GROWTH CURVE OF A TROPICAL MIXED-GRASS PASTURE IN A HOT AND HUMID CLIMATE †

[CURVA DE CRECIMIENTO DE UNA PASTURA TROPICAL DE GRAMÍNEAS MEZCLADAS EN UN CLIMA CÁLIDO-HÚMEDO]

Epigmenio Castillo-Gallegos*, Jesús Jarillo-Rodríguez, Miguel Ángel Alonso-Díaz, Eliazar Ocaña-Zavaleta and Braulio Valles de la Mora[1](✝)

Centro de Enseñanza, Investigación y Extensión en Ganadería Tropical (CEIEGT), Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México. Carretera federal 129 Amozoc-Nautla, tramo Martínez de la Torre-Tlapacoyan km 5.5, Municipio de Tlapacoyan, estado de Veracruz-Llave. C. P. 93600, México. E-mail: epigmeniocastillo@comunidad.unam.mx Phone (Teléfono): +52 23 2324 3941, ext. 127.

**Corresponding author*

SUMMARY

Background. Pasture growth rate (PGR, kg/ha/day) depends on climatic and management practices. However, studies on the influence of the environment on pasture production and productivity of dry matter are scarce in tropical, hot, and humid regions of México. **Objective.** To estimate the pasture growth curve using time and climatic variables. **Methodology.** We related, through nonlinear models, the accumulated growth of a pasture composed of native grasses mixed with exotic grasses, using time and the variables temperature and day length as independent variables, the latter integrated into a single variable called thermal photo units (PTU). We estimated the daily growth rates of five divisions; from these, the forage yields for ten days until completing 29 periods. The best-fit models had the largest coefficients of determination and the lowest Akaike's information criterion. **Results.** The model that best described the relationship between cumulative yield (Y) and cumulative growing days (X) was reciprocal-quadratic: $y = x/(0.097535 – 0.0000881x + 0.0000006810x^2)$ with $R^2_{Adj,}$ of 0.9988 and an AIC_C of 222.6. The model that best described the relationship between the accumulated performance and the accumulated PTU was rational: $y = (- 317.8 + 1.594x + 0.00001307x^2)/(1 + 0.001059x + 0.00000001964x^2)$, with R^2_{Adjt}.=0.9985 and AIC_C=233.4. Likewise, a two-segment model showed a close fit. The logarithmic model described the first segment: $y_1 = -2268 + 417.2*(\ln(x))$, when $y_2 = 1079.3e^{0.00003932X}$, if $x > 8415$; with $R^2_{Adj.} = 0.9975$ and AICc = 245.1. The value 8415 PTU was when the first derivative of both models coincided. **Implications.** The information generated is useful because it allows grazing system adjustment concerning the correct stocking rate application and designing more efficient grazing rotations. **Conclusions.** The conversion of growth rates to accumulated yield for ten-day periods produced a smooth curve that allowed fitting high-precision nonlinear models to predict forage accumulation from time and climatic variables.

Keywords: Tropics; nonlinear models; grasses; forage inventory.

RESUMEN

Antecedentes. La tasa de crecimiento de la pastura (TAC, kg/ha/día) depende del clima y de las prácticas de manejo. Sin embargo, los estudios sobre la influencia del ambiente en la producción y la productividad de materia seca de los pastos son escasos en las regiones tropicales, cálidas y húmedas de México. **Objetivo.** Estimar la curva de crecimiento de la pastura utilizando variables del clima y el tiempo. **Metodología.** Relacionamos, a través de modelos no lineales, el crecimiento acumulado de una pastura compuesta por gramas nativas mezcladas con gramíneas exóticas, utilizando como variables independientes el tiempo y las variables temperatura y duración del día, esta última integrada en una sola variable denominada unidades fototérmicas (UFT). Estimamos las tasas de crecimiento diarias de cinco divisiones; de estas, se calculó el rendimiento acumulado de forraje por diez días hasta completar 29 periodos. Los modelos de mejor ajuste tenían los mayores coeficientes de determinación y el criterio de información de Akaike más bajo. **Resultados.** El modelo que mejor describió la relación entre el rendimiento acumulado (y) y los días de crecimiento acumulados (x) fue recíproco-cuadrático: $y = x/(0.097535 – 0.0000881x + 0.0000006810x^2)$ con R^2_{Adj}, de 0.9988 y un AIC_C de 222.6. El modelo que

