









## ARTICLE

## Biometry, Modeling, and Statistics

# Improving the CROPGRO Perennial Forage Model for simulating growth and biomass partitioning of guineagrass

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## Abstract

Tropical forage grasses are used for several applications including grazing, silage, and biofuels; with harvesting at varying phenological stages. Mechanistic simulation models can be powerful tools to assist with planning and decision making of pasture utilization strategies. The objective of this study was to improve and evaluate the ability of the Cropping System Model-CROPGRO-Perennial Forage model (CSM-CROPGRO-PFM) to simulate growth and biomass partitioning of two guineagrass [*Panicum maximum* Jacq. syn. *Megathyrsus maximus* (Jacq.) BK Simon & SWL Jacobs] cultivars, Tanzânia and Mombaça. Data from two experiments with contrasting harvest management and field conditions were used. Model parameters were modified, targeting improvement in *d*-statistic and root mean square error (RMSE) for aboveground, leaf, stem biomass, leaf area index (LAI), and leaf proportion of aboveground biomass. Major improvement in model performance was achieved by modifying the vegetative partitioning parameters between leaf and stem through increasing partitioning to leaf during early regrowth while increasing it to stem during late regrowth. Modifications were made to parameters affecting leaf and stem senescence, leaf photosynthesis, and leaf area expansion sensitivity to cool weather. The RMSE values decreased from 2,261 to 1,768 kg ha<sup>-1</sup> for aboveground biomass, from 1,620 to 874 kg ha<sup>-1</sup> for stem biomass, from 11.41 to 7.27% for leaf percentage, from 1.91 to 1.68 for LAI, but increased slightly for leaf biomass. The *d*-statistic computed over all these variables increased from .86 to .93. The improved model performance for both short and long harvest cycles will facilitate further applications for diverse forage crops utilization strategies.

**Abbreviations:** LAI, leaf area index; PFM, Perennial Forage Model; RMSE, root mean square error; SLA, specific leaf area; SOC, soil organic carbon.

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# 1 | INTRODUCTION

Guineagrass [*Panicum maximum* (Jacq.) syn. *Megathyrsus maximus* (Jacq.) BK Simon & SWL Jacobs] is a forage grass native to Africa and is widely naturalized in the tropics. In Brazil, the species is the second most cultivated forage grass and is recommended for regions where annual rainfall ranges from 800 to 1,800 mm and the soils are well drained with medium-to-high soil fertility (Muir & Jank, 2004). ‘Tanzânia’ and ‘Mombaça’ guineagrass are the most planted cultivars in Brazil (Fernandes et al., 2014), and both are tall, bunch-type tropical grasses.

As for many forage species, guineagrass can be used for several purposes such as grazing, silage, hay, and bioenergy source. The harvesting process of forage species is very flexible when compared to annual crops, and varies according to the purpose of utilization, the manager’s goal, and the technology that is available. In pasture-based livestock systems, the forage biomass is harvested by the animal (i.e., grazing), where green leaf is preferred to stem as it enhances the animal grazing efficiency and forage nutritive value (Gontijo Neto et al., 2006). However, because of the difficulty of adjusting the stocking rate throughout the year, harvesting and grazing may occur at different frequencies (i.e., period of regrowth) and intensities (i.e., portion of the total biomass harvested) with consequences for the animals and the stubble left after harvest, which is important for pasture regrowth and perennation. This is especially important for tall bunch-type forage species that tend to accumulate a considerable amount of stem late in regrowth cycles (Carnevali et al., 2006). For silage and bioenergy use, on the other hand, longer regrowth periods may be beneficial even with the high amount of stem that is accumulated (Jank et al., 2013; Santos et al., 2014).

Mechanistic crop simulation models can aid in the understanding of the interaction between plant genetics, environment, and pasture management (Araujo et al., 2013; Pedreira et al., 2011) and can be powerful tools to assist decision-making and planning of forage crop utilization strategies. The original CROPGRO model was developed in the early 1990s with the aim of having a model which could be easily adapted to simulate different species (Boote et al., 1998; 2021). Initially, the model worked for simulating annual legume crops, but was later adapted and parameterized for forage grasses including bahiagrass (*Paspalum notatum* Fluegge) (Kelly, 1995). However, this early version of the CROPGRO model for forage grasses worked only with an “annual” approach, which consistently over-predicted dry matter growth during cooler months, in part because it required a minimum residual leaf area index (LAI) to prevent failure and because code limitations did not allow for winter dormancy or regrowth after 100% foliage harvest or freeze-kill (Rymph, 2004). The model was improved for the simulation of perennial grasses by adding a new storage organ, which aided pas-

## Core Ideas

- The CROPGRO-PFM model was calibrated for the guineagrass cultivars Tanzânia and Mombaça growth.
- Improvements were made to biomass partitioning over phenological stages.
- Growth under both warm and cool conditions was improved.
- The improved model is able to simulate short and long regrowth cycles.
- The improved model can simulate a wide range of forage crops harvesting strategies.

ture regrowth, leading to the development of the CROPGRO-Perennial Forage Model (PFM) (Rymph, 2004). The PFM (Rymph, 2004) has subsequently been used successfully for simulating warm-season grass yield and has been calibrated for major tropical forage grasses including ‘Xaraés’ palisadegrass [*Brachiaria brizantha* (A. Rich.) Stapf syn. *Urochloa brizantha* (Hochst. ex A. Rich.) R.Webster] (Pedreira et al., 2011), ‘Tanzânia’ guineagrass (Lara et al., 2012), ‘Mulato II’ palisadegrass (*Brachiaria* hybrid ‘Mulato II’), ‘Tifton 85’ bermudagrass [*Cynodon dactylon* (L.) pers.] (Pequeno et al., 2018), and ‘Piatã’ palisadegrass (Bosi et al., 2020).

Despite the unquestionable relevance of these prior perennial forage modeling studies, the data used were mostly from “short” regrowth cycles (about 28–35 d during warmer months and a maximum of 63 d during cool months). The data collected in these studies, therefore, did not allow for complete parameterization of biomass accumulation and partitioning during longer regrowth cycles, where the plants progressed to more advanced phenological stages. Furthermore, in most cases (including Lara et al. (2012)), the calibration was done using data with forage biomass sampled only at the time of harvest and, thus, appropriate parameterization of biomass accumulation and partitioning during early regrowth phases prior to the harvest was not performed with sufficient confidence. Parameterization of forage biomass accumulation and partitioning in early, mid- and late phases during regrowth cycles influences the amount of biomass and plant-part composition at diverse phenological stages, and, thus is an important aspect for model improvement for extending model use for different regrowth periods and management scenarios.

