Modeling of the biomass accumulation dynamics in *Pennisetum purpureum* cv. king grass in the Western region of Cuba

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Different regression models were adjusted to predict growth of *Pennisetum purpureum* cv. king grass in the rainy and dry periods in the Western region of Cuba through the accumulated dry matter yield. Information from experiments carried out by the Department of Pastures of the Institute of Animal was used. Data on biomass accumulation of the pasture at 13 regrowth ages in the rainy period and 10 in the dry one with 14 d of difference between ages were utilized. Five regression models (three linear and two non-linear) and five statistical criteria were evaluated. A sample obtained from the Bootstrap was used for selecting the best adjustment in the studied variable. The maximum growth rhythm, age at which was attained the inflection point and the appropriate moment for the exploitation of the forage area, were estimated. The model of best adjustment was the Gompertz. The highest value of biomass accumulation for the rainy period was of 23.82 t of DM ha^{-1} and in the rainy period of 7.31 t of DM ha^{-1}. The period of highest forage growth speed was between 14 and 57 d. In yield terms, the exploitation of this variety under the studied conditions must be from 88 to 90 d in the rainy period and of 78 to 88 d in the dry period. It is recommended to evaluate the curve of biomass accumulation of *Pennisetum purpureum* cv. king grass until 140 d of age and to confirm results obtained under different environmental and soil conditions.

Key words: *growth dynamics, accumulated yield, Gompertz model, Bootstrap*.

Pennisetum purpureum Schmach is a species of great usefulness for forage production and grazing in Cuban cattle raising (Martínez *et al*. 2010). In the majority of the countries where it is cultivated, annual yields above those obtained with other grasses, even of similar size and under equal conditions are attained (Machado *et al*. 1979).

Studies carried in king grass by Herrera and Ramos (1990) reported annual DM yields ranging between 20 and 28 t ha^{-1} higher than other varieties as napier and dwarf grass (14 to 16 t ha^{-1}). These characteristics make this species of vital importance for animal production.

The knowledge of the growth curves of different varieties which are of interest for livestock production is an important tool for research purposes and for taking the decisions at the cattle enterprises. Their adequate use can generate and implement programs helping to identify economical and productive parameters (Agudelo *et al*. 2007 and Santana *et al*. 2010) allowing to increase the efficiency and productivity of this sector.

In Cuba, Martínez *et al*. (2010) described the biomass accumulation curve of king grass in the rainy period through the Gompertz model. However, these authors did not reach to determine their growth rhythm, age at which the inflection point was attained and the adequate moment for forage exploitation, which will supply a way to support taking decisions for research and production.

The objective of this paper was to select the model of best adjustment to accumulated DM yield of *Pennisetum purpureum* cv. king grass, estimate the growth rates and daily increase and determine the adequate time for the exploitation of the forage area.

Materials and Methods

Information from experiments developed during one year by the Department of Pastures of the Institute of Animal Science, located in the municipality of San José de las Lajas, Mayabeque province, Cuba, between 22º 53' NL and 82º 02' WL at 92 m a.s.l. was used.

The experiment was carried out in a typical red ferrallitic soil, in 12 rows 40 m long. Each 14 d six strips, 5 m long were cut, which constituted six replications of each age.

The forage was harvested at 10 cm height and only 70 kg N/ha was applied as fertilization. There was irrigation in the dry season.

Data of biomass accumulation of king grass were registered at 13 regrowth ages in the rainy period (14, 28, 42, 56, 70, 84, 98, 112, 126, 140, 154, 168 and 182 d) and 10 in the dry period (14, 28, 42, 56, 70, 84, 98, 112, 126 and 140 d). The relationships between regrowth age and accumulated dry matter yield (ADMY) were established.

Considering the failure to comply the theoretical assumptions of the variance analysis of the regression (Montgomery *et al*. 2005), given the small size of observations for each age (six replications per cut), the original values were re-sampled. For that the Bootstrap method was applied for obtaining the model of best adjustment. A Bootstrap (B) magnitude, B = 50 for each age was employed. A sample of 650 and 500 observations was obtained for the adjustment in the rainy and dry periods, respectively.

The Bootstrap is a special type of simulation based on data, whose procedure is derived from the analogy between the sample and the population (Efron and Tibshirani 1986) from which the sample is extracted. This involves sampling again data obtained in a sample, many times to generate an empirical estimation of the complete sample distribution of a statistics.

