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Forage yield of buffel grass (*Pennisetum ciliare*) using PHYGROW model in thinned Caatinga

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Abstract: Animal production in semi-arid regions relies heavily on natural and cultivated pastures, which are vulnerable due to the variability of rainfall. This study evaluated the PHYGROW model's ability to predict the forage yield of buffel grass (*Pennisetum ciliare*) in thinned Caatinga and assess production risk. The research was conducted in Santa Terezinha, Paraíba, Brazil, in an experimental area under a silvopastoral system (15-20% woody cover) enriched with buffel grass. Field data from studies conducted between 2008 and 2014 were used, and biomass yield was estimated using PHYGROW software. The model's results were analyzed statistically, and risk analysis was conducted using the concept of the natural guarantee of local production. The PHYGROW model showed high accuracy in predicting forage yield, estimating an annual dry matter yield of 1,862.7 kg/ha with 95% confidence. The findings suggest that this modeling approach is a valuable tool for improving farm planning in semi-arid regions, helping reduce reliance on empirical methods by linking yield predictions to a quantified risk factor.

Keywords: mechanistic models; phygrow; risk analysis; semi-arid region; tropical grass.
Abbreviations: EE_ Estimation efficiency; MAE_Mean absolute error; PHYGROW_Phytomass Growth Model; RMSE_Mean square error.

Introduction

The rearing of small ruminants plays a crucial role in the economy and subsistence of the semi-arid region of Northeast Brazil, as these animals are well adapted to the harsh local conditions. Natural pastures are the primary source of forage for livestock in these semi-arid ecosystems (Mwangi et al., 2020). However, the inherent fragility of these ecosystems, due to the erratic and concentrated rainfall patterns, renders the region particularly vulnerable to prolonged droughts, which severely impact both agricultural and livestock activities.
The Caatinga, the characteristic biome of Northeast Brazil's semi-arid region, faces natural limitations in maintaining the carrying capacity needed to sustain the frequent stocking rates found in this area. To address these challenges, the cultivation of adapted exotic species, such as buffel grass (*Pennisetum ciliare*), has been implemented due to its drought tolerance and its suitability as livestock forage (Mota et al., 2018; Friedel, 2020). Additionally, the practice of thinning native vegetation, in combination with the introduction of exotic forage species, has been promoted as a strategy to improve forage availability in otherwise unproductive areas.
Thinning involves selectively removing trees and shrubs with low woody or forage potential in order to reduce tree density, enhance sunlight penetration, and facilitate the growth of herbaceous plants. Enrichment, on the other hand, entails introducing exotic forage species into thinned areas, ensuring that no more than 15% of the soil remains covered by woody vegetation (Pereira Filho et al., 2013).
To mitigate the uncertainties posed by the irregular distribution of rainfall and to enhance production efficiency, new strategies focused on forage management are needed. One such strategy is the use of mechanistic modeling, which can provide estimates of plant biomass production and serve as a valuable tool for forage management on farms (Wang et al., 2018; Shine et al., 2018; Mengistu et al., 2019; Bosi et al., 2020; Elbeltagi et al., 2020). Mechanistic models, such as the Phytomass Growth Model (PHYGROW), incorporate biological, chemical, and physical principles to simulate the

dynamics of plant production systems and have been successfully applied to monitor forage production in arid and semi-arid regions (Stuth, 2003b; Matere et al., 2020). Additionally, probabilistic methods, such as Monte Carlo simulations, can be used to assess the risk of forage productivity, given the stochastic nature of rainfall in the semi-arid environment.

In recent years, numerous studies have focused on crop growth modeling (Tolleson et al., 2010), pasture monitoring techniques (Rhodes et al., 2014), growing vegetables in desert conditions (Rhodes et al., 2022), natural pastures (Alhamad et al., 2023), and time series forecasting (Noa-Yarasca et al., 2024). However, there is a noticeable gap in research aimed at estimating forage growth in thinned and enriched vegetation systems.

This study, therefore, seeks to explore the feasibility of utilizing data from the existing scientific literature to model and assess the risk of buffel grass forage production in thinned Caatinga vegetation in the Brazilian semi-arid region.

Results and Discussion

The experimental area, though modest in size (1 hectare), exhibited heterogeneous characteristics due to interventions such as the thinning of the Caatinga (Figure 1). This intervention led to a random distribution of shrub and tree layers, which influenced light interception, precipitation patterns, and competition for water and nutrients, ultimately impacting the buffel grass layer. The vegetation diversity within the Caatinga region generates microenvironmental conditions with varying floristic heterogeneity, which can either promote or hinder plant growth. The broad range of vegetation types and subtypes in the region is likely a result of significant biophysical variability (Araujo et al., 2022).