The prior CROPGRO-PFM version calibrated for ‘Tanzânia’ guineagrass by Lara et al. (2012) was never released in an official version of the Decision Support System for Agrotechnology Transfer (DSSAT; Hoogenboom, Porter, Boote, et al., 2019) and, since then, several improvements have been made in the CROPGRO-PFM, including N effects on leaf area expansion and new entry options for initializing the soil

carbon pools. The objective of this research was to improve the ability of the CROPGRO-PFM to simulate the growth and biomass partitioning of guineagrass cultivars Tanzânia and Mombaça during early, mid- to late phenological phases using a single common species file for both cultivars.

## 2 | MATERIALS AND METHODS

### 2.1 | Field experiments

Two field experiments (a separate site experiment for each cultivar) were used for model improvement activities. The ‘Tanzânia’ guineagrass dataset originated from an experiment conducted by Moreno et al. (2014) at the University of São Paulo “Luiz de Queiroz” College of Agriculture (USP-ESALQ), in Piracicaba, state of São Paulo, Brazil (22°42’S, 47°30’W, 546 m asl). This is the same experiment from which Lara et al. (2012) developed the prior CROPGRO-PFM parameters for Tanzânia. The plots measured 10 by 4 m, with four replications, and were established on a highly fertile Kandiuclalfic Eutrudox. The harvesting occurred periodically from December 2002 to April 2004 and was performed by mechanical clipping at 35-cm height. From December 2002 through March 2003 and from November 2003 through April 2004, plots were harvested at 35-d intervals, while during the cooler months (from April to October 2003) they were harvested at 63-d intervals.

Plots were fertilized immediately after each harvest, and a total of 250 kg N ha<sup>-1</sup> yr<sup>-1</sup> and 210 kg K<sub>2</sub>O ha<sup>-1</sup> yr<sup>-1</sup> were applied as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> and KCL, respectively. To avoid drought stress, sprinkler irrigation was supplied to keep the soil water potential above -30 kPa. Whenever the soil moisture dropped below the targeted value, irrigation was supplied, totaling 1,388 mm yr<sup>-1</sup>. Weather data, including daily solar radiation, maximum and minimum temperature and rainfall, were recorded at a station located at a distance of 2 km from the experimental site.

To quantify forage accumulation, forage mass above the 35-cm stubble height was sampled within three 0.5 by 2-m quadrats prior to each harvest. Additionally, the aboveground mass below the stubble height was determined three times during the year (first spring–summer cycle, autumn–winter cycle and second spring–summer cycle) to characterize the stubble. On these three occasions, the forage mass collected both above and below stubble height was hand-separated into live leaf and stem, and dead material fractions. However, for modeling purposes, only the living leaf and stem were considered as stubble. The LAI was determined weekly using a model LAI 2000 plant canopy analyzer (Li-Cor) (Welles & Norman, 1991). For more details about the field sampling the reader is referred to Lara et al. (2012) and Moreno et al. (2014).

Data on Mombaça guineagrass were collected in a field experiment that was conducted from December 2017 to January 2019 at Embrapa Southeast Livestock, in São Carlos, state of São Paulo, Brazil (21°57’42”S, 47°50’28”W, 860 m asl). The experiment consisted of an irrigated plot measuring 12.5 by 23 m, where we used two replications for weekly sampling of forage growth attributes during three long regrowth cycles. The cycles occurred from December 2017 to February 2018, February 2018 to June 2018, and November 2018 to January 2019, totaling 10, 14, and 12 wk for the first, second, and third regrowth cycles, respectively. Within each regrowth cycle, cumulative biomass samples were collected weekly to characterize forage biomass and leaf–stem composition at each sampling time. At the end of each regrowth cycle the entire plot was clipped to 30-cm height. Between the second and third regrowth cycles, clipping to 30-cm height was also done every 30–60 d (without any measurements), depending on the pasture growth rate.

Mombaça guineagrass was sown on 28 Sept. 2017 with the aid of a seeder using 8 kg of viable seeds per hectare, spaced 0.25 m between lines on a Typic Hapludox. The plot was clipped twice for pasture establishment and, thereafter, the experimental regrowth cycles started on 18 Dec. 2017. During the experiment a total of 370 kg N ha<sup>-1</sup> was applied, split over time as three applications of 80 kg N ha<sup>-1</sup> as ammonium nitrate, one application of 80 kg N ha<sup>-1</sup> as urea, and one application of 50 kg N ha<sup>-1</sup> as calcium nitrate. In addition, plots were fertilized with 87.3 kg ha<sup>-1</sup> of phosphorus (P) split into five applications of 17.5 kg P ha<sup>-1</sup> applied as single superphosphate and 132.8 kg ha<sup>-1</sup> of potassium (K) split into four applications of 33.2 kg K ha<sup>-1</sup> applied as KCl. Sprinkler irrigation was applied, if needed, at a rate ranging from 4 to 8 mm per day based on the readily available water concept, assuming that readily available water amounts to 30% of the total of 60 mm soil water holding capacity (SWHC) (Pezzopane et al., 2018). Whenever the soil water content came close to depleting the readily available water (70% of the SWHC left), irrigation was supplied, totaling 703 mm yr<sup>-1</sup>. We computed a simple soil water balance using estimated values of evapotranspiration and measured values of rainfall and irrigation. The evapotranspiration was estimated by using the FAO56 Penman–Monteith (Allen et al., 1998) equation, while the rainfall was measured at a weather station located 1 km from the experimental site (Table 1). Other weather data used in this study including daily solar radiation, maximum and minimum temperature, were recorded at the same weather station (Table 1).