Eight regression models were appraised to select the best adjustment to the studied variable:

$$\text{Linear}\begin{cases} W(t)=\beta_0+\beta_1 t \\ W(t)=\beta_0+\beta_1 t+\beta_2 t^2 \\ W(t)=\beta_0+\beta_1 t+\beta_2 t^2+\beta_3 t^3 \end{cases}$$

$$\text{Non linear}\begin{cases} W(t)=\dfrac{\beta_1}{1+\beta_2 e^{-\beta_3 t}} & \text{logistical} \\ W(t)=\beta_1 e^{-\beta_2 e^{-\beta_3 t}} & \text{Gompertz} \end{cases}$$

where:

W (t) = variable representing growth or development

βi = parameters of the models i = 0, 1, 2, 3

t = time (days)

The adjustment of the models was made from the following statistical criteria: coefficient of determination (R^2, %), adjusted coefficient of determination (R^2adj, %), mean square of the error (MSE), significance of the complete model and significance of the parameters of the model (Guerra *et al*. 2003).

The biological performance of the variety, considered for selecting the best model, was described through the evolution curves in time of the common daily increase and the mean daily increase (Kiviste 2002). By common daily increase (CDI) is inferred the growth variation in a change of time. The mean daily increase (MDI) is the accumulated growth related to age.

The information was processed by the statistical programs Statgraphic Plus (Anon 1995), Statsoft (2003) and InfoStat (Di Rienzo *et al*. 2008).

Results and Discussion

Table 1 shows the result of the adjusted models between accumulated DM yield and age until 182 d. The statistical criteria used were considered for analyzing the goodness of fit of the models to the data.

The evaluated models accounted for 81 and 90 % of the variation between total yield and age. Among all models, the simple linear exhibited the worst results with the lowest values for R^2 and R^2 adjusted by the degrees of freedom, greater residual variance and one significant parameter.

There were high R^2 and R^2 adj, minimum residual variances and high significance of the model ($P < 0.001$) in the remaining models (quadratic, cubic, logistical and Gompertz). All their parameters resulted significant, though any of them could be selected for estimating the performance of the variable under study. However, the cubic model, although showing better results, had the disadvantage that their parameters have no biological interpretation (Jansen 1995) since the polynomial adjustment is arbitrary. That is, the gradual increase of the degree of the polynomial, although having the satisfactory adjustment, is of poor usefulness for future predictions (Blasco 2013).

The use of non-linear functions has the advantage that these could be derived from theoretical considerations and their parameters can reflect aspects of interest for the modeler or the user, since they allow to find out better parameters for the different growth stages (Schabenberger and Pierce 2002 and Carrero *et al*. 2008).

There are diverse non linear models describing the growth curve according to specific conditions (Ribeiro 2005), though it is important to determine which supplies better adjustment. The Gompertz's model is applied in different fields (Thornley and France 2007) and is one of the functions that with greater frequency are found in the literature for describing growth of individuals or organisms in time (Freitas 2005). This model presented the best results and showed the highest values of R^2 and R^2adj, lower MSE and high significance of the complete model ($P < 0.001$) and their parameters ($P < 0.05$, $P < 0.001$). Therefore, the best goodness fit was considered taking into account its sigmoid form, which has a logical relationship with plant growth.

In figure 1 are shown the values of accumulated dry matter yield, real and estimated, by the Gompertz's model.

Biomass growth was characterized by a fast DM accumulation since the first ages. It was maintained in a constant way, approximately until 42 d of age of the forage, with yields between 0.5 to 5 t DM/ha. From this age it started to change forming a horizontal asymptote. This indicated that the forage reached certain maturity degree. This characteristic agrees with the value of the parameter A = 23.82 t DM/ha, representing an estimate of the value of accumulated DM yield at 182 d.

Based on the parameters of the growth models, other indicators could be derived, as the degree of maturity at a given time, as well as age and weight in the inflection point (Goyache 2005) indicating change in the growth rate.

Figure 2 exhibits results obtained and specify the maximum growth speed, inflection point and appropriate time for the exploitation of the forage area for the variable under study in the rainy and dry periods.

There was a fast growth, produced between 14 and 56 d, with estimated growth rates between 0.1 and 0.25 t $ha^{-1}day^{-1}$. This is biologically related to the stage when the biomass is accumulated faster.