For model calibration, data from 2008 and 2009 were used (Table 1) to adjust the PHYGROW model parameters. The calibration process was designed to align the model with observed data under conditions where irrigation and fertilization were not applied, and forage samples were collected in 1 m^2 frames from areas with maximum forage accumulation, kept free of livestock. Additional data from 2010 and 2014 (Table 1) were later included for model validation, without the need for further parameter adjustments, ensuring the model's robustness and accuracy.

A historical series of buffel grass biomass productivity (1950-2020) was generated using the PHYGROW software (Figure 2), with the maximum annual biomass value extracted for each year. A synthetic series was then created through a Monte Carlo simulation using the @RISK software (Palisade Corporation, 2020).

The model demonstrated strong accuracy in predicting buffel grass biomass in the thinned Caatinga, particularly in December 2008 and 2009 (Table 2). The high accuracy of the estimates was reflected in the statistical performance metrics of the model, including the evaluation results and estimation efficiency (Table 3).

The results of the adherence test, conducted using the Monte Carlo method, varied. However, the Weibull distribution, as determined by the chi-square test, provided the best fit for the observed forage production behavior of buffel grass in the ecological site (Figure 3). The Weibull distribution revealed a slight negative skewness (-0.1498) and platykurtic kurtosis (2.7861). In terms of natural guarantee analysis (Silva et al., 2013), the model estimated a productivity of approximately 1,862.7 kg DM/ha/year for buffel grass, assuming a 95% confidence level (Figure 4).

During calibration, the PHYGROW model parameters were adjusted to better align with observed data. In July 2008, adjustments were made to parameters such as plant height (from 50 to 45 cm), tussock base diameter (from 15 to 12 cm), and maximum suppression temperature (from 43 to 42 °C), due to the model's overestimation of buffel grass productivity. However, no further adjustments were made when adding the second (December 2008) and third (December 2009) data sets. For the fourth data set (June 2010), modifications were made to the optimal growth temperature (from 25 to 27 °C) and leaf area index (from 2.7 to 3 m^2/m^2) to improve the model's forage productivity predictions. The most recent data set (November 2014) did not result in further parameterization of the model.

Although the model was calibrated, it was not fully validated due to challenges in fine-tuning the parameters, making the term "calibrated" more appropriate than "validated." Despite this, the model can be considered satisfactory for predicting buffel grass productivity in this context (Ladson, 2008).

The data were sourced from a literature database, which introduces potential biases, either overestimating or underestimating buffel grass productivity in the study area. Additionally, drought conditions can significantly affect the results, potentially leading to overestimations of biomass productivity (Noa-Yarasca et al., 2024).

A calibration algorithm was employed to adjust unobserved parameters (θ) at each location, minimizing the difference between model outputs (y) and independent measurements (z) (McAvaney et al., 2001). This approach is common in process models, such as those used for rainfall-runoff and ecosystem dynamics, where certain parameters remain unobservable and require calibration (Sorooshian et al., 2008; Paniconi et al., 2015; Luo et al., 2020).

The PHYGROW model accurately estimated the loss of dry matter (DM) from buffel grass in thinned Caatinga during the dry seasons of 2008 and 2009 (-66.87 kg DM/ha in December 2008 and -31.06 kg DM/ha in December 2009), indicating that it effectively predicts dry matter loss, whether due to decomposition or plant physiological processes. Rigorous statistical analyses, including regression analysis, confirmed this downward trend, prompting further investigation into potential contributing factors such as climate change, land use, and soil conditions (Alhamad et al., 2024).

This information is valuable for managing forage resources in the Brazilian Northeast's semi-arid region, particularly in pasture deferment scenarios. In this region, dry matter loss from deferred pastures is a significant issue, and there is limited research on the subject. Thus, the findings from this study can provide guidance for forage resource management, whether in thinned Caatinga or not. These results are critical for advancing the understanding of arid lands and can inform future research in collaboration with experts to

Table 1. Biomass production of buffel grass (data extracted from the literature) in the experimental area of Lameirão Farm, Santa Terezinha, Paraíba, Brazil, from 2008 to 2014

Studies carried out in the experimental area	Buffel grass biomass production (kg DM/ha)*
July 2008 (Silva, 2009)	688.24
	2,669.17
	2,765.79
	4,939.96
December 2008 (Silva, 2009)	430.57
	637.75
	691.49
	2,057.44
December 2009 (Mota, 2011)	845.00
	855.90
	853.86
	999.99
June 2010 (Soares, 2012)	2,560.72
	2,784.78
	2,866.88
	2,943.59
November 2014 (Soares et al., 2016)	468.12
	492.54
	794.17
	1,421.83

1 = kg of dry matter/ha

Table 2. Means of prediction of buffel grass biomass (kg DM/ha) by the PHYGROW model for Lameirão Farm, Santa Terezinha, Paraíba, Brazil

Means	July 2008	December	December 2009	June 2010	November 2014
Measured	2,765.80	954.28	888.70	2,788.83	908.35
PHYGROW	3,207.50	887.41	857.64	2,342.24	1,115.22
Variation	441.70	-66.87	-31.06	-446.68	206.87

Fig. 1. Experimental site in Farm Lameirão, owned by the Center for Health and Rural Technology of the Federal University of Campina Grande – CSTR/UFCG, located in the municipality of Santa Terezinha, Paraíba, Brazil

strengthen conservation and resource management strategies in arid environments (Alhamad et al., 2024).

