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Pineapple growth and development modeling based on nitrogen rate and planting density

Paula Patrícia Oliveira da Silva[1,2*], Victor Martins Maia[1], Rodinei Facco Pegoraro[3] and Fernanda Soares Oliveira[1]

[1]Universidade Estadual de Montes Claros, Campus Janaúba, 34440-000, Janaúba, Minas Gerais, Brazil. [2]Instituto Federal Baiano de Ciência e Tecnologia, Campus Guanambi, 46430-000, Guanambi, Bahia, Brazil. [3]Universidade Federal de Minas Gerais, Montes Claros, Minas Gerais, Brazil. *Author for correspondende. E-mail: paula.guanambi@gmail.com

ABSTRACT. Plant growth models, derived from reliable databases, enable development of software for recommending cultural practices, harvest predictions, and enhancing productivity. This study aimed to create, refine, and simulate reference models for pineapple growth and development, adapting them based on nitrogen supply per plant and plant density per hectare. We utilized a field test database with periodic assessments of root, stem, leaf, fruit, and stem diameter fresh and dry weight, along with climate data from meteorological stations in or near the experimental areas. These growth models were developed, considering significant correlations and high correlation coefficients, using both simple non-destructive (stem diameter) and destructive (fresh or dry weight of D leaf) plant evaluations, either separately or in combination. The resulting models can provide estimated predictions for pineapple growth, adaptable to varying plant populations and nitrogen fertilization rates (measured in grams of N per plant).

Keywords: *Ananas comosus var*; *comosus*; pineapple; crop simulation model; harvest prediction.

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Introduction

Growth analysis plays a crucial role in understanding the variations among cultivars due to genetic factors or environmental changes. It also aids in selecting promising cultivars for multiplication studies aimed at increasing productivity (Hanafi, Selamat, Husni, & Adzemi, 2009; Fournier, Dubois, Benneveau, & Soler, 2010). Plant growth curves offer insights into various physiological processes (e.g., photosynthesis) and provide indirect information about growth variables such as absolute growth rate, net assimilation rate, and crop growth rate, all of which are valuable in agricultural research (Graciano, Nogueira, Lima, Pacheco, & Santos, 2011).

Understanding the growth of pineapple plants is essential for identifying issues in crop development, including water and nutrient deficiencies, weed competition, and challenges related to soil compaction and drainage (Souza, Silva, & Azevedo, 2007; Rodrigues, Mendonça, Silva, Silva, & Pereira, 2010). This knowledge informs agronomic practices and aids in characterizing different growth phases, facilitating pineapple production during favorable seasons for commercialization. Pegoraro, Souza, Maia, Amaral, and Pereira (2014a) and Maia et al. (2016b) categorized the vegetative phase of pineapple into five growth stages based on D leaf weight, which correlates with plant size and weight. Pineapple productivity can be predicted by measuring D leaf weight or stem diameter during floral induction (Vilela, Pegoraro, & Maia, 2015; Silva et al., 2022).

Robust databases must be used to construct reliable growth models. Since 2005, the tropical fruit growing research group at the State University of Montes Claros has been conducting studies on various cultural practices and their impact on pineapple growth and production, including fruit growth curves. Several of these studies have been published, resulting in the accumulation of a substantial and credible database (Cardoso, Pegoraro, Maia, Kondo, & Fernandes, 2013; Amaral, Maia, Pegoraro, Kondo, & Aspiazú, 2014; Pegoraro et al., 2014a; Pegoraro et al., 2014b; Santos et al., 2018; Souza, Pegoraro, Reis, Maia, & Sampaio, 2019; Amaral et al., 2021; Mota et al., 2021; Oliveira et al., 2022; Silva et al., 2022).

Considering the above, our primary goal is to create, refine, and simulate reference models for pineapple growth and development, tailoring them based on nitrogen supply per plant and plant density per hectare. These models will be constructed using the extensive and well-established database resulting from our research efforts.

Material and methods

Data Collection

The data used in this study were obtained from tests and experiments conducted by the fruit-growing research group at the State University of Montes Claros since 2005. The study is structured into three distinct phases: the development, adjustment, and validation of reference models (standard models); the correction of reference models based on nitrogen (N) doses and plant population per hectare; and the validation of the proposed models.

Development, adjustment, and validation of reference models

Data collection involved a field trial focusing on the 'Pérola' pineapple cultivar (Maia, Oliveira, Pegoraro, Aspiazú, & Pereira, 2016a). Observations were made at 11 specific time points between planting and harvest. The recorded data, in days after planting (DAP), were transformed into heat units, as described by Malézieux, Zhang, Sinclair, and Bartholomew (1994).

At each evaluation time, the plants were carefully harvested and categorized into distinct components: roots, stem, leaves, D leaf, fruit, crown, and propagules (seedlings). Subsequently, all collected materials underwent drying in a forced ventilation oven at 65°C until reaching a constant weight to determine the dry weight of plant parts, both vegetative (stems, leaves, and roots) and total weights.

Comprehensive data analysis was performed, involving variance and regression techniques, facilitated by the utilization of Sigma Plot 12.5 software (Demo version). Model selection was based on the criteria of explaining the biological phenomenon effectively, a high coefficient of determination, an adjusted coefficient of determination, and the statistical significance of regression coefficients by the t-test. Regression analyses were performed considering linear and non-linear models that describe plant growth following the methods of Hunt (1990) and Soltani and Sinclair (2012) and interpreted by Archontoulis and Miguez (2015).

Absolute growth rate (AGR) and relative growth rate (RGR) were derived from these adjusted models. Additionally, Pearson's correlations among the evaluated characteristics were scrutinized, and specific models were developed to estimate the variables of interest.

As a result, stem diameter (SD) emerged as a pivotal parameter for predicting pineapple growth. The SD values measured at floral induction served as basis for estimating total weight and, consequently, vegetative growth.

Validation of adjusted models:

To validate the adjusted models, we conducted a simulation of pineapple growth and compared the results with data collected from a different field trial, distinct from the one used for model adjustments.