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ORCID = Epigmenio Castillo-Gallegos, https://orcid.org/000-00002-2850-9795; **Jesús Jarillo-Rodríguez**, https://orcid.org/000-0001-6010-5865; **Miguel Ángel Alonso-Díaz**, https://orcid.org/0000-0003-4912-8403; Eliazar Ocaña-Zavaleta, https://orcid.org/000-0003-4302-4486; **Braulio Valles de la Mora**, https://orcid.org/0000-0003-3296-5627

mejor describió la relación entre el rendimiento acumulado y las UFT acumuladas fue el racional: $y = (-317.8 + 1.594x + 0.00001307x^2)/(1 + 0.001059x + 0.00000001964x^2)$, con $R^2_{Adj}=0.9985$ y $AIC_C=233.4$. Asimismo, un modelo de dos segmentos mostró un ajuste cercano a la unidad. El modelo logarítmico describió el primer segmento: $y_1 = -2268 + 417.2*(\ln(x))$, en tanto que $y_2 = 1079.3e^{0.00003932x}$, si $x > 8415$; con $R^2_{Adj} = 0,9975$ y AICc = 245.1. El valor de 8415 UFT ocurrió cuando coincidían la primera derivada de ambos modelos. **Implicaciones.** La información generada es útil porque permite ajustar el sistema de pastoreo en cuanto a la correcta aplicación de la carga animal y diseñar modelos de rotación de pastoreo más eficientes para predecir la acumulación de forraje a partir del tiempo y las variables climáticas. **Conclusiones.** La conversión de tasas de crecimiento a rendimiento acumulado por períodos de diez días produjo una curva suave que permitió ajustar modelos no lineales con una alta precisión para predecir la acumulación de forraje a partir de variables climáticas y el tiempo.

Palabras clave: Trópicos; modelos no lineales; gramíneas; inventario forrajero.

INTRODUCTION

Extensive grazing of mixed-grass pastures is the basis of bovine milk and meat production in Latin America and the Caribbean (Magaña *et al*., 2006). In tropical pastures, dual-purpose livestock and traditional cow-calf system develop, mainly with crosses in various proportions of European x Zebu cattle. Animals receive little or no supplementation throughout critical times of the year (Orantes-Zebadúa *et al*., 2014; Espinoza *et al*., 2018). For this reason, knowing pasture biomass daily production permits the calculation of the seasonal carrying capacity of the pasture. Also, one can plan when and how much forage to conserve and offer to cattle to avoid weight losses at critical times of the year.

The fit of nonlinear models to accumulated data has been used in different areas of livestock research. Kamidi (2005) used the regression of the cumulative daily yield of milk vs. days in milk to estimate parameters that would describe the persistence of lactation without depending on the values of the model parameters. The basis of this approach was a quadratic regression model without intercept ($y = \beta*t - \gamma*t^2$), which gave high values greater than 0.98 for the coefficient of determination and allowed estimating a persistence parameter based on percentiles. Lopez *et al*. (2015) fitted standard growth functions to cumulative milk yield. They found that variable inflection point sigmoid functions were feasible alternatives to obtain lactation curves and estimators of lactation characteristics, such as persistence. Castillo and Marín (2019) analyzed the lactations of F1 cows. They used accumulated milk production data, fitted to a segmented model with a quadratic polynomial segment from the beginning of lactation at four months and another quadratic component for the rest of lactation, finding a high fit ($R^2 = 0.9995$) for this model.

Pasture growth has attracted the attention of researchers (Brougham, 1955), particularly its mathematical modeling (Landsberg, 1977; Almeida *et al*., 2011). Aerial biomass estimates for temperate pastures can be made with small quadrats because their variability is less than that of tropical pasture grasses. Even so, they result in highly variable curve profiles. The variability in the case of the tropical grasses would lead to impractical sampling quadrants due to their large size (100-400 m^2) (French and Rodríguez, 1960). However, suppose forage yield is computed from daily growth rate estimates as the cumulative yield. In that case, a smooth, upward curve monotonic in time is the result, and nonlinear models can describe it with great precision. Overman *et al*. (1989) fitted a Gaussian function to cumulative forage yield of coastal Bermuda grass (Cynodon dactylon (L) Pers.) at Watkinsville, Georgia, USA. They found a good agreement (R^2 from 0.9943 to 0.9981) between the model and the observed data, concluding that the model was appropriate for those locations.