The model's efficiency was evaluated using the Nash-Sutcliffe efficiency coefficient (0.87) and the concordance index (d) (0.95), both of which indicated a high level of agreement between the model's predictions and the observed data. This suggests that the model provides a reliable estimate of buffel grass productivity in the study area.

The results of this study outperform those of Zilverberg et al. (2017), who reported an agreement index (d) of 0.69 for the APEX model calibration in Kansas prairie pastures, and Cheng et al. (2021), who found a d value of 0.69 when comparing total biomass across different pasture systems. Similarly, Manyowa et al. (2023), in their calibration and validation of the APEXgraze model for pastures in the USA, reported Nash-Sutcliffe efficiency (NSE) values greater than 0.50 and d values close to 1 (> 0.80). In comparison, the performance statistics of the

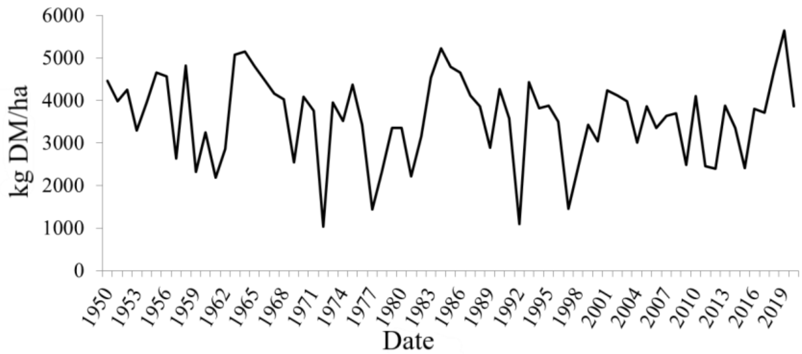

Fig. 2. History (1950 to 2020) of maximum annual biomass production of buffel grass, estimated by PHYGROW, for Fazenda Lameirão, Santa Terezinha, Paraíba, Brazil.

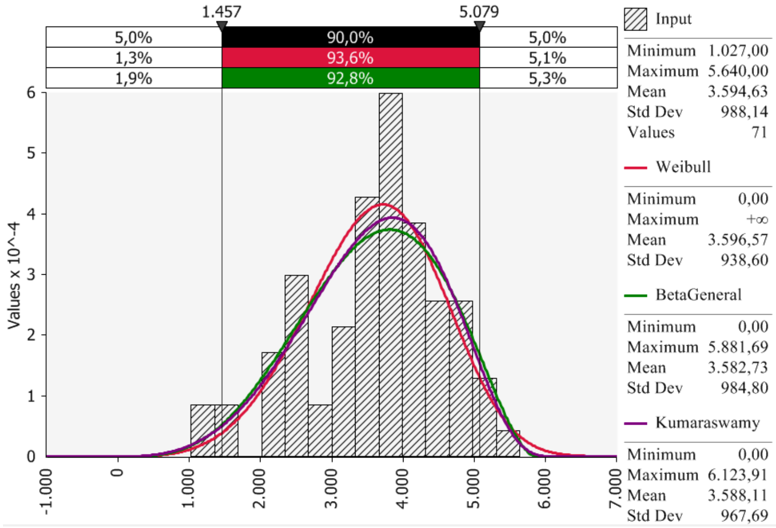

Fig. 3. Adherence test (Monte Carlo method) to estimate the behavior of buffel grass biomass production at Fazenda Lameira, Santa Terezinha, Paraíba, Brazil, classified by the chi-square test.