Correction of reference models

Data collected by Cardoso et al. (2013) from another field trial, which featured different plant populations per hectare and varying N doses, were employed to determine correction factors for the reference models when pineapples faced these variations.

We utilized Sigma Plot 12.5 software (Demo version) to fine-tune the new growth models and correct them for predicting pineapple growth under varying N doses and plant populations. In this process, we adjusted multiple models to predict pineapple SD based on N dosage (urea or manure), plant density per hectare, and degree-days (heat units). These models allowed us to estimate both absolute growth rate (AGR) and relative growth rate (RGR) values, in addition to calculating a correction factor for predicting the SD value and, consequently, pineapple growth.

These corrections were carried out with respect to standard or ideal values for pineapple cultivation, specifically 15 g of N per plant and 51,282 plants per hectare. The corrected models provide a valuable tool for predicting pineapple growth across a spectrum of N doses (ranging from 0 to 20 g per plant) and population densities (ranging from 51,282 to 126,984 plants per hectare).

Validation of the proposed models

To validate the proposed models, data were collected from another field trial conducted by Mota et al. (2018), under optimal conditions, including irrigation, nutrition, pest, disease, and weed control.

SD evaluations were conducted at 153, 270, 318 and 356 DAP and then converted into heat units following the method described by Malézieux et al. (1994). Fresh weight measurements of the D leaf were taken at 366 DAP, and fruit weight was recorded at harvest.

SD served as the basis for estimating 'Pérola' pineapple growth, with AGR or RGR used to determine specific curve points. These values were adapted from reference models (standard) when plants reached precise levels of vegetative and total fresh and dry weights. Additionally, we utilized observed degrees days (DD) or heat units to estimate growth, leading to the construction of a new growth curve.

Results and discussion

A significant correlation was established through the t-test ($p \leqslant 0.05$) between stem diameter (cm) and vegetative fresh/dry weights (g) in pineapple plants. The Pearson's correlation coefficients observed were 0.796 and 0.891, respectively. Furthermore, a significant correlation ($p \leqslant 0.05$) was identified between D leaf fresh and dry weights (g) and vegetative fresh and dry weights (g). The coefficients observed were as follows: DLFW vs. DLDW, r = 0.96; DLFW vs. VFW, r = 0.94; DLFW vs. VDW, r = 0.89; DLDW vs. VFW, r = 0.91; and DLDW vs. VDW, r = 0.91.

Figure 1 depicts illustrative graphs along with their respective equations and R^2 values.

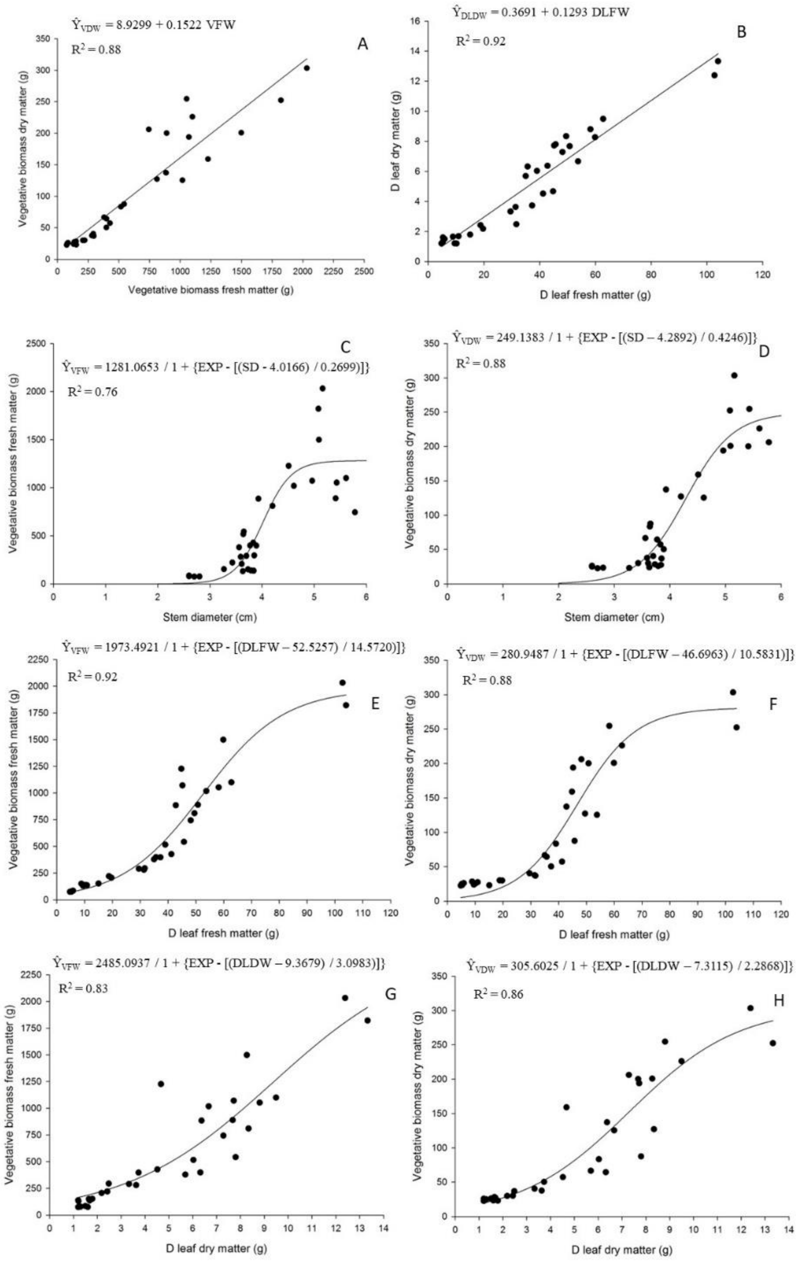

Figure 1. Relationships between variables until artificial induction of flowering: vegetative dry weight as a function of vegetative fresh weight (A); D leaf dry weight as a function of D leaf fresh weight (B); vegetative fresh weight as a function of stem diameter (C); vegetative dry weight as a function of stem diameter (D); vegetative fresh weight as a function of D leaf fresh weight (E); vegetative dry weight as a function of D leaf fresh weight (F); vegetative fresh weight as a function of D leaf dry weight (G); vegetative dry weight as a function of D leaf dry weight (H); until the date of the artificial induction of flowering.