In Brazil, Villa Nova *et al*. (1999) fitted a logistic model to growth data to empirically simulate DM yield from effective growing degree days and day length integrated into a single value called photothermal unit (PTU). The use of the PTU to predict the accumulated yield of forage requires contemporary recordings of daily average temperature to calculate the growing degree days (GDD, °C), day length estimates (N, light-hours) throughout the year, and also pasture growth rates (PGR, kg/ha/day of dry matter – DM).

In tropical regions, pasture growth rates are highly variable throughout the year, which impedes the fit of simple models to the continuous ups and downs that this variable presents. The growth rate of our pastures has been highly variable (Castillo *et al*., 2009; Valles *et al*., 2010). Therefore, we proposed the hypothesis that the fit of nonlinear models to accumulated DM yields against time (days) or photothermal units (PTU) could be an option to forecast the mixed-grass pasture's accumulated yield with precision and accuracy as daily growth rates.

MATERIALS AND METHODS

This investigation took place in the Centro de Enseñanza, Investigación y Extensión en Ganadería Tropical de la Facultad de Medicina Veterinaria y Zootecnia de la Universidad Nacional Autónoma de México (CEIEGT, FMVZ, UNAM) (Center for Teaching, Research, and Extension in Tropical Animal Science, Veterinary and Animal Science School, National Autonomous University of México). The center coordinates are 23° 04' N latitude and 97° 03' longitude, and 114 m of altitude. It lies about 40 km from the Gulf of México coastline in the State of Veracruz. The climate is hot and humid, with rain all year round, and classifies as A(f) w”ig according to Köeppen as modified by García (1981). The mean temperature is 23.5 °C, and the yearly rainfall average for 1980-2000 was 1980 ±350 mm. Table 1 presents the monthly averages of minimum, maximum and mean temperatures (°C) and rainfall (mm) for the research period.

Table 1. Average monthly temperature and rainfall at the research site.

Month	Days	Temperature (°C)		Rainfall (mm)
		Maximum	Minimum	
December	18	24.8	16.8	38
January	31	23.9	15.4	71
February	28	24.0	16.0	112
March	31	27.1	18.7	22
April	30	30.3	19.9	76
May	31	33.1	23.7	84
June	30	34.6	22.5	71
July	31	34.7	21.8	25
August	31	31.9	22.1	277
September	29	31.5	21.3	89
Means or totals	290	29.6	19.8	865

We used aerial biomass data measured at the beginning and end of the recovery period of five individual divisions of an intensive rotational grazing system (one to three days of grazing and 24 to 117 days of recovery). There were 38 divisions (0.8 to 1.4 ha) grazed by 45 Holstein – Zebu multiparous cows with an average live weight of 440±50 kg (Valles *et al*., 2010). Native and exotic grasses dominated the botanical composition (BC), predominating the native ones. Table 2 presents the percent contribution to the botanical composition by each group of species at the beginning of each climatic season. We used the ´t Mannetje and Haydock (1963) comparative yield method to estimate the BC of the pastures. We evaluated the 38 paddocks of the rotation scheme at the beginning of each season.

Pasture sampling went from 13 December 1994 to 29 September 1995 (290 days). The pasture disc meter technique was used (Santillán *et al*., 1979). On each sampling, we measured 100 compressed height readings (HT, cm). Every 20 measurements, the forage under the disc was cut to ground level to have a calibration equation relating the compressed vegetation height by the aluminum disc of 0.25 m^2 and a weight equivalent to 4 kg/m^2, with the amount of forage. We used the equation AB = b_1*HT, where AB was the amount of aerial biomass (AB, g/0.25 m^2 of DM), b_1 was the linear regression coefficient (g/0.25 m^2/cm), and HT was the height measured with the disk. We assumed that at zero height, the amount of forage was zero. We made 5760 HT readings and 240 forage harvests under the disk (g /0.25 m^2 of DM). Table 3 presents the ranges of parameters of the fitted equations.

