mediterranean environment. In fact, the study found that the height growth of hop plants was best described by the Gompertz model, showing distinct phases: an initial slow growth, a substantial increase in height between days 30 and 60, and a subsequent slow growth until reaching the trellis tops. Indeed, the model has also been used widely by previous studies to describe the growth of other plant species [50–52]. The HGRs, modeled by a modified Gaussian function, exhibited similar dynamics in both semi-arid Mediterranean and sub-tropic environments, with the sub-tropic environment displaying higher overall HGR values. Considering the HGR trends outcomes, it seems that the vegetative growth rate of hops is greatly influenced by external environmental factors. Indeed, according to our results, it becomes evident that there are comparable growth trends between these regions; however, it is worth noting that under subtropical conditions, there is a propensity for accelerated development because of the beneficial environmental factors in effect.

Regression analysis revealed a strong correlation between leaf emission and vertical elongation in both environments, although greater asynchrony was observed in the Mediterranean setting. Specifically, in the Mediterranean environment, a slight mismatch emerged between axis elongation and the completion of vegetative development. This discrepancy was likely due to the premature cessation of axis growth before the plants reached the trellis top, prompting an earlier transition to the reproductive stage.

Initially, the relationship between growth and developmental stages was synchronous across both environments, but divergences became apparent as growth progressed. The strong correlation observed suggests that morphological discontinuities are intrinsically linked to shifts in growth dynamics. While the F1-score—an integrative metric combining Precision and Recall—was positive for all growth stages in both environments, it did not reach the optimal range of 0.90–0.99, which would have been ideal for fully validating the classification model.

As a preliminary study, these results demonstrate that the proposed classification model is effective in identifying and characterizing the growth stages. However, according to the possible variability due to the different experimental settings (i.e., genotype-environment interactions), further research is necessary to refine our understanding of hop growth dynamics with other genotypes and under varying cultivation conditions. This understanding is critical for managing the interactions among plant development, pests, and diseases.

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