To quantify and characterize forage attributes during regrowth, forage mass was sampled weekly by clipping the biomass above and below the 30-cm stubble within 0.5- by 1.0-m quadrats. The forage mass in the sample was subsampled and then hand separated into living leaf, living stem, and dead material fractions. Whenever a leaf had 50% or more of

TABLE 1 Weather data at the Mombaça experimental site in São Carlos, SP, Brazil

Month/year	Minimum temperature	Maximum temperature	Avg temperature <sup>a</sup>	Avg radiation <sup>b</sup>	Accumulated rain fall	Avg day length <sup>b</sup>
	C°			MJ m <sup>-2</sup>	mm	h
July 2017	7.1	26.5	16.8	16.6	0.0	10.82
Aug. 2017	9.4	32.7	21.0	16.1	20.2	11.29
Sept. 2017	13.6	33.1	23.3	22.0	39.0	11.91
Oct. 2017	13.6	35.6	24.6	19.0	129.2	12.56
Nov. 2017	13.7	31.5	22.6	21.6	158.8	13.08
Dec. 2017	16.9	32.2	24.5	20.5	272.0	13.32
Jan. 2018	16.6	32.2	24.4	19.0	242.8	13.17
Feb. 2018	16.3	32.8	24.5	19.5	106.0	12.71
Mar. 2018	16.9	32.7	24.8	20.7	203.9	12.11
Apr. 2018	13.9	31.7	22.8	18.6	21.0	11.46
May 2018	7.5	30.6	19.1	16.2	25.6	10.93
June 2018	12.1	29.0	20.5	13.1	0.8	10.68
July 2018	6.6	29.8	18.2	16.1	0.0	10.82
Aug. 2018	6.7	30.6	18.6	16.6	84.0	11.29
Sept. 2018	9.4	34.6	22.0	17.6	56.0	11.91
Oct. 2018	12.0	32.8	22.4	19.7	295.0	12.56
Nov. 2018	15.1	32.0	23.5	19.2	235.4	13.08
Dec. 2018	13.6	33.5	23.6	23.7	186.6	13.32
Jan. 2019	17.1	34.6	25.8	23.7	129.8	13.17

<sup>a</sup> Average of maximum and minimum temperatures of the month.

<sup>b</sup> Average of daily rate over days of the month.

its tissue senesced (visual assessment), it was considered as dead material. Subsequently, the living leaf subsample fraction was scanned on a model LI-3100 leaf area meter (Li-Cor). Additionally, the growth stage, that is, vegetative or reproductive, of 10–25 tillers was recorded weekly by cutting tillers longitudinally and visually observing the presence or absence of floral buds in the apical meristems using a Coleman XTB Stereoscope Microscope.

## 2.2 | Crop model adaptation

The Cropping System Model (CSM)-CROPGRO-PFM model that is part of DSSAT Version 4.7.5 was used in this study (Hoogenboom, Porter, Shelia, et al., 2019; Jones et al., 2003). We used the species, ecotype, and cultivar files for Tanzânia taken from Lara et al. (2012) with the addition of two missing parameters new to the latest DSSAT V4.7.5 version that were not in the version used by Lara et al. (2012). The new parameters describe the N stress effect on specific leaf area and the reallocation of photosynthates from shoot to root due to N stress. Hereafter this set of V4.7.5 parameterization (species, ecotype, and cultivar) will be referred to as “original”.

The fact that guineagrass was grown at two sites under different management conditions aided in the robust parameter-

ization of different aspects of growth. The ‘Tanzânia’ guinea-grass dataset had data for the entire calendar year, allowing for evaluation of growth under cooler conditions with short daylength months, aspects not present on the ‘Mombaça’ guineagrass data set. On the other hand, the Mombaça data set had very long regrowth cycles with weekly sampling that allowed for the parameterization of biomass accumulation and partitioning to leaf and stem from very early to very late maturation phases (approaching stem elongation/reproductive onset).

With the goal to improve model parameterization, model simulation outputs were compared to the observed data of the field experiments. The simulated output variables were above-ground live biomass, leaf biomass, stem biomass, LAI, and percentage leaf of aboveground live biomass. Parameters of various functions in the species file were manually changed, and then the statistical improvement was evaluated. Statistics were computed across both cultivars because the goal was to improve model performance over both cultivars and sites. The statistical indicators used were the root mean square error (RMSE) and the Willmott agreement index (*d*-statistic) (Willmott et al., 1985). It is important to recognize that our goal was to use a single common species file parameterization to simulate both cultivars, and not to distinguish between cultivars.

**TABLE 2** Total and stable organic carbon, ammonium and nitrate, and properties of soil–water relations used in the soil analysis and initial conditions for the two experimental sites where the cultivars Tanzânia and Mombaça were grown

Soil analysis			Initial conditions		Properties of soil–water relations		
Layer	Soil organic carbon	C (SOM3)	SNH <sub>4</sub> <sup>+</sup>	SNO <sub>3</sub> <sup>−</sup>	LL	DUL	SSAT
cm	%		mg N kg soil <sup>−1</sup>		cm <sup>3</sup> H <sub>2</sub> O cm <sup>−3</sup> soil		
Tanzânia							
5	1.74	0.99	0.1	0.8	0.242	0.366	0.48
15	1.74	0.99	0.1	0.8	0.242	0.366	0.48
25	1.1	0.63	0.1	0.8	0.242	0.366	0.48
40	0.7	0.40	0.1	0.8	0.242	0.366	0.48
55	0.4	0.23	0.1	0.8	0.24	0.34	0.48
75	0.4	0.23	0.1	0.8	0.24	0.34	0.49
85	0.36	0.21	0.1	0.8	0.24	0.34	0.49
200	0.36	0.21	0.1	0.8	0.25	0.35	0.49
450	0.1	0.06	0.1	0.8	0.25	0.35	0.49
Mombaça							
10	2.82	1.692	63.6	63.6	0.269	0.423	0.497
20	2.82	1.692	32.5	45.4	0.269	0.423	0.497
40	2.04	1.224	52	72.4	0.279	0.405	0.469
60	1.59	0.954	56.6	75.6	0.268	0.382	0.454
80	1.45	0.87	47.8	79.7	0.269	0.378	0.448
100	1.09	0.654	54.3	77.7	0.257	0.36	0.436
200	0.36	0.216	1	1	0.257	0.36	0.436
450	0.36	0.216	1	1	0.257	0.36	0.436

Note. LL, lower limit of plant extractable soil moisture; DUL, drained upper limit; SSAT, saturated soil water content.

## 2.3 | Soil organic matter simulation

The CENTURY module (Gijssman et al., 2002) was selected instead of the Godwin-based soil organic matter module (Godwin & Jones, 1991) to simulate the soil organic carbon (SOC) and soil N. The CENTURY option is recommended for all CROPGRO-PFM simulations as it accounts for the decomposition of plant tissue that drops to the soil surface as well as sloughed roots within the soil, which both occur for perennial forage species. The model considers three soil organic matter (SOM) fractions or pools to describe organic carbon (SOC) in the soil: the active (microbial) soil organic matter existing in both the surface mulch layer and in the soil (SOM1), the intermediate soil organic matter (SOM2), and the passive or stable soil organic matter (SOM3) (Gijssman et al., 2002). For both study sites, the observed total SOC was input to the model (Table 2). The SOM3 is also an input (Table 2), but must be calibrated for each given soil, as SOM3 is not a value that is easily measured. The SOM1 and SOM2 are calculated internally by the model as 5 and 95% of the remaining SOC, respectively.