Between 42 and 70 d, there was a concavity of the function, indicating a reason for the change in the growth speed, with tendency to decrease sharply. From that

Table 1. Adjusted models between the variable accumulated dry matter yield and cutting age of regrouth of the forage in the rainy period

Model	R^2 (%)	R^2aj (%)	MSE	Sign, Model	β_0 EE(±) Sign.	β_1 EE(±) Sign.	β_2 EE(±) Sign.	β3 EE(±) Sign.
Simple linear	81.0	81.0	13.09	***	0.54	0.14	----	----
					0.30	2.7×10^{-3}		
					NS	***		
Quadratic	88.5	88.5	8.08	***	-5.77	0.32	9×10^{-4}	----
					0.39	0.009	5×10^{-5}	
					***	***	***	
Cubic	90.0	90.0	7.01	***	-1.38	0.10	0.002	-9.5×10^{-6}
					0.57	0.02	0.0002	9.5×10^{-7}
					*	***	***	***
Logistical	87.5	87.5	8.78	***	23.13	19.20	0.04	----
					0.26	2.17	0.002	
					***	***	***	
Gompertz	88.3	88.3	8.24	***	23.81	5.01	0.03	----
					0.33	0.35	0.001	
					***	*	***	

$^*P<0.05$ $^{**}P<0.01$ $^{***}P<0.001$ NS $P>0.05$

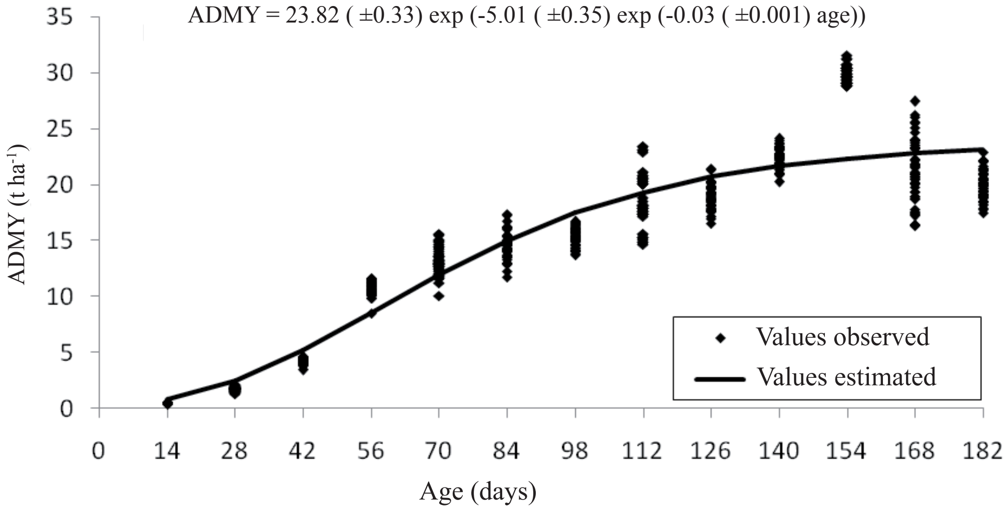

Figure 1. Performance of the accumulation curve of the dry matter yield with pasture age in the rainy period

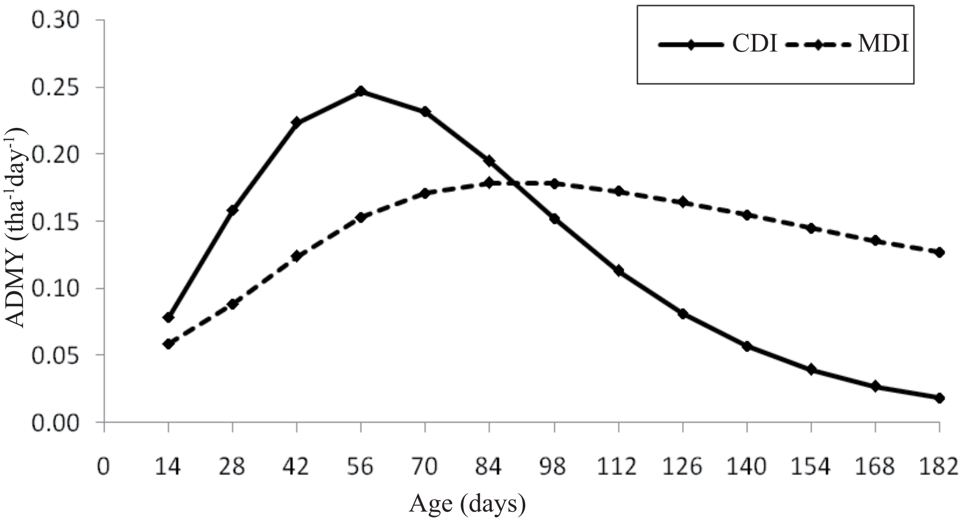

Figure 2. Increase of accumulated DM yield, according to the application of the Gompertz model in the rainy period

moment, growth was less fast and its rates started to be stabilized in time.