After completing data collections (11 evaluations), pineapples could be measured for total weight up to the harvest, denoted as TFW (total fresh weight) and TDW (total dry weight). A Pearson correlation study between TFW and TDW revealed a highly significant correlation with an R-value (Pearson's correlation coefficient) of 0.99. Based on this, the equation presented below was then refined (Figure 2):

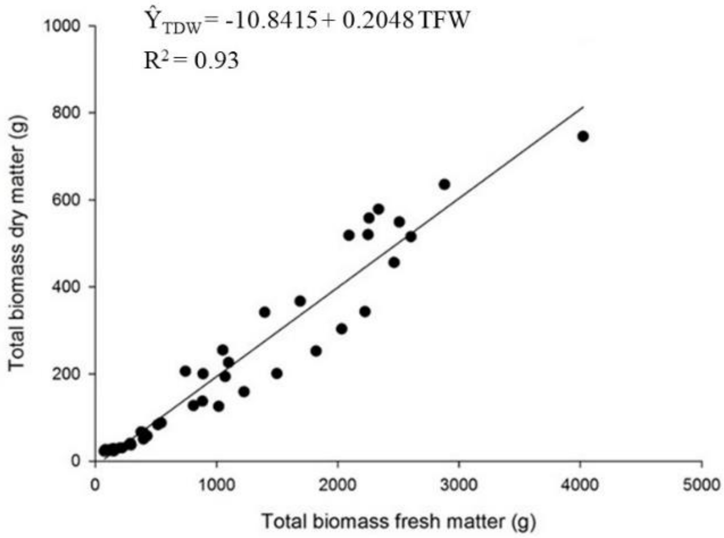

Figure 2. Variations in total dry weight as a function of total fresh weight until harvest. TDW = total dry weight (g) and TFW = total fresh weight (g).

The TDW and TFW values allowed for calculation of pineapple harvest indices regarding fresh weight, both with and without the crown, which were determined to be 0.4699 and 0.5181, respectively. Similarly, concerning dry weight, pineapple harvest indices, with and without the crown, were found to be 0.3049 and 0.2795, respectively. As supported by data from other research including studies from the fruit-growing research group at the State University of Montes Claros, TDW and TFW have been established as fixed and specific for each cultivar (Pegoraro et al., 2014a; Vilela, Pegoraro, & Maia, 2015; Maia et al., 2016a).

Planting dates were converted into heat units (degree days = DD), and models were developed for each assessed compartment (roots, stem, leaves, fruit), along with growth characteristics (leaf number, stem diameter, plant height, and D leaf dry and fresh weights). These models were finely adjusted and are regarded as reference or standard models. Using these models/equations, we calculated absolute growth rates (AGR) and relative growth rates (RGR) for each characteristic, as illustrated in Figure 3.

Equations were also adjusted for accumulation of total and vegetative weights (both fresh and dry), along with their corresponding R^2 values. Using these equations, we calculated absolute and relative growth rates (AGR and RGR) for both total and vegetative fresh and dry weights, as depicted in Figure 4.

To estimate AGR in g m^{-2} based on fresh and dry weights, simply multiply the value in g DD^{-1} by the population density of plants per m^{-2} adopted. The calculated results will be expressed as g m^{-2} DD^{-1}. Regarding RGR, the values are consistent in g g^{-1} DD^{-1} or g g^{-1} m^{-2} DD^{-1}.

The vegetative phase was interrupted by artificial floral induction when the accumulated heat units reached 9,126.7 DD. At this point, the observed data showed that D leaf fresh weight was 68 g. According to the adjusted values, at floral induction, total fresh and dry weights were 1,665.64 and 318.34 g, respectively. Furthermore, at floral induction, AGR and RGR for total fresh weight were 0.3778 g DD^{-1} and 0.000227 g g^{-1} DD^{-1}, respectively. As for total dry weight, AGR and RGR were 0.08451 g DD^{-1} and 0.000266 g g^{-1} DD^{-1}, respectively. It is worth noting that AGR values, both for total fresh weight and for total dry weight, were close to the maximum calculated values at this specific moment (Figure 4).

AGR and RGR values for other compartments (roots, stem, leaves, and fruit) were also estimated (Figure 5). However, in this case, it was exclusively based on dry weight, as models for the growth of crown and seedlings were not adjusted due to limited data collection (gathered at only two evaluation points).