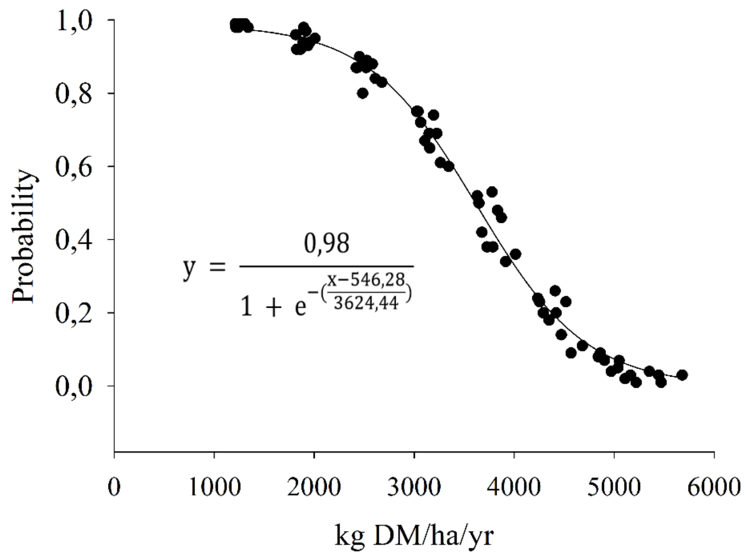

Fig. 4. Estimate of the natural guarantee of buffel grass forage production for Fazenda Lameirão, Santa Terezinha, Paraíba, Brazil.

PHYGROW model in this study indicate strong performance, consistent with findings from Rhodes et al. (2022), who used the same software to model herbaceous biomass for grazing and fire risk management. The Monte Carlo method was applied to assess the fit of the Weibull distribution to the historical buffel grass productivity data from the PHYGROW model. The Weibull function demonstrated the best fit, with a slight left-skewness in the asymmetry parameter (-0.1498).

By generating synthetic data, the study was able to assess the concept of natural guarantee, which seeks to minimize the risk of feed shortages for livestock by estimating the minimum potential forage production for the study site. The methodology used involved simulating 10,000 data points to calculate the range of annual biomass values and assess the probability of occurrence.

The maximum guarantee (100%) corresponds to the lowest recorded biomass values, representing the highest probability of occurrence.

The larger dataset used in this study, consisting of 10,000 data points, is considered superior to the smaller datasets (1,000–1,800 values) used in previous studies (Makridakis et al., 2018; Cerqueira et al., 2019). Moreover, Vabalas et al. (2019) identified limitations in model performance with small sample sizes for machine learning validation.

The estimated biomass production for Lameirão Farm in Paraíba, Brazil, was 1,862.7 kg DM/ha/year of buffel grass, with a 95% guarantee. Under a 20-year projection, this would imply that only one year would yield less than the simulated biomass.

Many producers adjust animal stocking rates to optimize forage utilization, a dynamic strategy that involves complex decision-making and risk management (Krueger et al., 2021). This approach offers farmers new insights into planning for herd nutrition, taking into account the variability of forage production over time.

While the natural guarantee of biomass potential in a specific area is largely empirical, it is crucial to consider factors like usable biomass, whether for human use (e.g., haymaking) or livestock grazing. For buffel grass, it is recommended that up to 60% of biomass be used for forage, leaving the remainder to protect the soil from wind and laminar erosion (Araújo Filho, 2013). Therefore, the effective biomass available to livestock is estimated at 745.08 kg DM/ha/year, which helps determine the pasture's carrying capacity.

Incorporating risk management tools that allow farmers to store and analyze information can aid in making timely decisions that minimize the impact of drought on productivity and the long-term sustainability of pastures (Shrum et al., 2018). If the guarantee level falls below 95%, additional strategies such as leasing pasture areas or purchasing supplementary feed may be required to meet livestock needs during times of forage scarcity. Without these strategies, the use of this tool becomes less meaningful, as empirical decision-making will continue to dominate, hindering effective short-term planning.

Materials and methods

Characterization of the study area

The study was conducted at Fazenda Lameirão, part of the Center for Rural Health and Technology at the Federal University of Campina Grande (CSTR/UFCG), located in the municipality of Santa Terezinha, Paraíba, Brazil (coordinates: 7°02'49.64" S, 37°29'34.33" W, at an elevation of 208 meters above sea level). The region experiences a hot semi-arid climate - BSh (Köppen, 1936), characterized by low relative humidity, irregular rainfall (average annual precipitation: 839.1 mm), and an average annual temperature of 28°C (Climatempo, 2021).

The soils in the study area are classified as Chromic Luvosols (*Alfisols*) and Regolitic Neosols (*Psamments*), often found in association with varied topographic conditions (Pronasolos, 2020).

The experimental site is covered by caatinga vegetation, which is currently in the early stages of secondary succession. The flora consists of woody plants distributed across three distinct strata: arboreal, shrubby, and herbaceous. The dominant species in the arboreal stratum include *Mimosa tenuiflora* (Willd.) Poir. (jurema-preta), along with other woody species such as *Croton sonderianus* (marmeleiro), *Caesalpinia pyramidalis* (catingueira), *Combretum leprosum* (mofumbo), and *Ziziphus joazeiro* Mart. (joazeiro). In the herbaceous layer, grasses such as *Brachiaria plantaginea*, *Panicum* sp., *Aristida setifolia* H. B. K. (panasco), *Digitaria* sp. (roça grass), and *Setaria* sp. (fox tail grass) are prevalent. The herbaceous dicotyledonous plants include species such as *Hyptis suaveolens* Poit. (field mint), Senna obtusifolia, *Stylozanthes* sp., Sida cordifolia (white mallow), and *Macroptilium lathyroides* L. (Santos et al., 2020; Gama et al., 2022).