Pasture growth rate (PGR, kg/ha/day of DM) is the difference between the aerial biomass at the end minus the aerial biomass at the beginning of a given recovery period divided by the length of the same period (days). Figure 1 shows the overlapping of growth rates per division.

We formed 29 periods of continuous ten-day PGR means, then the means per period were calculated. The forage yield (Y, kg/ha) for each period was the product of the average PGR by 10. The accumulated yield (ACY, kg/ha) resulted from the current period’s yield added to the previously accumulated one (Table 4).

We fitted the accumulated yield data (y) and the accumulated days with the reciprocal quadratic model:

$$y = \frac{x}{b_0 + b_1 x + b_2 x^2}$$

where: y is the accumulated yield (kg DM/ha), b_0 to b_2 are parameters without biological meaning, and x is the accumulated days.

Table 2. Botanical composition of the pastures. All quantities are percentages.

Botanical component[1]	Seasons			Mean	S. D.[2]	C. V.[2]
	Winter	Dry	Rainy			
Stargrass	24.60	24.97	28.25	25.9	2.0	7.75
Tannergrass	13.85	13.44	15.94	14.4	1.3	9.30
Native grasses	45.31	46.25	39.80	43.8	3.5	7.96
Native legumes	4.76	4.93	6.06	5.3	0.7	13.46
Narrow-leaved weeds	8.20	8.39	6.60	7.7	1.0	12.72
Wide-leaved weeds	3.28	2.02	3.35	2.9	0.7	25.96
Total	100.00	100.00	100.00	100.00		

[1] Exotic grasses: Stargrass (Cynodon nlemfuensis Vanderyst); Tannergrass (Brachiaria arrecta (Hack.) Stent). Native grasses: Paspalum notatum Flügge; P. conjugatum Swartz; Axonopus compressus (Swartz) Beauv; A. affinis Chase. Native legumes: Desmodium intortum (Mill.) Urb.; D. uncinatum (Jacq.) DC. Narrow-leaved weeds: P. virgatum L; Sporobolus poiretii (Roem. Et Schult.). Wide-leaved weeds: Mimosa pigra L.; M. pudica L.

[2] S. D. is the standard deviation (%). C. V. is the coefficient of variation (%).

Table 3. Range of values per paddock for the slopes and coefficients of determination from pasture aerial biomass sampling with a disk meter, using the method described by Santillán *et al*. (1979). The aerial biomass (AB, kg/ha) was estimated from pasture height (HT, cm) with the linear regression equation without intercept: AB = HT*Slope. The HT was calculated as compressed pasture height by an aluminum disk of 0.25 m^2 and a weight equivalent to 4 kg/m^2. We sampled five paddocks on different occasions, 24 times in the beginning and 24 times at the end of a recovery period performing five double samplings and 100 HT disk readings each time, for a total of 240 double-samples and 5760 HT readings.

Time of sampling	Paddock	Samplings	Slope	R^2
End of the recovery period	14B	6	200.8 - 303.5	0.9543 - 0.9759
	5A	6	195.6 - 269.1	0.8980 - 0.9759
	8D	5	195.9 - 253.9	0.8341 - 0.9629
	18A	4	214.3 - 290.1	0.9371 - 0.9703
	8B	3	222.6 - 256.3	0.9223 - 0.9842
Beginning of the recovery period.	14B	6	148.4 - 206.1	0.9539 - 0.9759
	5A	6	123.9 - 203.9	0.8980 - 0.9730
	8D	5	143.4 - 209.3	0.9352 - 0.9692
	18A	4	158.6 - 240.8	0.9550 - 0.9842
	8B	3	155.2 - 198.0	0.8980 - 0.9842