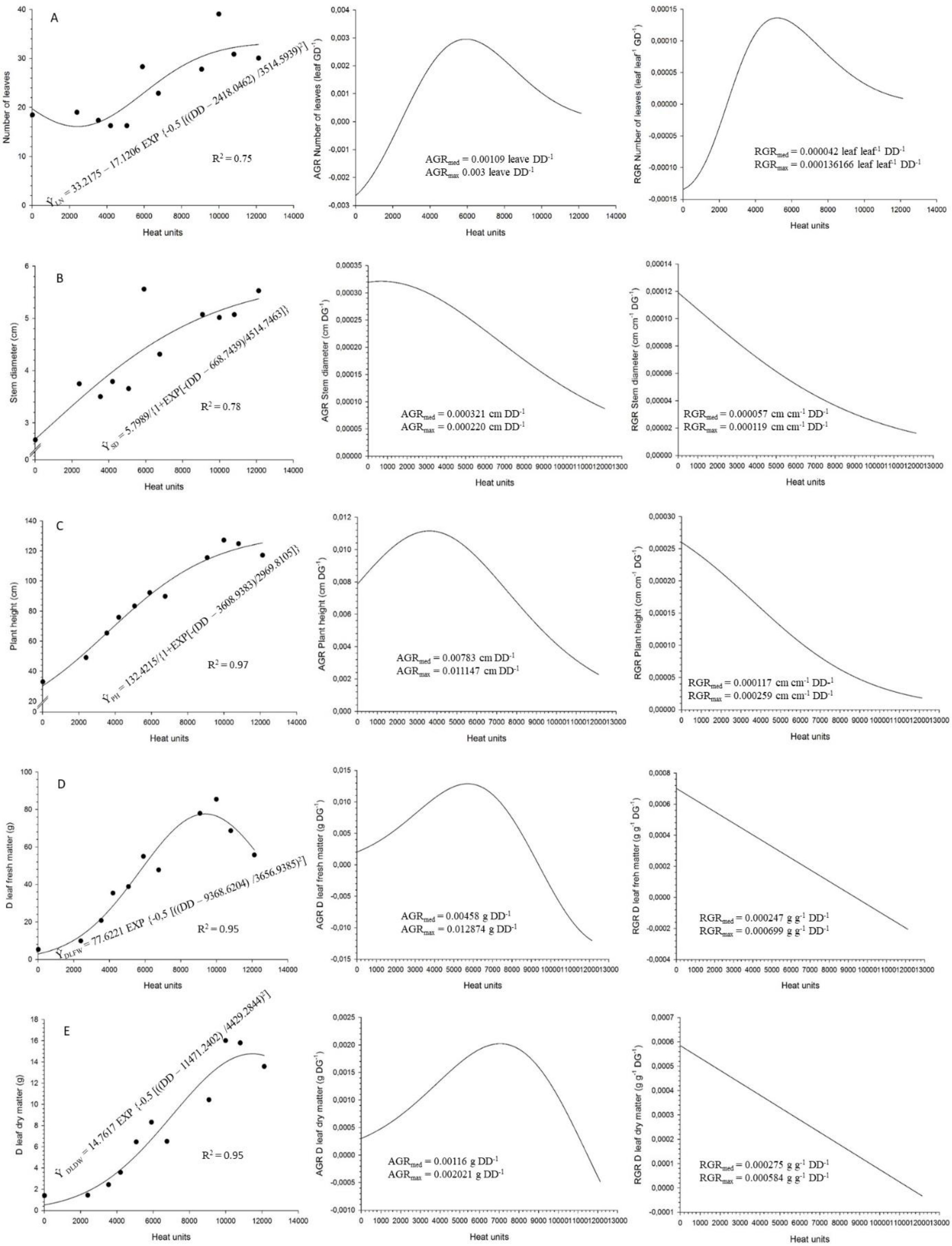

Figure 3. Leaf number (A), stem diameter (B), plant height (C), D leaf fresh weight (D), D leaf dry weight (E), and their respective absolute and relative growth rates (AGR and RGR) as a function of heat units up to collection date. (AGRmed = mean absolute growth rate of the entire period; AGRmax = maximum absolute growth rate; RGRmed = mean relative growth rate of the entire period; and RGRmax = maximum relative growth rate). DD = degrees day; $\hat{Y}_{LN}$ = (leaf number) - adjusted Gaussian model with 4 parameters; $\hat{Y}_{SD}$ = (stem diameter) - adjusted sigmoidal model with 3 parameters; $\hat{Y}_{PH}$ = (plant height) - adjusted sigmoidal model with 3 parameters; $\hat{Y}_{DLFW}$ = (D leaf fresh weight) - adjusted Gaussian model with 3 parameters; $\hat{Y}_{DLDW}$ = (D leaf dry weight) - adjusted Gaussian model with 3 parameters.