Manipulation of the Caatinga

Since 2006, the vegetation in the experimental area has been selectively thinned and managed under a silvopastoral system, with 15 to 20% of the soil surface covered by woody species, as outlined by Araújo Filho (2013). Endangered species were protected, and the area was enriched with *Pennisetum ciliare* (buffel grass) (Alencar, 2019). Initially, the area had 60% soil coverage by woody plants (trees and shrubs), but selective cutting reduced this coverage to approximately 20%. The removal targeted trees and shrubs with limited timber value and low nutritional value for ruminants. Following this, the area was seeded with buffel grass, using a broadcasting method to ensure even distribution. A total of 5 kg/ha of seed, mixed with 5 kg of manure, was applied to prevent wind-induced seed displacement.

Conduction of study

This study utilized data extracted from previously conducted field surveys in the experimental area, as reported in the scientific literature. The objective was to assess the forage value of caatinga vegetation enriched with buffel grass for meeting the livestock production needs in these semi-arid environments. In particular, the study aimed to explore the potential. of using literature-derived data to model and evaluate forage production risks in natural caatinga pastures.

Discussions were held with researchers from the institution to gain insights into the data collection methodologies used in the earlier experimental studies. After an initial review, five relevant academic studies conducted between 2008 and 2014 in the same experimental area were selected. These studies provided biomass production data for buffel grass (kg dry matter/ha) (Table 1), which were used for model configuration.

The selected studies met the criteria for proper calibration in the PHYGROW model, including: biomass measurements taken without irrigation or fertilization; samples collected within a 1 m^2 quadrat under maximum forage accumulation conditions; the absence of livestock; and the inclusion of relevant ecological data, such as canopy height, species composition, and vegetation cover.

Experimental design

The selected studies employed transects across experimental plots to collect random plant biomass samples using a 1x1 m^2 metal frame. As secondary data from the literature, these measurements were collected at various time points.

Model configuration

The PHYGROW model was used to simulate the growth of buffel grass based on soil properties, plant species, pasture management practices, and stocking rates, with climate data serving as the primary input (Stuth et al., 2003a). The model operates on the principle of light use efficiency and simulates plant growth under optimal conditions (Montieth, 1972; Montieth, 1977).

Originally developed in 1990, PHYGROW has undergone continuous refinement. Its algorithms integrate formulas adapted from other plant growth models, including CREAMS, GLEAMS, EPIC, WEPP, SPUR, CENTURY, and ERHYM-II, in conjunction with research on grass tillering and forage selection conducted at Texas A&M University. The model configuration involved three primary steps: parameterization, calibration, and validation. Ecological site data, including geographic coordinates, soil and plant characteristics, and topographical features, were entered into the model, as outlined by Maranhão (2021). Subsequently, the model was calibrated by adjusting unmeasured parameters and comparing simulated results with observed data from the literature. Validation was performed by introducing new data sets, while keeping model parameters unchanged, and assessing the model's predictive accuracy (PHYGROW = +/- 1 standard error of the mean).

Statistical analysis

To assess the model's predictive accuracy, several statistical measures were used, including bias estimation (%) (Angerer, 2010), mean absolute error (MAE) (Legates et al., 1999), and root mean square error (RMSE) (Willmott, 1982). Simulation errors were also evaluated using the Nash-Sutcliffe efficiency (EE) and the Willmott concordance index (d) (Legates et al., 1999; Knoben et al., 2019; Woli et al., 2020).

An adherence test was performed using the Monte Carlo method to determine the probability density function of buffel grass forage production in the experimental area. This function was used to generate a comprehensive dataset (10,000 values) in @RISK, which was subsequently analyzed to estimate the minimum and maximum forage yields under the local edaphoclimatic conditions, as proposed by Silva et al. (2013).

Conclusion

The PHYGROW model effectively estimated buffel grass biomass under rainfed conditions in thinned caatinga vegetation in the semi-arid region. The application of the Monte Carlo method proved to be a valuable tool in enhancing the accuracy of the model, thereby supporting more informed decision-making in animal feeding management.