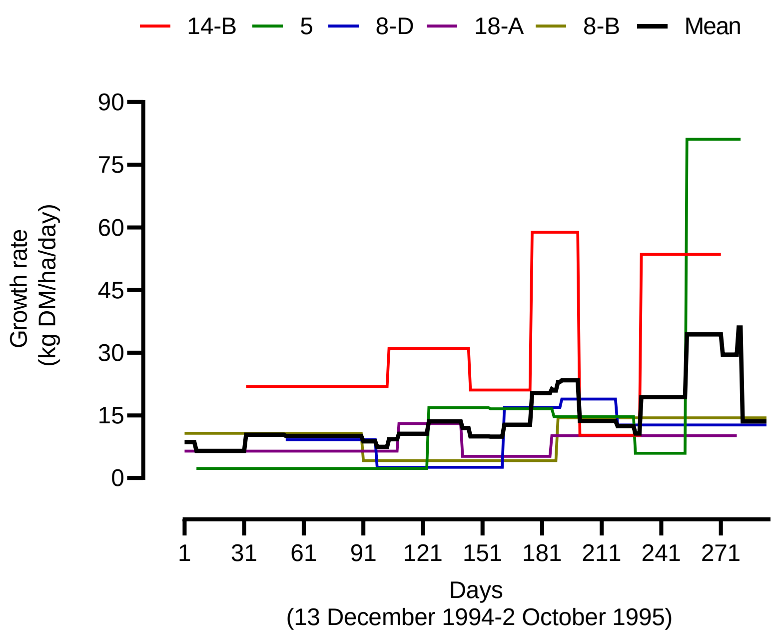


Figure 1. Absolute pasture growth rates (PGR, kg/ha/day of DM). The thin lines of different color belong to the PGR of each division and their changes through time. The thick black line is the daily mean PGR from the five sampled divisions. The horizontal part of each line is the value of the PGR between two successive samplings.

We computed the growing degree days (GDD, °C) with the following formula:

$$GDD = (\overline{T} - T_{base})$$

Where: $\overline{T}$ is the average temperature, and T_{base}, or base temperature, the one at which grass growth stops. We do not have an estimated base temperature in the present case, so we used fifteen degrees centigrade after the results obtained in Brazil by Andrade *et al*. (2015) and Moreno *et al*. (2014). We used the CBM procedure of Forsythe *et al*. (1995) to compute day length according to the following formulae:

$$\theta = 0.2163108 + 2\tan^{-1[0.9671396*\tan[0.00860*(J-186)]]}$$

$$\phi = \sin^{-1}[0.39795 * \cos\theta]$$

$$N = 24 - \frac{24}{\pi}\cos^{-1}\left[\frac{\frac{\sin p\pi}{180} + \frac{\sin L\pi}{180}\sin\phi}{\frac{\cos(L'\pi)}{180}\cos\phi}\right]$$

where: θ, in radians, is the predicted angle of revolution from the day of the year (J), φ, in radians, is the sun's declination angle, or angular distance at solar noon between the sun and the equator of the angle of revolution of the Earth's orbit, N is the length of the day predicted from latitude (L), longitude (L') and the solar declination angle. The equation was modified to include p, degrees, or day length coefficient. Finally, according to Villa Nova *et al*. (2007), the calculation of the PTU was:

$$PTU = \frac{\left(\frac{n}{2} * GDD\right)^{\frac{N_f}{N_i}+1}}{\frac{N_f}{N_i} + 1}$$

where: Ni and Nf are the light hours of the day that begins and the day that the growth period ends, n is the number of days of the growth period, and GDD was already defined. Table 5 presents the calculation of the PTU.

The accumulated forage production (y, kg DM/ha) was related to the accumulated PTU in the same period using the following rational model:

$$y = \frac{b_0 + b_1x + b_2x^2}{1 + b_3x + b_4x^2}$$

Where: b_0, b_1, b_2, b_3, and b_4 are parameters with no apparent biological meaning, and x represents the accumulated PTU (°C) over time.

Table 4. Computation of dry matter yield and accumulated yield according to Overman *et al*. (1989).

Period	Days	Dates		Accumulated days	PGR[1] (kg/ha/day)	Yield[1] (kg/ha)	
		Initial	Final			y	ACy
1	10	13-dic.-94	22-dic.-94	10	7.55	75.5	75.5
2	10	23-dic.-94	01-ene.-95	20	6.50	65.0	140.5
3	10	02-ene.-95	11-ene.-95	30	6.50	65.0	205.5
4	10	12-ene.-95	21-ene.-95	40	10.06	100.6	306.1
5	10	22-ene.-95	31-ene.-95	50	10.36	103.6	409.7
6	10	01-feb.-95	10-feb.-95	60	10.14	101.4	511.1
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

[1] PGR is the pasture growth rate in kilograms of dry matter per hectare per day; Y is dry matter yield in kilograms per hectare; ACY is accumulated dry matter yield in kilograms per hectare.