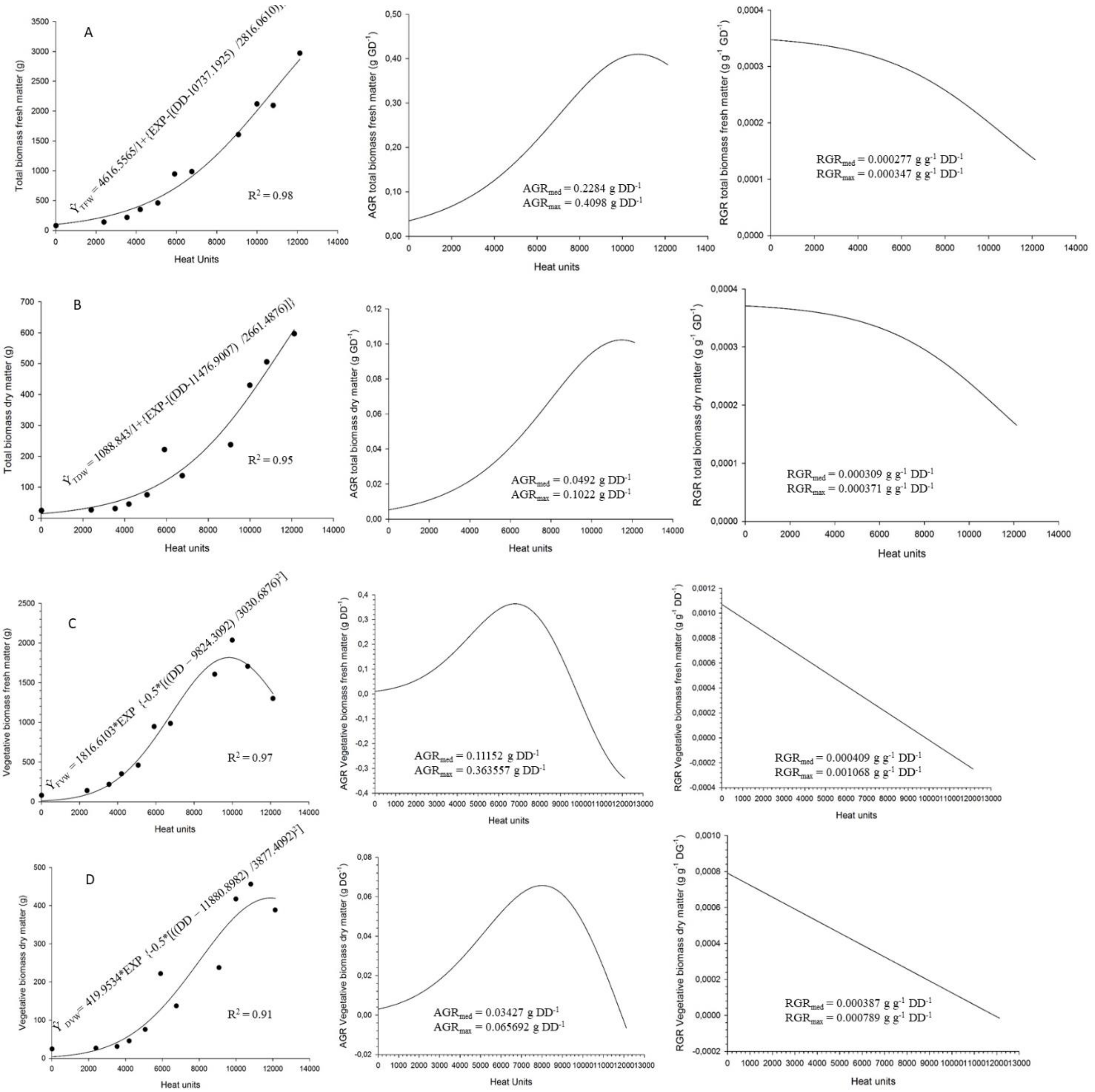

Figure 4. Accumulation of fresh (A) and dry (B) total weights, accumulation of fresh (C) and dry (D) vegetative weights, and their respective absolute (AGR) and relative (RGR) growth rates as a function of the accumulated heat units until the harvest. $\hat{Y}_{TFW}$ = total fresh weight; $\hat{Y}_{TDW}$ = total dry weight; $\hat{Y}_{FVW}$ = fresh vegetative weight; $\hat{Y}_{DVW}$ = dry vegetative weight; DD = degrees day.

Following the adjustment of the models, a correlation study was conducted, as presented in Table 1. This study explored the relationships between stem diameter (SD), D leaf fresh and dry weights, and vegetative and total fresh and dry weights, using the refined dataset.

Table 1. Correlation study (cell content: Correlation Coefficient, *p*-value by t-test and sample size).

	DLFW	DLDW	VFW	VDW	TFW	TDW
SD	0.965<0.001858	0.968<0.001 858	0.947<0.001858	0.931<0.001858	0.899<0.001858	0.875<0.001858
DLFW		0.951<0.001858	0.979<0.001858	0.903<0.001858	0.855<0.001858	0.801<0.001858
DLDW			0.982<0.001858	0.991<0.001858	0.964<0.001858	0.946<0.001858
VFW				0.959<0.001858	0.904<0.001858	0.878<0.001858
VDW					0.987<0.001858	0.977<0.001858
TFW						0.998<0.001858
TDW						

SD = stem diameter (cm); DLFW = D leaf fresh weight (g); DLDW = D leaf dry weight (g); VFW = vegetative fresh weight (g); VDW = vegetative dry weight (g); TFW = total fresh weight (g); TDW = total dry weight (g).