At 57 d the inflection point of the model was attained, indicating the optimum yield from the mathematical point of view for the exploitation of this variety. Average yield was of 8.82 t DM ha^{-1}, coinciding with Martínez *et al.* (2010). However, on analyzing the mean daily increase curve, it can be observed that the appropriate moment for the exploitation of the forage area must be in the intersection point of both curves. This agrees with the 88 to 90 d interval of regrowth age, with a growth rate of 0.18 t ha^{-1}d^{-1} and average accumulated yield of 15.95 t ha^{-1} (figure 1).

In Costa Rica, Chacón and Vargas (2009) recommended the harvesting of the forage area between 60 and 75 d, period when lower values to those reported in this study were obtained. Fernández and Valdés (2009) recommended not using intervals between cuttings higher than 75 d in any season. However, their results were inferior to those obtained here in. This suggests more specific analyses according to the experimental or production conditions.

Likewise, the analysis was conducted in the dry season. Table 2 informs the mathematical models and statistical criteria used in the adjustment between the accumulated DM yield and the age up to 140 d.

It was observed that linear as non-linear models showed good goodness of fit for the accumulated DM yield data. Among all models tested, the same as in the rainy period, the Gompertz showed the best statigraphs, thus it was chosen for describing adequately the biological performance of the variety.

Figure 3 shows real and estimated values for accumulated DM yield by the Gompertz model between

Table 2. Models adjusted between the variable accumulated dry matter yield and regrouth of the forage in the dry period

Model	R^2 (%)	R^2aj (%)	MSE	Sign, Model	β_0 EE(±) Sign.	β_1 EE(±) Sign.	β_2 EE(±) Sign.	β3 EE(±) Sign.
Simple linear	97.3	97.3	0.14	***	-0.36 0.04 ***	0.06 0.0004 ***	----	----
Cuadratic	98.8	98.8	0.06	***	-1.20 0.04 ***	0.09 0.001 ***	-1.9x10^{-4} 7.8x10^{-6} ***	----
Cubic	99.4	99.4	0.03	***	0.03 0.003 ***	6.0x10^{-4} 3.9x10^{-5} ***	-3.5x10^{-6} 1.65x10^{-7} ***	-3.5x10^{-6} 1.6x10^{-7} ***
Logistical	99.2	99.2	0.04	***	6.74 0.03 ***	23.32 0.72 ***	0.05 5*10^{-4} ***	----
Gompertz	99.5	99.5	0.02	***	7.31 0.03 0.33 ***	4.83 0.06 0.35 *	0.03 0.0003 0.001 ***	----

*P<0.05 **P<0.01 ***P<0.001

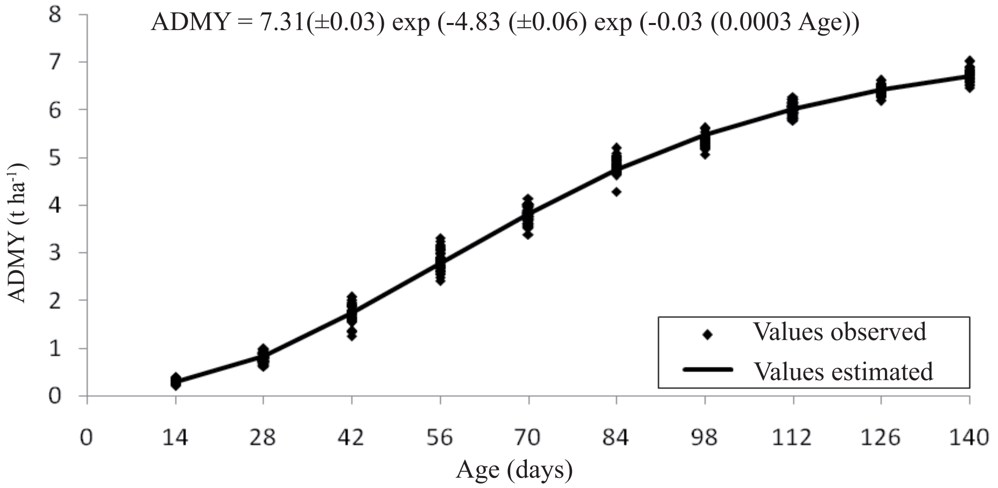

Figure 3. Performance of the accumulated DM yield curve with pasture age in the dry period