Table 5. Computation of photothermal units (PTU) per period and accumulated, according to Villa Nova *et al*. (2007).

Period	Temperature (°C)		Daylength (hours)			Photo Thermal Units[1]	
	Average	GDD	Ni	Nf	Nf/Ni + 1	Period	Accumulated
1	19.85	4.85	12.394	12.225	1.986	283.5	283.5
2	19.53	4.53	12.206	12.036	1.986	247.3	530.8
3	16.65	1.65	10.936	10.916	1.998	33.9	564.7
4	16.65	1.65	10.916	10.937	2.002	34.1	598.8
5	16.65	1.65	10.942	11.002	2.005	34.3	633.2
6	19.90	4.90	11.011	11.105	2.009	307.1	940.3
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

[1] PTU = (((n/2)*GDD)^(Nf/Ni + 1))/(Nf/Ni + 1). Where n is the days of the growth period, GDD is the effective growing degree days equal to the average temperature for a given period minus the base temperature, 15 °C, in the present investigation. Ni and Nf are daylengths in hours at the beginning and end of the growth period.

We also fit a two-segment nonlinear model (Motulsky, 2022), the first for $x \leq x_0$, and the second for $x > x_0$, corresponding respectively to a logarithmic and an exponential model:

$$y_1 = a + b * (\ln(x))$$

$$y_2 = a' e^{b' x}$$

If $x = x_0$, then the smooth union of both segments is only obtained if the first derivatives with respect to x coincide at x_0 (SAS, 2013), then $x_1 = x_2$. We chose the above from 148 models implemented in the software CurveExpert Professional v. 2.7.3 (Hyams, 2020), which were solved using the Levenberg-Marquardt method. The statistics to assess the goodness of fit were the adjusted coefficient of determination ($0 \leq R^2_{adj.} \leq 1$); the higher the value, the better the fit), and the corrected Akaike information criterion (AIC_C; the lower the value, the better the fit). The following formula was used to compare two models: $p = (e^{-0.5\Delta})/(1+e^{-0.5\Delta})$, which estimates the probability of selecting the best model. We also used the evidence ratio, whose formula is $ER = 1/e^{-0.5\Delta}$, with the delta being the difference between the most complicated rational model minus the least complex segmented model (Motulsky, 2022).

RESULTS

Figure 1 presents the absolute growth rates of the five divisions sampled (thin lines) and the average growth rate (thick line). As can be seen, the variation between divisions increased as the accumulated days, and the values of the absolute growth rate increased over time.

Figure 2 (A) presents the accumulated yield curve (continuous line) as a function of accumulated days. A classical S-shaped response from the logistic model was expected, but a response resembling exponential growth occurred. This reciprocal-quadratic model of the yield-density family presented a more than reasonable fit, indicated by the coefficient of determination that was only 0.0012 fractional units short of reaching the value of one. Furthermore, this model had an AICC value of 222.6, the lowest of the three. The dotted line in Figure 2 (A) is the first derivative of the reciprocal model and represents the pasture growth rate. The PGR fluctuated between 9 kg DM/ha/day between the start of sampling and 145 days, to rise from there in shape similar to the exponential way up to 36 kg of DM/ha/day at 290 days, that is, the growth rate increased four times in this last period.

Figure 2 (B) presents the cumulative performance curve against the cumulative photothermal units. This model, known as rational, is the ratio between two second-order polynomials and showed a high fit, reaching only 0.0015 units fractional below the perfect fit, unity.

Figure 3 presents the same data as Figure 2(B) but fits a segmented model. The dark circles represent the logarithmic segment, and the gray circles represent the exponential segment. The union point of both pieces occurred when x_0 = 8415 PTU and y_0 = 1502.6 kg/ha. The reciprocal quadratic model (AIC_C = 222.6) was 222.4 and 76881 times more likely to be the correct model than the rational (AIC_C = 233.4) and the segmented (AIC_C = 245.1) models, respectively.