Furthermore, incorporating a guarantee level linked to biomass forecasts provides a crucial framework for technicians and producers to make more informed decisions when planning animal feed. While the risks associated with livestock production in semi-arid regions are well recognized, farmers' net incomes often remain at minimal levels. Therefore, minimizing this trade-off is essential. Establishing a guarantee level for the availability of forage resources over the long term can offer a viable solution, ensuring more sustainable feeding practices for livestock.

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Authors' Contribution

Feitosa, J.F.F., Figueiredo, J.R., and Pereira-Filho, J.M. conducted visits to the experimental area to collect data and compare it with the data obtained by Formiga, L.D.A.S. Maranhão, S.R., and Cândido, M.J. provided support during the parameterization, calibration, and validation stages of the PHYGROW model, while Bakke, O.A. contributed to the statistical analysis of the material. Feitosa, J.F.F. and Maranhão, S.R. developed the manuscript, and all authors, without distinction, reviewed the material before submission.

Conflicts of interest

The authors declare there are no conflicts of interest.

Ethical Standards

Not applicable.

References

Alencar EJS (2019) Aspectos fitossociológicos e produção de fitomassa pastável da jurema-preta (*Mimosa tenuiflora [Wildd.]* Poir) em área de caatinga sucessorial. Masters dissertation, Federal University of Campina Grande, Paraíba, Brazil.

Alhamad MN, Abdullah S (2023) Modeling of rangeland ecossystems in northern Jordan. Proceedings of 23rd International Multidisciplinary Scientific GeoConference SGENM 2023.

Angerer JP (2008) Examination of high resolution rainfall products and satellite greenness indices for estimating patch and landscape forage biomass. PhD thesis, Texas A&M University, Texas, USA.

Araújo filho JA (2013) Manejo Pastoril Sustentável da Caatinga. Recife, PE: Projeto Dom Helder Câmara.

Araújo HFP, Garda AA, Silva WAG, Nascimento NFF, Mariano EF, Silva JMC (2022) The Caatinga region is a system and not an aggregate. Journal of Arid Environments, 203: 104778. https://doi.org/10.1016/j.jaridenv.2022.104778.

Bosi C, Sentelhas PC, Huth NI, Pezzopane JRM, Andreucci MP and Santos PM (2020) APSIM-Tropical Pasture: A model for simulating perennial tropical grass growth and its parameterisation for palisade grass (*Brachiaria brizantha*). Agricultural Systems, 184: 102917. https://doi.org/10.1016/j.agsy.2020.102917.

Cerqueira V, Torgo L, Soares C (2019) Machine Learning vs Statistical Methods for Time Series Forecasting: Size