For the Tanzânia experiment, the values for SOC and SOM3 proposed by Lara et al. (2012) were used. The ratio of stable organic carbon fraction (SOM3) to total SOC computes to be 0.57. The initial soil and prior crop residue conditions were also obtained from Lara et al. (2012): ammonium and nitrate were assumed to be 0.1 and 0.8 mg N kg soil<sup>−1</sup> (Table 2), the residue of the previous crop was assumed as 2,000 kg DM ha<sup>−1</sup> with 1% of nitrogen (N), incorporated to a 20-cm depth by tillage (Table 2).

For the Mombaça experiment, SOC (Table 2) was measured to 1-m depth near the experimental site. The assumed values of stable organic C and residue of the previous crop were those of Pequeno et al. (2014), as both experiments were conducted in tropical environments and had pasture as the previous crop. The ratio of SOM3/SOC was assumed as .6 of total soil organic carbon (SOC) for each layer (Table 2). The residue of the previous crop was assumed as 4,000 kg DM ha<sup>−1</sup> of shoot and 4,000 kg DM ha<sup>−1</sup> of roots, both with 1% N, incorporated to a 20-cm depth by tillage. Ammonium and nitrate in the soil for initial conditions section were measured near the experimental site (Table 2).



## 2.4 | Forage harvest simulation

The CROPGRO-PFM relies on several inputs to characterize the harvesting conditions. These inputs are provided in the “MOW” model input file: (a) dates of harvests, (b) the amount of living stubble left after harvest (MOW, in kg ha<sup>-1</sup>), (c) the percentage of live leaves in the stubble (RSPLF), and a “re-staged” leaf number (MVS) used to define the vegetative stage (V-stage) at which regrowth begins after harvest. For the Tanzânia experiment, the MOW file was set based on the same field data values as observed by Lara et al. (2012). For the Mombaça experiment, the MOW file was set with observed data when available (at the beginning and the end of each regrowth cycle). There were two regrowth cycles (during which data were not collected) that occurred between the second and third regrowth cycles. For those regrowth cycles, the stubble mass was set to the same as that ending the second regrowth cycle and the leaf percentage was set to 6% of leaf in the stubble.

## 2.5 | Soil water holding characteristics

The soil–water properties for the Tanzânia experiment (Table 2) were the same as those used by Lara et al. (2012). For the Mombaça experiment, the soil–water properties (Table 2) were calculated by DSSAT pedotransfer equations, which use clay, silt, and SOC content as inputs. Those texture and SOC variables were measured to a 1-m depth next to the experimental site.

The actual crop management, soil characterizations, and daily weather data for each experimental site were used for running the model.

## 2.6 | Statistical analysis for model parameterization and evaluation

The statistics that were used for model parameterization and evaluation included the RMSE and the Willmott agreement index (*d*-statistic) (Willmott et al., 1985).

The equation for RMSE is:

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^N (Y_i - \hat{Y}_i)^2 \right]^{\frac{1}{2}} \quad (1)$$

where *N* is the number of observed data points for comparison, *Y<sub>i</sub>* is a given observed value and  $\hat{Y}_i$  is the corresponding value predicted by the model. The RMSE is low when the model gives a good prediction. The equation for Willmott

agreement *d*-statistics is:

$$d = \frac{\sum_{i=1}^N (Y_i - \hat{Y}_i)^2}{\sum_{i=1}^N \left( |\hat{Y}_i - \bar{Y}| + |Y_i - \bar{Y}| \right)^2} \quad (2)$$

where *N* is the number of observed data points for comparison, *Y<sub>i</sub>* is a given observed value,  $\hat{Y}_i$  is the corresponding value predicted by the model, and  $\bar{Y}$  is the mean of observed data. The *d*-statistic ranges from 0 to 1, and values near 1 indicate good model prediction near to observed values while values near 0 indicate model prediction far from the observed values.

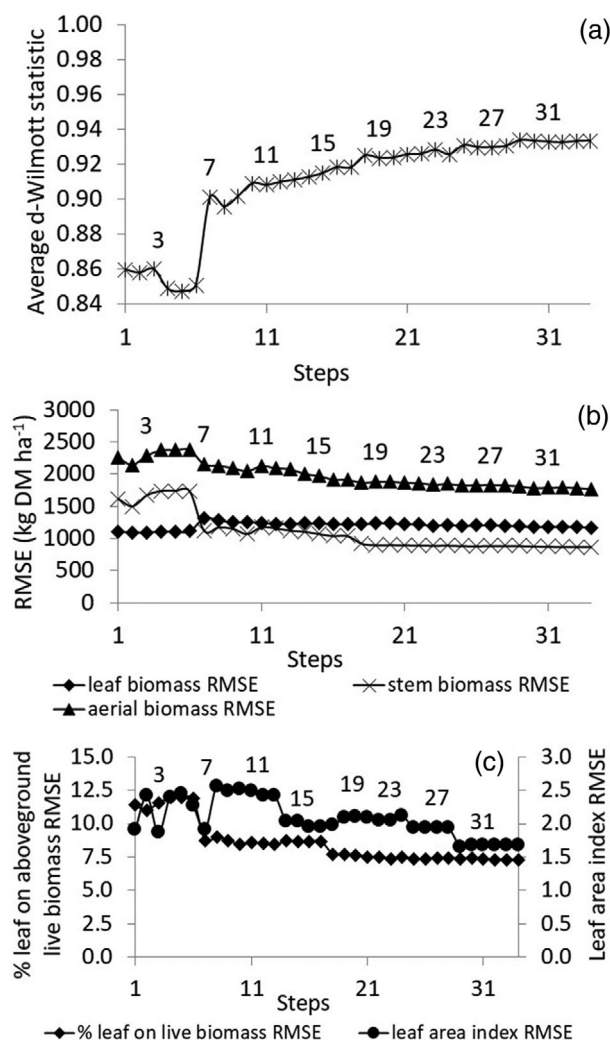
## 3 | RESULTS AND DISCUSSION

First, we discuss model improvement by presenting step-by-step improvements in *d*-statistic and RMSE. Then, we discuss the parameters that were modified for model improvement by showing simulated outcomes of the parameterized version compared to simulations with the original parameter values, along with the initial and final parameterized values of parameters that were modified. The simulated water balance by the model did not show any drought stress for either experiment (data not shown) based on input of irrigation and rain data; therefore no parameters related to drought stress were modified. Finally, we discuss the importance of the main model improvements and provide recommendations for further model development that is needed for the simulation of tropical grasses.