DISCUSSION

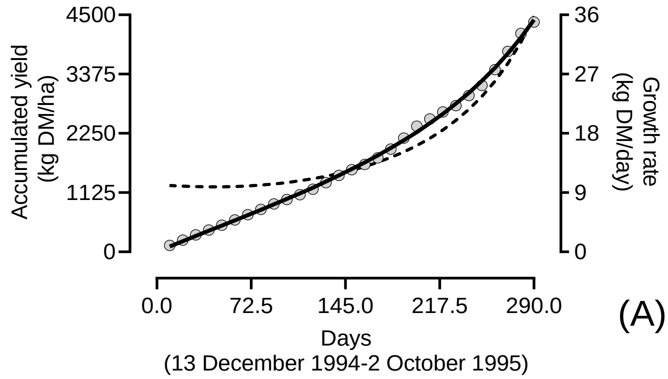
Forage grasses that present the C4 photosynthetic route are from warm climates. Their biomass production is seasonal as growth generally ceases when climatic conditions are cold, dry, or both situations occur (Moser *et al*., 2004). In subtropical regions, low winter temperatures stop the growth of C4 grasses. Suppose the temperature persists below the base temperature for two or three days. The clearance of carbohydrates, mainly starch, from the chloroplast is interrupted because amylase activity is temperature-dependent. Eventually, the excess carbohydrate breaks down the chloroplast wall, and the aerial part of the plant dies (Hilliard and West, 1970).

In the present study, low temperatures prevailed in winter but were never lower than the base temperature (Table 1). Also, there was no drought, so soil moisture availability did not play an essential role in plant growth. Cold fronts are persistent, bringing dense cloudiness, which reduces the photosynthetic rate even with temperatures above the base temperature. Suppose cloud cover and the diffuse radiation of light increase in the canopy of C4 vegetation. Then photosynthesis and CO_2 and $CO^{18}O$ isofluxes become limited by light (Still *et al*., 2009). The above suggests that pasture growth prediction models must incorporate the effects of cloud cover on the radiation the pasture plant community receives. PTU units integrate day length and air temperature but do not consider cloudiness.

The usual model for growth is the logistic one: $y = a/(1+be^{-c*x})$. Figure 2(A) presents the relationship between the accumulated performance against the accumulated days. The shape of the curve resembled exponential growth (Landsberg, 1977), which is part of the logistic model and occurs when the regrowth time is short so that the asymptote does not appear or when the moisture and fertility resources of the soil are scarce. Hence, growth rates are low and do not allow for reaching the asymptote. The soils of the Experimental Center are shallow (0-30 cm deep), acidic (pH 4.5-5.2), and not very fertile (1-2 ppm of absorbable P-Bray II)(Castillo *et al*., 2005). Added to this situation is a hardpan under the topsoil that causes frequent flooding and poor pasture growth.

$$y = \frac{x}{0.097535 - 0.0000881064 * x - 0.000000680985 * x^2}$$

$$R^2 = 0.9988 \quad AIC_C = 222.56 \quad RSD = 44.59 \quad EDF = 26$$



$$y = \frac{-317.77 + 1.594 * x + 0.00001307 * x^2}{1 + 0.0010585 * x - 0.00000001964 * x^2}$$

$$R^2 = 0.9985 \quad AIC_C = 233.35 \quad RSD = 52.00 \quad EDF = 24$$

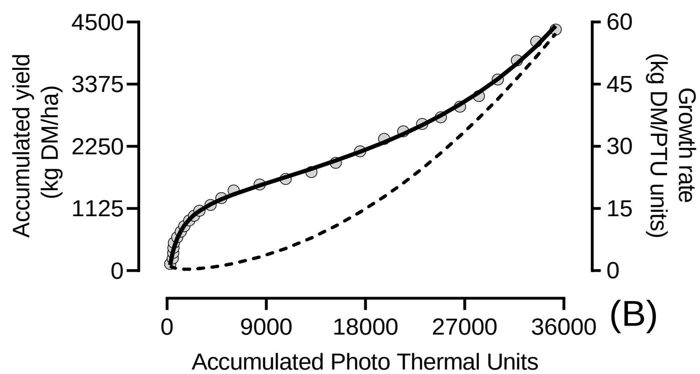


Figure 2. Accumulated yield (continuous line) and growth rate (dotted line) curves of mixed-grass pastures according to accumulated days (A) or accumulated photo thermal units (B). Circles represent the observed accumulated yield. The best-fit nonlinear model is at the top of each plot. RSD is the residual standard deviation, and EDF is the error degrees of freedom.