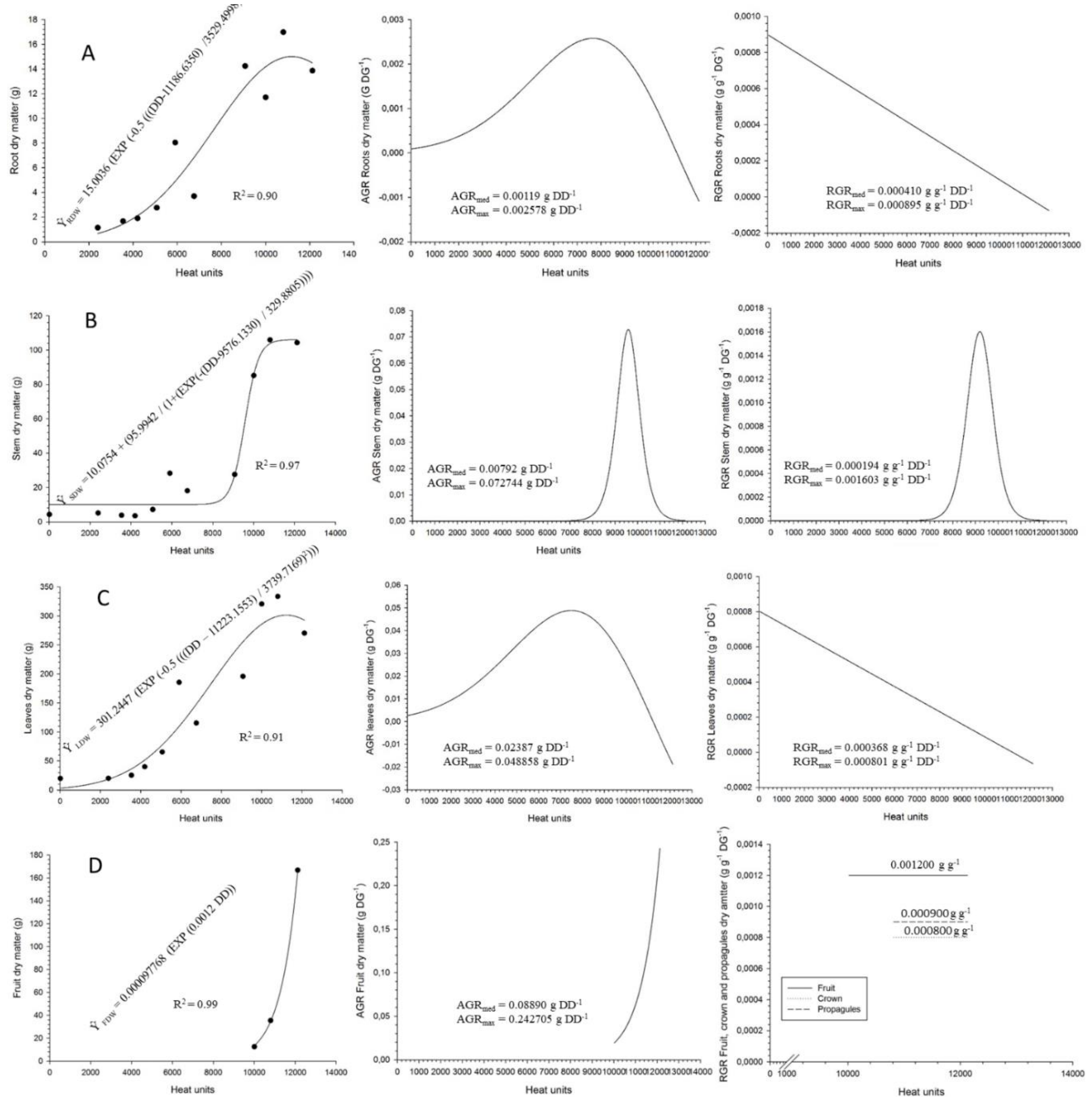

Figure 5. Dry weight accumulation in roots (A), stems (B), leaves (C), and fruit (D) with their respective absolute (AGR) and relative (RGR) growth rates as a function of heat units accumulated up to the harvest. $\hat{Y}_{RDW}$ = (root dry weight) - adjusted Gaussian model with 3 parameters; $\hat{Y}_{SDW}$ = (stem dry weight) - adjusted sigmoidal model with 4 parameters; $\hat{Y}_{LDW}$ = (leaf dry weight) - adjusted Gaussian model with 3 parameters; $\hat{Y}_{FDW}$ = (fruit dry weight) - adjusted exponential model with 2 parameters.

The equations were refined based on the reference models (default), employing DLDW, SD, and DLFW as parameters, as outlined in Table 2 below.

Table 2. Equations adjusted from standard models, using DLDW and SD as parameters, along with their corresponding R^2 values.

Equation	R^2
VFW = 1740.4456 EXP {-0.5 [((DLDW – 13.0850) /4.9206)^2]}	0.99
VDW = 484.8417 EXP {-0.5 [((DLDW – 19.0552) / 7.3224)^2]}	0.99
TFW = 195.5973 EXP (0.1720 x DLDW)	0.99
TDW = 27.0874 EXP (0.1988 x DLDW)	0.98
VFW = 1723.8406 EXP {-0.5 [((SD – 5.1272) / 0.5870)^2]}	0.99
VDW = 574.6602 EXP {-0.5 [((SD - 6.0721) / 0.9681)^2]}	0.99
TFW = 1.2580 EXP (1.4345 SD)	0.99
TDW = 0.0669 EXP (1.6910 x SD)	0.99
VFW = 2041.6680 EXP {-0.5 [((DLFW - 94.4722) /33.3099)^2]}	0.99
VDW = 350.2819 EXP {-0.5 [((DLFW - 79.9853) /24.6027)^2]}	0.86
TFW = 205.9182 EXP (0.0297 x DLFW)	0.70

VFW = vegetative fresh weight; DLDW = D leaf dry weight; VDW = vegetative dry weight; TFW = total fresh weight; TDW = total dry weight; SD = stem diameter; DLFW = D leaf fresh weight.

The pineapple harvest indices from the adjusted models regarding total fresh weight, without and with the crown, were respectively: 0.5837 and 0.6438. As for total dry weight, the indices, without and with the crown, were found to be 0.3351 and 0.3726, respectively.

In addition, based on data collected from another experiment, as previously described, the standard model equations were refined to correct the estimation of pineapple growth. This correction involved determination of stem diameter (SD) as a function of nitrogen (N) doses, plant population per hectare, and degree days (heat units). Multiple models were employed to estimate SD from N dose (urea source), plant population per hectare, and degree days, allowing for the calculation of AGR and RGR as correction factors to predict SD values and, consequently, pineapple growth. The Sigma Plot 12.5 software (Demo version) was used for fitting the models.

The equation representing this relationship is as follows:

$SD = 7.265 + 0.0211^{***}N - 0.00182^{***}\ DD + 2.08\ x10^{-7***}\ DD^2$, $R^2 = 0.98$.

where: SD = stem diameter (cm); N = nitrogen dose (g); and DD = Degrees Day.

***Significant at the 0.001 level by the t-test.

Using this model, SD values could be estimated for the studied range of N doses (0 - 20 g per plant), while considering AGR and RGR. Based on the SD values, it becomes feasible to estimate total and vegetative weights, predict pineapple growth, and calculate productivity. Additionally, it is possible to construct a 'new plant.'

For SD from the standard N dose (15 g plant^{-1}), the following relationships hold:

$SD_{0g} = 0.9292\ SD_{15}g\ R^2 = 0.99$; $SD_{5g} = 0.9528\ SD_{15g}\ R^2 = 0.99$; $SD_{10g} = 0.9764\ SD_{15g}\ R^2 = 0.99$; $SD_{15g} = 1.0000\ SD_{15g}$; $SD_{20g} = 1.0236\ SD_{15g}\ R^2 = 0.99$.

These parameters illustrate that for each 1 g of N applied above 15 g of N per plant, it is necessary to add 0.00472 to obtain the new parameter. Conversely, for each 1g of N removed below 15 g of N per plant, it is necessary to subtract 0.00472 to obtain the new parameter (parameter of 15 g = 1.0000).

Therefore, the equation for SD at a specific dose of N (SDNg) is as follows: $SD_{Ng} = \{1.0000 – [0.00472\ x\ (15-N)]\}\ x\ (SD_{15g})$; where: SD_{Ng} = stem diameter at a specific dose of N (g per plant); N = specific nitrogen dose (g per plant); SD_{15g} = stem diameter at a dose of 15 g of N per plant (standard).

This equation allows for simulating plant growth under different N doses and predicting yield or productivity when using this N dose (urea source). The same procedures applied to various N doses were also employed for different plant populations.