### 3.1 | Statistics of sequential steps of model improvement

There were a total of 34 sequential steps associated with model improvement, starting with the original version until the final parameterized version (Figure 1). Some parameters were modified more than once (there was iteration on several parameters) until reaching the final value. The RMSE and *d*-statistic of the time-series data were computed over both cultivars. Because the *d*-statistic is already normalized within each variable, an average *d*-statistic over all five growth variables (Figure 1a) was computed to show the step-by-step model improvement, while RMSE is shown separately for leaf, stem and aboveground live biomass (Figure 1b), leaf percentage in aboveground live biomass, and LAI (Figure 1c).

The RMSE values were reduced from 2,261 to 1,768 kg ha<sup>-1</sup> for aboveground live biomass, from 1,620 to 874 kg ha<sup>-1</sup> for stem biomass, from 11.4 to 7.3% for leaf percentage, and from 1.91 to 1.68 for LAI, but slightly increased from 1,114 to 1,172 kg ha<sup>-1</sup> for leaf biomass. The small RMSE increase



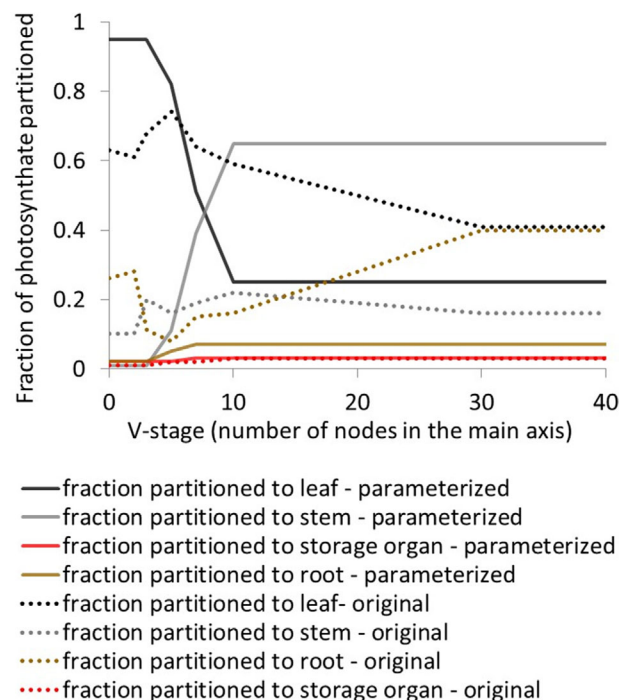
**FIGURE 1** Wilcott *d*-statistic and root mean square error (RMSE) for aboveground live biomass, leaf biomass, stem biomass, leaf area index and percentage leaf on aboveground live biomass of the cultivars Tanzânia and Mombaça throughout the steps of parameterization: (a) *d*-statistic (averaged over all the variables); (b) RMSE of leaf mass, stem mass, and aboveground live biomass; (c) RMSE of percentage leaf on aboveground live biomass and leaf area index

for leaf biomass was considered a minor effect compared with the much larger RMSE decreases for the other variables. The *d*-statistic of model performance averaged over all variables (Figure 1a) increased from .86 for the original to .93 for the final parameterization.

### 3.2 | Parameter modifications underlying model improvement

#### 3.2.1 | Parameters affecting biomass partitioning

Parameters were modified to increase photosynthate partitioning to leaf (YLFESE) early during the life cycle and shifting



**FIGURE 2** Original (dashed) and final parameterized (solid) fraction of photosynthate partitioned to leaf, stem, root, and storage organ as a function of vegetative stage (V-stage) during the established perennial phase for guineagrass. The values are defined in the species file

to stem (YTEST) late during the life cycle (Table 3). The first attempt to modify the partitioning parameters (LFESE, YTEST, YSREST) had the largest effect toward increasing the average *d*-statistic (Figure 1a, step 7) and decreasing RMSE of leaf percentage and stem biomass (Figure 1b), although additional adjustments in these parameters were done in steps 15 and 19. The parameterization resulted in a progressive shift from leaf to stem between V-stage 3 to 10, along with a decrease in partitioning to roots (Figure 2). It is important to note that leaf number (V-Stage) for the short regrowth cycles of the Tanzânia experiment only varies from 3 to 7 (sometimes up to 8) during regular harvests at 35 up to 65 d, and that each harvest triggers a re-set of V-Stage to a value of MVS = 3.0. Thus, the old and new partitioning functions are not that different in range of 3 to 7 for the short cycles of Tanzânia, but had major impact for long regrowth cycles of Mombaça where V-stage approached 9 for the first cycle and 11 for both the second and third cycles. V-stage values of 30 and 40 are there to cover a full upper range for the model, but are rarely reached in practice. It is worth noting that we did not parameterize the rate of node appearance toward predicting observed dates of growth stages or leaf number, and that the reference to simulated V-stage is used only for defining the dry matter partitioning function.

Early during regrowth of tropical forage species, biomass production is composed mostly of leaf, thus restoring the

**TABLE 3** Initial (Lara et al., 2012) and final values of species parameters affecting biomass partitioning (during perennial/ established phase) modified in species genetics file (SPE) of guineagrass for the simulation of Tanzânia and Mombaça cultivars and the steps at which the parameters were modified throughout parameterization