Matters. arXiv: 1909.13316. https://doi.org/10.48550/arXiv.1909.13316.
Cheng G, Harmel RD, Ma L, Derner JD, Augustine DJ, Bartling PNS, Fang QX, Williams JR, Zilverberg CJ, Boone RB, et al. (2021) Evaluation of APEX modifications to simulate forage production for grazing management decision-support in the western US great plains. Agricultural Systems, 191: 103139. https://doi.org/10.1016/j.agsy.2021.103139.
Climatempo (2021) Climatologia Santa Terezinha – PB. Available online from: https://www.climatempo.com.br/climatologia/6615/santaTerezinha-pb-pb (Accessed 20 March 2021).
Elbeltagi A, Deng J, Wang K, Malik A and Maroufpoor S (2020) Modeling long-term dynamics of crop evapotranspiration using deep learning in a semi-arid environment Agricultural Water Management, 241: 106334. https://doi.org/10.1016/j.agwat.2020.106334.
Friedel MH (2020) Unwelcome guests: a selective history of weed introductions to arid and semiarid Australia. Australian Journal of Botany 68: 75-99. https://doi.org/10.1071/BT20030.
Gama JFP, Pereira Filho JM, Nascimento GV, Cezar MF, Gonzaga Neto S, Pessoa, RMS, Ferreira JM, Cordão MA (2022) Carcass traits of goats finished with different levels of concentrate supplementation and kept on caatinga enriched with Urochloa trichopus. Brazilian Animal Science, 23: e-71730P. https://doi.org/10.1590/1809-6891v23e-71730P.
Knoben WJ, Freer JE and Woods RA (2019) Inherent benchmark or not? Comparing Nash–Sutcliffe and Kling–Gupta efficiency scores. Hydrology and Earth System Sciences, 23: 4323-4331. https://doi.org/10.5194/hess-23-4323-2019.
Köppen W (1936) Das geographische System der Klimate. In Köppen W and Geiger R (eds). Handbuch der Klimatologie, pp. 1-44. Berlin: Gebrüder Bornträger.
Krueger ES, Ochsner TE, Levi MR, Basara JB, Snitker GJ, Wyatt BM (2021) Grassland productivity estimates informed by soil moisture measurements: statistical and mechanistic approaches. Agronomy Journal, 113(4): 3498-3517. https://doi.org/10.1002/agj2.20709.
Ladson AR (2008) Hydrology: an Australian IntroductionOxford University Press, Oxford, England.
Legates DR, McCabe Jr and Gregory J (1999) Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. Water resources research, 35: 233-241. https://doi.org/10.1029/1998WR900018.
Lu Y, Tian Z, Zhou R, Liu W (2020) Multi-step-ahead prediction of thermal load in regional energy system using deep learning method. Energy and Buildings, 233: 110658. https://doi.org/10.1016/j.enbuild.2020.110658.
Luo Y, Schuur EAG (2020) Model parameterization to represent processes at unresolved scales and changing properties of evolving systems. Global Change Biology, 26: 1109–1117. https://doi.org/10.1111/gcb.14939.
Makridakis S, Spiliotis E, Assimakopoulos V (2018) Statistical and Machine Learning forecasting methods: Concerns and ways forward. PLoS ONE 13(3): e0194889. https://doi.org/10.1371/journal.pone.0194889.
Manyowa NM, Osorio-Leyton J, Steglich EM, Kiniry JR, Propato M, Winchell M, Rathjens H, Angerer JP, Norfleet LM (2023) Plant parameterization and APEXgraze model calibration and validation for US land resource region H grazing lands. Agricultural Systems 207: 103631. https://doi.org/10.1016/j.agsy.2023.103631.
Maranhão SR (2021) Modelagem de sistemas aplicada à produção de forragem e ao uso da água, nas condições atuais e sob mudanças climáticas, no semiárido brasileiro. PhD thesis, Universidade Federal do Ceará, Ceará, Brazil.
Matere J, Simpkim P, Angerer J, Olesambu E, Ramasamy S, Fasina F (2020). Predictive Livestock Early Warning System (PLEWS): Monitoring forage condition and implications for animal production in Kenya. Weather and Climate Extremes, 27: 100209. https://doi.org/10.1016/j.wace.2019.100209.
McAvaney BJ et al. (2001) Climate Change 2001: The Scientific Basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Chapter 8 (eds. Houghton, J. T. et al.) 881 (Cambridge University Press, 2001).
Mengistu AG, van Rensburg LD and Woyessa YE (2019) Techniques for calibration and validation of SWAT model in data scarce arid and semi-arid catchments in South Africa. Journal of Hydrology, 25: 100621. https://doi.org/10.1016/j.ejrh.2019.100621.
Montieth JL (1972) Solar radiation and productivity in tropical ecosystems. Journal Applied Ecology, 9: 747-766. https://doi.org/10.2307/2401901.
Montieth JL (1977) Climate and efficiency of crop production in Britian. Biological Sciences, 281: 277-294. https://doi.org/10.1098/rstb.1977.0140.
Mota NSO (2011) Desempenho e características de carcaça de caprinos e ovinos terminados em caatinga enriquecida com (*Pennisetum ciliare* L. cv. Biloela). Master dissertation, Universidade Federal de Campina Grande, Paraíba, Brazil.
Mota NSO, Pereira Filho JM, Formiga, LDAS, Cézar MF, Bakke OA, Bourburema JB, Oliveira RL (2018) Comparison between lambs and goat kids meat production of animals fed Caatinga vegetation enriched with buffel (*Cenchrus ciliaris* L.) grass. Semina: Ciências Agrárias, 39: 2795-2806. https://doi.org/10.5433/1679-0359.2018v39n6p2795.
Mwangi V, Owuor S, Kiteme B and Giger M (2020) Beef production in the rangelands: A comparative assessment between pastoralism and large-scale ranching in Laikipia county, Kenya. Agriculture, 10: 399. https://doi.org/10.3390/agriculture10090399.
Noa-Yarasca E, Leyton JMO, Angerer JP (2024) Deep learning Model effectiveness inf forecasting limited-size aboveground vegetation biomass time series: Kenyan grasslands case study. Agronomy, 14(2): 349. https://doi.org/10.3390/agronomy14020349.
Palisade Corporation (2020) The Decision Tools Suite 8.0.0. New York.
Paniconi C, Putti M (2015) Physically based modeling in catchment hydrology at 50: Survey and outlook. Water