The equation representing the relationship is as follows:

$SD = 7.908 - 4.99\ x\ 10^{-6***}\ P - 1.82\ x\ 10^{-3*}\ DD + 2.08\ x\ 10^{-7***}\ DD^2$, $R^2 = 0.98$

where: SD = stem diameter (cm); P = population (plants per hectare); DD = Degree days.

***and *denote significance levels of 0.001 and 0.05, respectively, by the t-test.

Using this model, SD value can be estimated for the range of populations studied (51,282 – 126,984 plants per hectare), while considering AGR and RGR. For SD from the standard population P (51,282 plants per hectare), the following relationships apply:

$SD_{51,282} = 1,000\ SD_{51,282}$; $SD_{76,923} = 0.9718\ SD_{51,282}\ R^2 = 0.99$; $SD_{90,909} = 0.9564\ SD_{51,282}\ R^2 = 0.99$; $SD_{126,984} = 0.9168\ SD_{51,282}\ R^2 =0.99$.

These parameters indicate that for every 1 plant beyond 51,282 plants per hectare (parameter of 51,282 = 1.0000), it is necessary to subtract 0.000001105 to obtain the new parameter.

Therefore, the equation for SD in a specific plant population (SDpopulation) is as follows:

$SD_{population} = \{1.0000 – [0.000001105\ x\ (P – 51,282)]\}\ x\ (SD_{51,282})$,

where: $SD_{population}$ = stem diameter in a specific plant population (plants per hectare); P = specific plant population (plants per hectare); $SD_{51,282}$ = stem diameter in the population of 51,282 plants per hectare (default).

For model validation, SD measurements were collected at 153, 270, 318, and 356 DAP, which were then converted into heat units (Malézieux et al., 1994). Additionally, D leaf fresh weight was determined at 366 DAP, with average fruit weight being validated at harvest time (Table 3).

Table 3. D Leaf fresh weight (DLFW) (g) and average fruit weight (FW) (g) of the 'Pérola' cultivar.

DLFW*		FW**	
sewage sludge	mineral fertilization	sewage sludge	mineral fertilization
64.46	59.77	1.135	1.053

**At 366 days after planting. *Fruit with crown.

In this trial, the collected SD values were higher than those observed in the reference models. To prevent an overestimation of plant growth in this scenario, DLFW values were used for validation and growth prediction. Consequently, for the 'Pérola' pineapple variety, the initial values of total and vegetative fresh and dry weights were estimated based on previously adjusted growth models (reference models) using DLFW as a starting point for the growth curve estimation.

To estimate subsequent points on the growth curve, we employed AGR (absolute growth rate) or RGR (relative growth rate) values. These AGR and RGR values were calibrated according to the reference models when the plants exhibited exact values of total and vegetative fresh and dry weights. Additionally, we considered the degree days (DD), or heat units observed in the present study to construct and predict the growth curve.

Using the reference models (standard) and the observed stem diameter (SD) values, we were able to estimate the AGR and RGR values for fresh (VFW) and dry (VDW) vegetative weights during the vegetative phase (up to floral induction) as shown in Table 4.

Table 4. Absolute (AGR) and relative (RGR) growth rates, vegetative fresh (VFW) and dry (VDW) weights estimated from the observed stem diameter (SD) values.

Treatments	DAP[1]	DD[2]	SD[3]	AGR[4] ($x10^{-5}$)	RGR[5] ($x10^{-5}$)	VFW[6]	VDW[7]
sewage sludge	153	2798.2	5.75	-	-	1279.0	241.3
mineral fertilization			5.40	-	-	1273.5	232.2
sewage sludge	270	4542.3	5.88	8.1	1.4	1279.8	243.4
mineral fertilization			5.85	27.1	4.8	1279.6	243.0
sewage sludge	318	5195.8	5.97	12.9	2.2	1280.1	244.5
mineral fertilization			6.15	43.8	7.3	1280.6	246.0
sewage sludge	356	5782.6	5.90	-10.8	-1.8	1279.9	243.7
mineral fertilization			6.10	-8.3	-1.3	1280.5	245.7

[1]Days after planting. [2]Degrees Day. [3]Stem diameter (observed data). [4]Absolute growth rate (cm DD^{-1}). [5]Relative growth rate (cm cm^{-1} DD^{-1}). [6]Estimated vegetative fresh weight. [7]Estimated vegetative dry weight. (To estimate vegetative weights: $\hat{Y}_{VFW}$ = 1281.0653/1+{EXP-[(SD-4.0166)/0.2699)]} - R^2 = 0.76; $\hat{Y}_{VDW}$ = 249.1383/1+{EXP-[(SD-4.2892)/ 0.4246)]} - R^2 = 0.88).

In Table 5, the RGR values, calculated from the observed SD values, were utilized to estimate the new SD value in the standard model. The new SD value was derived from the same RGR value as in the standard model.

In Table 6, the AGR values, calculated from the observed SD values, were employed to estimate the new SD value in the standard model. The new SD value was determined based on the same AGR value as in the standard model.

Table 5. Relative (RGR) and absolute (AGR) growth rate, as well as stem diameter (SD) values observed in the present study as a function of treatments with sewage sludge and mineral fertilization and their respective AGR, SD, and DD values from the standard model for the same RGR value.

	Values observed in the present study				Default model adjusted values			
	DD[3]	RGR[4] ($x10^{-5}$)	AGR[5] ($x10^{-5}$)	SD[6]	RGR ($x10^{-5}$)	AGR ($x10^{-5}$)	SD	DD
[1]SS	4542.3	1.4	8.1	5.88	1.4	**	**	**
[2]MF		4.8	27.1	5.85	4.8	21.8	4.5	6471.1
SS	5195.8	2.2	12.9	5.97	2.2	11.5	5.22	10628.0
MF		7.3	43.8	6.15	7.3	28.4	3.89	8363.9
SS	5782.6	-1.8	-10.8	5.90	**	**	**	**
MF		-1.3	-8.3	6.10	**	**	**	**

[1]Sewage sludge (SS). [2] Mineral fertilization (MF). [3] Degrees Day. [4] Relative growth rate (cm cm^{-1} DD^{-1}). [5] Absolute growth rate (cm DD^{-1}). [6] Observed stem diameters. **There are no negative values in the default model.