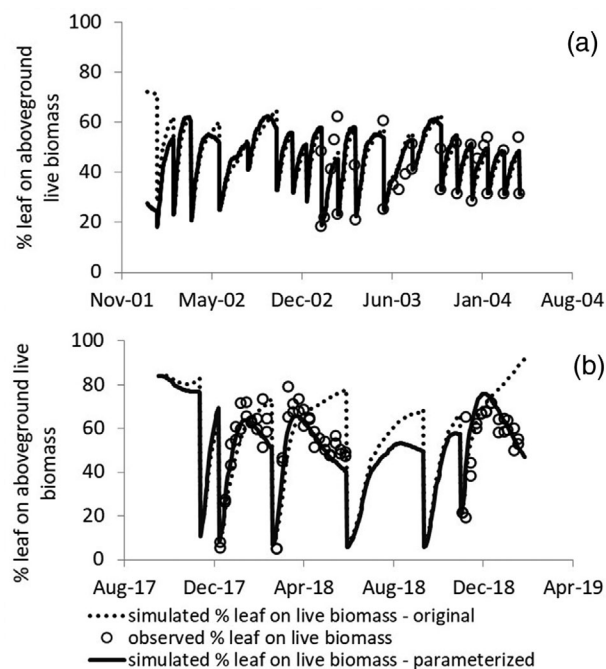
Parameter (and step)	Description	Initial value	Final value
XLTEST (not changed)	Leaf number or vegetative stage at which the partitioning is defined	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0	0.0, 2.0, 3.0, 5.0, 7.0, 10.0, 30.0, 40.0
YLTEST (7, 15, 19) <sup>a</sup>	Dry matter partitioning to leaf as a function of V-stage, fraction	0.63, 0.61, 0.68, 0.74, 0.64, 0.59, 0.41, 0.41	0.95, 0.95, 0.95, 0.82, 0.51, 0.25, 0.25, 0.25
YSTEST (7, 15, 19) <sup>a</sup>	Dry matter partitioning to stem as a function of V-stage, fraction	0.10, 0.10, 0.20, 0.16, 0.19, 0.22, 0.16, 0.16	0.01, 0.01, 0.01, 0.11, 0.39, 0.65, 0.65, 0.65
YSREST (7, 15, 19) <sup>a</sup>	Dry matter partitioning to storage as a function of V-stage, fraction	0.01, 0.01, 0.01, 0.02, 0.02, 0.03, 0.03, 0.03	0.02, 0.02, 0.02, 0.02, 0.03, 0.03, 0.03, 0.03
SDLEST (22)	Photothermal days from sowing to established pasture, °C	25	30

<sup>a</sup>Parameters with more than one step are due to iteration. The final values were set in the final steps of each parameter, while the intermediate values (not shown) were set in preceding steps.

LAI for photosynthesis for ensuring rapid regrowth (Da Silva & Nascimento Júnior, 2007). However, late in the regrowth cycle a considerable amount of biomass is allocated to stem (Carnevali et al., 2006; Congio et al., 2018), including during long vegetative regrowths (Santos et al., 1999). The late stem accumulation is particularly important to simulate correctly for tall bunch-type forage species such as guineagrass because the amount of stem accumulated is quite high (Carnevali et al., 2006). The modified partitioning increased the percentage leaf in the early cycle while decreasing it significantly from the midpoint to late V-stage (later in regrowth cycle), allowing for a much better simulation of percentage leaf in the live aboveground biomass for Mombaça while maintaining an already good prediction for Tanzânia (Figure 3). Similarly, the parameterization increased the stem mass accumulation from the midpoint to the end of three cycles for Mombaça, and consequently, the aboveground live biomass during the same period, showing a much better fit for these variables (Figures 4b and 5b). On the other hand, the parameterization had almost no effect on stem and aboveground live biomass simulations for Tanzânia, which were already good (Figures 4a and 5a). The simulated leaf biomass was somewhat underestimated towards the end of the second and third cycles of Mombaça after changing the partitioning, but with small consequences for the fitting of the regrowth (Figure 6b). For Tanzânia there was almost no change in leaf biomass, which was predicted well after parameterization (Figure 6a).

### 3.2.2 | Parameters affecting senescence

Senescence due to excessive self-shading by the canopy was decreased by lowering the light compensation point at which lower leaves abscise (ICMP; Table 4) and increasing the half-



**FIGURE 3** Original and parameterized simulated percentage leaf of aboveground live biomass as a function of date for Tanzânia in (a) Piracicaba and (b) Mombaça in São Carlos

life time constant at which leaves under the light compensation point abscise (TCMP). These changes allowed the plants to carry more leaves even with a large LAI, improving the simulation of leaf accumulation, and LAI, even in long regrowth cycles, as is the case for Mombaça (Figures 6b and 7b, respectively).

The natural heat-unit related senescence of leaves (LFSEN) was decreased (Table 4) and also resulted in a decrease in senescence. The leaf life span with the parameterized value



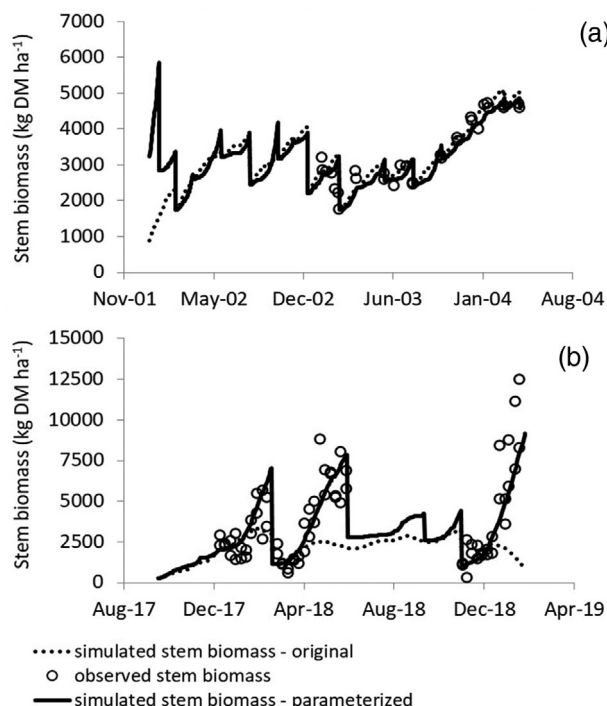
**TABLE 4** Initial (Lara et al., 2012) and parameterized values of parameters affecting aboveground biomass accumulation (senescence, photosynthesis, dormancy, and N stress) modified in species (SPE), ecotype (ECO), and cultivar (CUL) genetics files of guineagrass for the simulation of the Tanzânia and Mombaça cultivars and the steps at which the parameters were modified throughout the parameterization