Resources Research, 51: 7090–7129. https://doi.org/10.1002/2015WR017780.
Pronasolos (2020) Mapa de solos. Available online from: https://geoportal.cprm.gov.br/pronasolos/ (Accessed 10 April 2021).
Rhodes EC, Tolleson DR, Angerer JP (2022) Modeling Herbaceous Biomass for Grazing and Fire Risk Management. Land, 11: 1769. https://doi.org/10.3390/land11101769.
Rhodes EC, Tolleson DR, Angerer JP, Kava JÁ, Dyess J, Nicolet T (2014) A comparison of Rangeland Monitoring Techniques for Modeling Herbaceous Fuels and Forage in Central Arizona, EUA. Fire Ecology, 10: 76-91. https://doi.org/10.4996/fireecology.1002076.
Santos WS, Bakke OA, Santos WS, Silva AA, Justino STP (2020) Firewood and forage production from *Poincianella pyramidalis* (Tul.) L. P. Queiroz subjected to anual pruning. Ciência Florestal, 30: 89-103. https://doi.org/10.5902/1980509832500.
Shine P, Scully T, Upton J and Murphy MD (2018) Multiple linear regression modelling of on-farm direct water and electricity consumption on pasture based dairy farms. Computers and Electronics in Agriculture, 148: 337-346. https://doi.org/10.1016/j.compag.2018.02.020.
Shrum TR, Travis WR, Williams TM, Lih E (2018) Managing climate risks on the ranch with limited drought information. Climate Risk Management, 20: 11-26. https://doi.org/10.1016/j.crm.2018.01.002.
Silva LDA (2009) Ovinos e caprinos terminados em caatinga raleada enriquecida com capim buffel (*Pennisetum ciliare* L.). Master dissertation, Universidade Federal de Campina Grande, Paraíba, Brazil.
Silva RG, Lopes MN, Araújo JC, Neiva JNM, Cândido, MJD (2013) Orçamentação Forrageira de Longo Prazo no Semiárido. Revista Científica de Produção Animal, 15(2): 98-110. http://dx.doi.org/10.15528/2176-4158/rcpa.v15n2p98-110.
Silva RG, Lopes MN, Araújo JC, Neiva, JNM and Cândido MJD (2013) Orçamentação forrageira de longo prazo no semiárido. Revista Científica de Produção Animal, 1: 98-110. https://doi.org/10.15528/2176-4158/rcpa.v15n2p98-110.
Soares RF (2012) Ovinos e caprinos terminados em caatinga enriquecida: 1. Efeito do pastejo na vegetação herbácea; 2. Efeito da suplementação no desempenho animal. Master dissertation, Universidade Federal de Campina Grande, Paraíba, Brazil.
Soares RF, Pereira Filho JM, Gama KVMF, Silva AMA, Cezar MF, Ramos JM, Borburema JB and Bakke OA (2016) Performance of sheep and goats finished in enriched Caatinga and given supplementation. Livestock Research for Rural Development, 28: 10-179. http://www.lrrd.org/lrrd28/10/barb28179.html.
Sorooshian S, Hsu K, Coppola E, Tomassetti B, Verdecchia M, Visconti G (2008) Hydrological Modelling and the Water Cycle: Coupling the Atmospheric and Hydrological Models. Springer eBooks. https://dx.doi.org/10.1007/978-3-540-77843-1.
Stuth J, Schmitt D, Rowan RC, Angerer J and Zander K (2003a) PHYGROW users guide and technical documentation. Texas, USA: Texas A&M University.
Stuth JW, Angerer J, Kaitho R, Zander K, Jama A, Hearth C, Bucher J, Hamilton W, Conner R, Inbody D (2003b). The livestock early warning system (LEWS): blending technology and the human dimension to support grazing decision. Arid Lands Newsletter, 53.
Tolleson D, Kava JA, Brown T, Rhodes EC (2010). Validation of the Phytomass Growth (Phygrow) model to predict fire fuel or forage standing crop on Arizona rangelands. Conference: Society for Range Management 64rd Annual Meeting, Denver, CO.
Vabalas A, Gowen E, Poliakoff E, Casson, AJ (2019) Machine learning algorithm validation with a limited sample size. PLoS ONE, 14: e0224365. https://doi.org/10.1371/journal.pone.0224365.
Wang B, Waters C, Orgill S, Cowie A, Clark A, Li Liu D, Sides T (2018) Estimating soil organic carbon stocks using different modelling techniques in the semi-arid rangelands of eastern Australia. Ecological indicators, 88: 425-438. https://doi.org/10.1016/j.ecolind.2018.01.049.
Willmott CJ (1982) Some Comments on the Evaluation of Model Performance. Bulletin of the American Meteorological Society, 63: 1309-1313. http://www.jstor.org/stable/26222954.
Woli P, Rouquette Jr FM, Long CR, Tedeschi LO (2021) Estimating the daily nutritive value of bermudagrass for grazing livestock. Applied Animal Science, 37: 1-10. https://doi.org/10.15232/aas.2020-02087.
Zilverberg CJ, Williams J, Jones C, Harmoney K, Angerer J, Metz .J, Fox W (2017) Process-based simulation of prairie growth. Ecological Modelling 351: 24–35. https://doi.org/10.1016/j.ecolmodel.2017.02.004.