Table 6. Relative (RGR) and absolute (AGR) growth rates, as well as stem diameter (SD) values observed in the present study as a function of treatments with sewage sludge and mineral fertilization and their respective RGR, SD, and DD values from the standard model for the same AGR value.

	Values observed in the present study				Default model adjusted values			
	DD[3]	AGR[4] ($x10^{-5}$)	RGR[5] ($x10^{-5}$)	SD[6]	AGR ($x10^{-5}$)	RGR ($x10^{-5}$)	SD	DD
[1]SS	4542.3	8.1	1.4	5.88	8.1	**	**	**
[2]MF		27.1	4.8	5.85	27.1	6.7	4.04	4440.0
SS	5195.8	12.9	2.2	5.97	12.9	2.5	5.14	9962.7
MF		43.8	7.3	6.15	43.8	**	**	**
SS	5782.6	-10.8	-1.8	5.90	**	**	**	**
MF		-8.3	-1.3	6.10	**	**	**	**

[1]Sewage sludge (SS). [2] Mineral fertilization (MF). [3] Degrees Day. [4] Relative growth rate (cm cm^{-1} DD^{-1}). [5] Absolute growth rate (cm G D^{-1}). [6] Observed stem diameters. **There are no negative values in the default model.

In this study, D leaf fresh weight was determined at 366 DAP (5,782.6 degree days). Total fresh weight was estimated based on vegetative fresh and dry weights to establish the growth curve, while total dry weight was derived from the vegetative weights. Reference (default) models were adjusted using DLFW (D leaf fresh weight), and total and vegetative weights should only be employed if SD or DLDW values are unavailable or fall outside the range of the reference models (standards), as was the case in this specific study. DLFW was used to determine the initial point of the model, which served as the starting point of the growth curve. Afterwards, the AGR and RGR values from the standard model, along with the degree days observed in this study, were used to estimate the subsequent values of the growth curve, thus generating the complete growth curve up to the harvest point.

It is evident that the estimated values closely resemble the values observed in the present study, particularly regarding FW as a proportion of fresh weight (as shown in Table 3 and Table 7). Furthermore, the estimated values of total and vegetative fresh and dry weights exhibited remarkable consistency across all adjusted curves, underscoring the low coefficient of variation for these variables.

Table 7. Total and vegetative fresh and dry weights, fresh and dry weights of fruits with crown, and carbon content in the total and vegetative dry weights at harvest as a function of the fertilizations with sewage sludge and mineral fertilization, starting from a specific value of stem diameter estimated from the absolute and relative growth rates and heat units (last points of the adjusted curves in Figures 4 and 5).

	DD[3]	DLFW[4]		TFW[7]	TDW[8]	VFW[9]	VDW[10]	FFW [11]	FDW[12]	CTW[13]	CVW[14]
[1]SS	5782.6	64.46	AGR[5]	2073.1	432.6	1807.5	385.9	1074.1	131.9	213.5	178.5
			RGR[6]	2076.7	433.2	1814.2	386.1	1076.0	132.1	213.9	178.6
[2]MF	5782.6	59.77	AGR	1850.7	383.8	1735.5	359.6	958.8	117.0	189.5	166.3
			RGR	1861.0	384.9	1748.3	360.8	964.2	117.4	190.0	166.9
Average				1965.4	408.6	1776.4	373.1	1018.3	124.6	201.7	172.6
Standard deviation				126.5	28.0	40.2	14.9	65.6	8.5	13.8	6.9
CV (%)				6.44%	6.86%	2.27%	3.99%	6.44%	6.86%	6.86%	4.00%

[1] Sewage sludge. [2] Mineral fertilization. [3] Degree days in the present study (prediction started at this point and ended on the collection date). [4] D leaf fresh weight observed in the present study (g). [5] Estimated from the absolute growth rate. [6] Estimated from the relative growth rate. [7] TFW= total fresh weight estimated from the standard model (g). [8] TDW = total dry weight estimated from the standard model (g). [9] VFW = vegetative fresh weight estimated from the standard model (g). [10] TDW = vegetative dry weight estimated from the standard model (g). [11] FFW = crowned fruit fresh weight (g) (harvest index = 0.52). [12] FDW = crowned fruit dry weight (g) (harvest index = 0.30). [13] CTW = carbon accumulation in total dry weight (g) (49.36%). [14] CVW = carbon accumulation in vegetative dry weight (g) (46.26%).

The most effective method for estimating pineapple growth involves using AGR and RGR values, rather than relying solely on accumulated heat unit values. Several factors can influence plant growth, such as the origin and weight of seedlings or various cultural practices. However, when plants possess the same weight and are subjected to optimal or similar growing conditions, they tend to exhibit similar AGR or RGR values.

Our findings demonstrate that the estimates generated using AGR and RGR closely align with the observed values for characteristics like fruit weight and D leaf fresh weight. Moreover, the estimated values for both total and vegetative fresh and dry weights consistently exhibit low coefficient of variation values across all adjusted curves. This consistency suggests the robustness and reliability of the models developed in this study for estimating various aspects of pineapple growth.

Conclusion

The proposed reference models (standard) effectively simulate the growth of pineapple plants, allowing for estimation of both total and vegetative weights. These estimations can be made using either stem diameter (SD) or D leaf dry weight (DLDW) as inputs. In cases where DLDW data is not available, D leaf fresh weight (DLFW) can be used. The adjusted standard models serve to refine the estimation of pineapple growth by incorporating determination of D leaf fresh weight (DLFW) as a function of factors like nitrogen (N) doses or plant population per hectare and degree-days (heat units). In the simulation process, it is imperative to establish a starting point for predicting the growth curve. This starting point can be determined using the AGR or RGR values obtained from the standard model in conjunction with the observed heat units.

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