Parameter (and step)	Description and associated genetics input file	Initial value	Final value
ICMP (9)	Light compensation point ( $\text{mol PPFD m}^{-2} \text{ d}^{-1}$ ) for abscission of lower leaves due to excessive self-shading by crop canopy (SPE)	1.17	0.8
TCMP (10)	Time constant (days) for abscission of lower leaves due to excessive self-shading by crop canopy (SPE)	13.1	20
LFSEN (8, 14) <sup>a</sup>	Natural leaf abscission rate/photothermal day (0.015 means 66.67 d of life span) (SPE)	0.02	0.015
PORPT (11, 13) <sup>a</sup>	Stem abscission as a function of the abscised leaf mass (gram stem per gram leaf abscised) (SPE)	0.27	0.15
LFMAX (12, 33) <sup>a</sup>	Maximum photosynthetic rate at 30 °C, 350 $\mu\text{L L}^{-1} \text{ CO}_2$ , and saturating light, $\text{mg CO}_2 \text{ m}^2 \text{ s}^{-1}$ (CUL)	1.91	1.91 (changed in step 12 but reverted to original in step 33)
XLMAX (17, 20, 27) <sup>a</sup>	Relative rate of photosynthetic electron transport in response to temperature; linear shape, first values defines base (0.0) and second value defines maximum (1.0), °C (SPE)	8.7, 33.4	8.0, 40.0
FNPGL (21, 23, 34) <sup>a</sup>	Relative effect of minimum night temperature on next day's leaf light-saturated photosynthesis rate; quadratic shape, first value defines base (0.0) and second defines maximum (1.0), °C (SPE)	5.9, 17.4	7.8, 18.0
FNPTD (16, 24, 31) <sup>a</sup>	Daylength effect on partitioning to storage (and away from shoot), first value defines maximum to storage, second is minimum to storage, h (SPE)	9.1, 13.5	10.8, 13.7
RDRMT (26, 32) <sup>a</sup>	Relative partitioning/dormancy sensitivity, daylength effect on partitioning (ECO)	0.299	0.35
NSTFAC (30)	Reallocation of photosynthates from shoot to root due to N stress (0–1) (SPE)	0.7	0.8

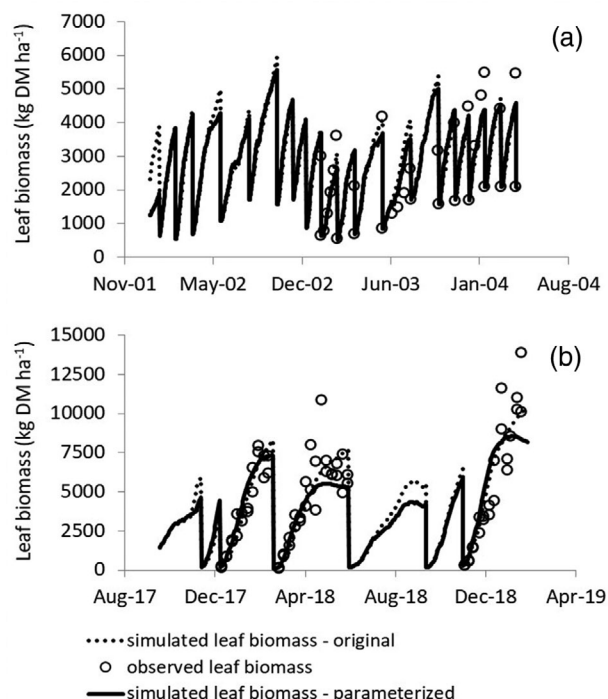
<sup>a</sup>Parameters with more than one step are due to iteration. The final values were set in the final steps of each parameter, while the intermediate values (not given) were set in the preceeding steps.

is about 67 d, similarly to the 70 to 80 d found by Silveira et al. (2010), who studied the leaf life span of four cultivars of guineagrass under free growth. The stem portion to abscise dependent on leaf abscission (PORPT) was also decreased (Table 4), which contributed to the greater stem mass accumulation for the parameterized Mombaça simulations (Figure 4b). It is important to appreciate that the CROPGRO-PFM originated from a model which simulated grain legumes such as soybean [*Glycine max* (L.) Merr.], which has leaf and petiole abscission. However, forage grasses tend not to abscise leaves (rather they die and hang on despite senescence) and forages do not abscise stem tissue (grasses lack petioles). To accomplish this, leaf senescence (abscission from shading and aging) and stem abscission were reduced. Furthermore, in forage grasses the leaf sheath senesces after leaf laminae senesce, but in reality, the dead leaf sheath material remains on the plant allowing for greater stem accumulation and is included in stem mass in the model.

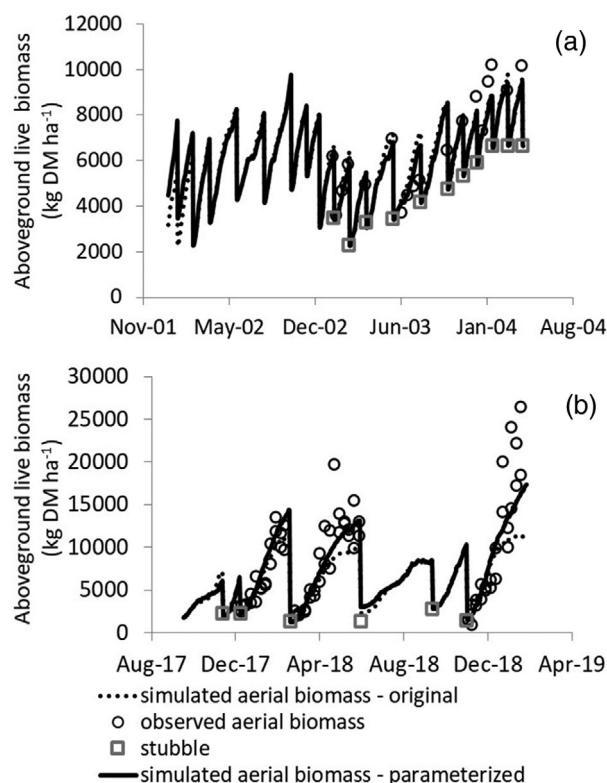
The parameterization of senescence was performed from steps 8 to 14 and had particular importance for decreasing RMSE and increasing *d*-statistic of many growth variables (Figure 1), mainly because less abscission of leaf and stem increased production in long regrowth cycles with significant self-shading, as those of the Mombaça experiment. The model is capable of simulating abscised dead tissue with time after each harvest cycle, and the comparison of simulated to observed dead foliage mass (data not shown) also confirmed the need to reduce the rate of leaf and stem mass abscission. The slight under-estimation of leaf mass toward the end of the second and third cycles indicates that we possibly did not sufficiently reduce rate of leaf abscission during late stages, but we were hesitant to push it further. Available data on dead foliage mass are scarce and there are also sampling issues such as the extent of dead mass carried over from prior regrowth cycles and the extent of dead mass lost to the soil surface due to wind, rainfall, and animal tracking.