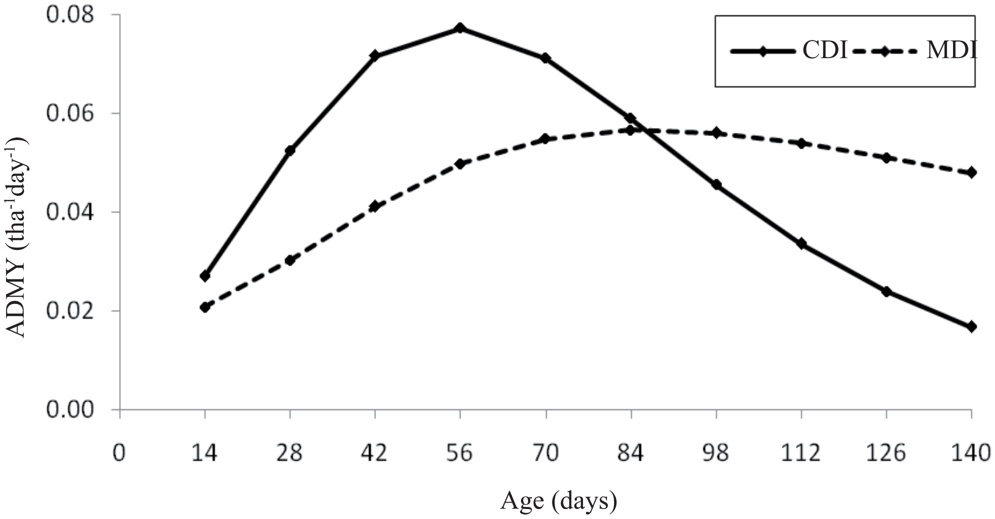

Figure 4. Increment of accumulated DM yield in the dry period, adjusted according to Gompertz

14 and 140 d of regrowth in the dry period.

The highest yield was attained in 92.8 % of the asymptotic value of the curve, where A = 7.31 t DM /ha, and resulted in an estimated value of the DM yield at 140 d (cut 10) in the dry period.

Figure 4 illustrates the performance in time of the accumulated DM yield. There was similar performance between the rainy and dry periods, regarding the highest growth speed, which was found between 14 and 55 d, being at 55 d when the inflection point was produced. This corresponded to the maximum value of common growth curve (2.71 t ha^{-1}). In the agronomical evaluation of new varieties of *Pennisetum purpureum* under drought conditions in Cauto Valley, Díaz (2007) obtained similar results.

From that moment, yield decreased gradually, therefore, the CDI values started to decrease. In the period from 78 to 88 d the curves with increase rate of 0.06 t $ha^{-1}day^{-1}$ and average yield of 4.7 t DM ha^{-1} until that age were intercepted as observed in the figure of adjustment of the model (figure 3). This indicated that, from the mathematical point of view, higher efficiency was achieved, although from the biological one, the reserve substances needed for the second or third regrowth are not replaced, so further specific studies would be necessary to determine the amount of reserves stored when reaching these rates of maximum development.

This performance could be related with the low temperatures, low soil humidity and shorter duration of the day, characterizing the dry period (Rodríguez *et al*. 2011). That is why, cutting the forage after the proposed period is not recommended because, apart from diminishing drastically the growth rate, from that age on, the MDI rate decreases, although more stable in time.

In the oldest regrowth ages, high biomass productions are obtained but with less quality, so a balance point between production and quality should be found and assure the animals' nutritional requirements and guarantee also the forage persistence and productivity.

On evaluating the inflection point in the function estimated for the accumulated DM yield in the dry period it was attained that, at 55 d of regrowth, the optimum DM yield (2.71 t/ha) was reached, from the mathematical point of view.

It can be inferred from the previous statement that from 140 d growth stability was reached, since at this age 94 and 92 % of the asymptotic yield value was obtained in the rainy and dry periods, respectively. Thus, it is not recommended to evaluate the growth curve beyond this age, which represents the productive potential limit of this variety under the conditions studied. This will allow to a certain extent to save resources.

Finally, the model allowing better goodness of fit to the real values of accumulated DM yield was the Gompertz. The asymptotic value or the highest biomass accumulation value for the rainy period was of 23.82 t of DM ha^{-1} and in the dry period of 7.31 t DM ha^{-1}. The period of highest forage growth speed was produced between 14 and 57 d. In yield terms, the exploitation of this variety under the conditions studied should be realized from 88 to 90d in the rainy period and from 78 to 88 d in the dry period. The curve of biomass accumulation of *Pennisetum purpureum* cv. king grass beyond 140 d must not be evaluated. Results obtained require to be validated under different environmental and soil conditions.

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