Figure 2(B) shows the relationship between cumulative growth and cumulative PTU. This response differed from the logistic function described by Villa Nova *et al*. (2007). Almeida *et al*. (2011) described the model we used but for two variables. Being a quotient between two quadratic polynomials presents the high flexibility to fit variable growth data. However, it is not simple to assign units to these functions. If the purpose is forecasting per se, polynomials should be preferred. Still, suppose one wants to use models to explain biological processes like the growth of an organ. In that case, one can sacrifice the high fit of polynomials for nonlinear models that help to explain the processes involved. Polynomials should not be used freely, nor should the proliferation of empirical parameters be allowed when fitting them (Lansberg, 1977; Pollard, 1977). Figure 3 shows that the cumulative growth had two components, an initial stage from the origin to $X_0 = 8415$, similar to a reciprocal response, and the second, exponential growth, from $x > x_0$. According to the coefficients of determination, the models would result in similar fits. However, the AIC_C values indicated that the reciprocal quadratic model was 356 and 76881 times more likely to be correct than the rational and segmented models.

$$y_1 = -2268 + 417.2 * (ln(x)), \quad if\ x < 8415$$
$$y_0 = -2268 + 417.2 * (ln(8415)), \quad if\ x = 8415$$
$$y_2 = 1079.28 * e^{0.00003932 * x}, \quad if\ x > 8415$$

$$R^2 = 0.9975 \quad AIC_C = 245.10 \quad RSD = 61.17 \quad EDF = 26$$

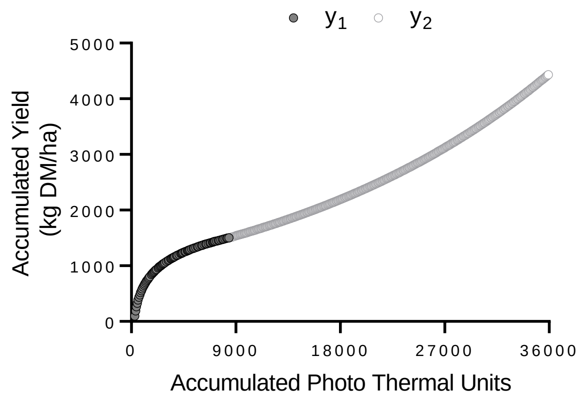


Figure 3. The segmented model fitted to accumulated yield data (kg DM/ha). The first segment (y_1, dark-grey circles) is a logarithmic model which describes growth if x < 8415, and the second segment (y_2, light-grey circles) is a model describing the exponential growth when x > 8415. Both segments join smoothly at x_0 = 8415 PTU, y_0 = 1502.6 kg DM/ha. RSD is the residual standard deviation, and EDF is the error degrees of freedom.

The division of the curve into two different models does not imply that the relationships are not empirical unless their parameters explain the pasture's phenological state as it produces forage. In the present case, the pasture system accumulated 8415 PTU logarithmically before the exponential accumulation. This intersecting point could be a critical value indicating the amount of PTU accumulated for meristematic maturation. The mobilization of reserves leads to accelerated cell growth, characteristic of the intermediate stages of plant regrowth. Also, the calculation of the accumulated yield started in December, a month with low temperatures and high cloudiness and, therefore, low growth rates, which could have led to the logarithmic response observed in the first segment.

The reciprocal model presented the lowest value of AICC, = 222.6 (Figure 2 (A)), so for these data, the accumulated days were better predictors than the PTU. This phenomenon is possible since time integrates all the biotic and abiotic factors that affect the growth of pasture plants without it being necessary to measure variables such as solar radiation, cloudiness, air temperature, precipitation, and usable soil moisture. Nonetheless, using PTUs is a successful attempt to predict cumulative growth by integrating climatic variables like temperature and day length.

In conclusion, the accumulated time and the accumulated photothermal units were excellent predictors of forage accumulation throughout the measurement time of 290 days. However, it is necessary to insist on fitting the models to local environmental conditions and rationalizing models that integrate the factors that explain growth based on cause-effect relationships.

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