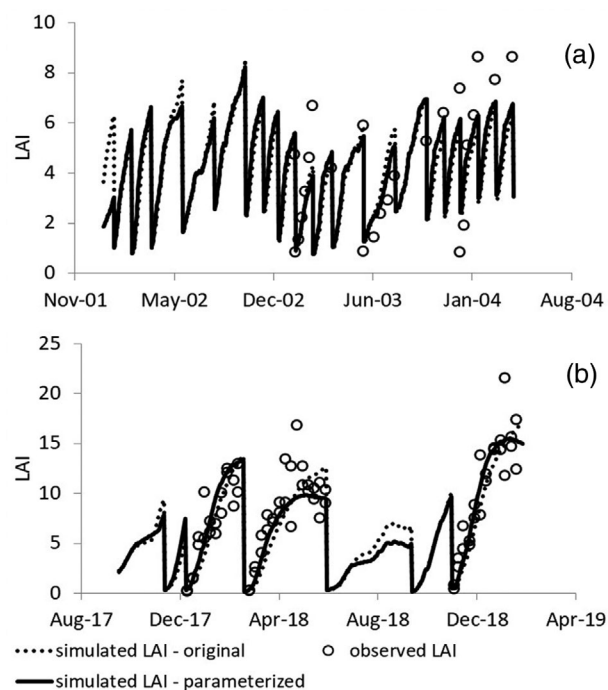
**FIGURE 4** Original and parameterized simulated stem biomass as a function of date for (a) Tanzânia in Piracicaba and (b) Mombaça in São Carlos



**FIGURE 6** Original and parameterized simulated leaf biomass as a function of date for Tanzânia in (a) Piracicaba and (b) Mombaça in São Carlos



**FIGURE 5** Original and parameterized simulated aboveground live biomass as a function of date for (a) Tanzânia in Piracicaba and (b) Mombaça in São Carlos



**FIGURE 7** Original and parameterized simulated LAI as a function of date for Tanzânia in (a) Piracicaba and (b) Mombaça in São Carlos

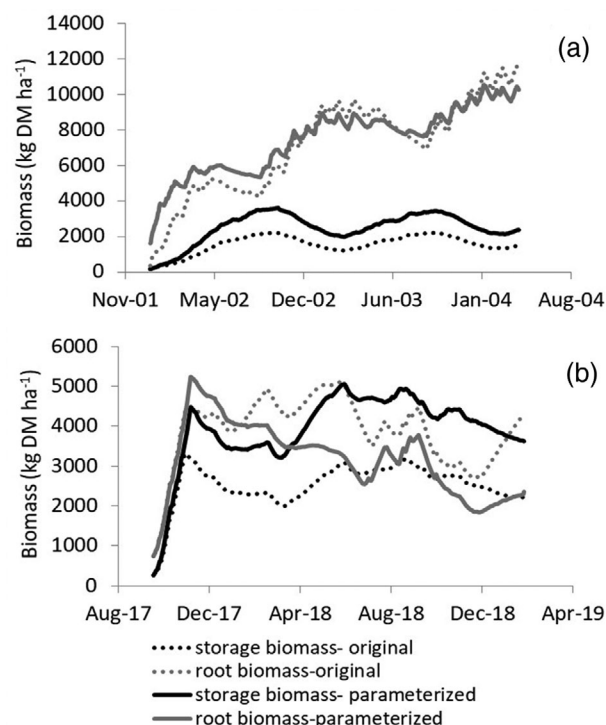
### 3.2.3 | Parameters affecting photosynthesis

Photosynthesis parameterization aided on increasing production during warm months. Therefore, the optimum temperature for the relative rate of photosynthetic electron transport in response to instantaneous hourly temperature for photosynthesis (XLMAXT) was increased to 40 °C (Table 4), benefiting both Tanzânia and Mombaça aboveground biomass simulation (Figure 5). This value is consistent with the known optimum temperature for C4 photosynthesis (Percy & Ehleringer, 1984). This change was sufficient to increase production under good conditions and, therefore, the light-saturated leaf photosynthesis (LFMAX), which was the same for both cultivars, was not changed from the original value (Table 4).

For the Tanzânia trial, data were also collected during the coolest months of the year (June–August), bringing out the need for parameterizing growth under cool conditions. The base temperature for photosynthesis was increased to reduce production during the cool months for Tanzânia. Specifically, the base temperature threshold for relative rate of photosynthetic electron transport in response to instantaneous hourly temperature (XLMAXT) (Table 4) was increased, and the function (FNPGI) that reduces photosynthesis during the following day as a function of night temperature ( $T_{min}$ ) was made more sensitive to cold night temperature, which is described by an asymptotic function with a base and an optimum (Table 4). These changes were applied iteratively in several steps with other parameters throughout parameterization (Table 4 and Figure 1) and they improved aboveground live biomass simulations for Tanzânia (Figure 5a).

### 3.2.4 | Parameters for daylength effect on shifting photosynthate from shoot to storage organ

Along with the parameterization of photosynthesis under cool conditions, the daylength effect on dormancy was modified to reduce the allocation to aboveground live biomass and increase the allocation to storage tissue organs under short days. The CROPGRO-PFM model is coded to allow assimilate allocation to storage organs to increase and the allocation to the shoot to decrease under short daylengths, which is a type of dormancy. The critical daylength range as described by a pair of daylengths (FNPTD; Table 4) was modified. The lowest daylength value for maximum allocation to storage was increased from 9.1 to 10.8 h, which increased the allocation to storage and that reduced shoot growth during winters. The maximum daylength value for highest partitioning to shoot was increased slightly from 13.5 to 13.7 h. In addition, the relative strength of the daylength effect for partitioning photosynthate to storage organ (RDRMT; Table 4), was



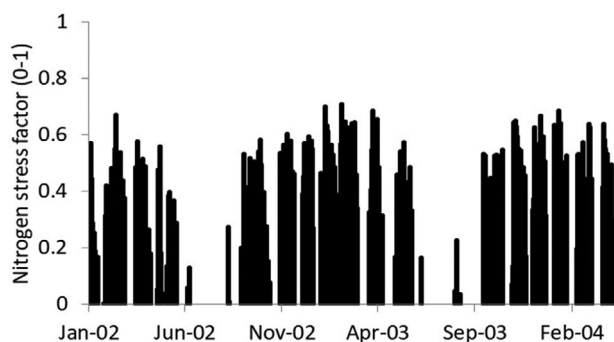
**FIGURE 8** Original and parameterized simulated storage organ and root biomass as a function of date for Tanzânia in (a) Piracicaba and (b) Mombaça in São Carlos

increased, which also decreased aboveground biomass under short days. The parameterization of sensitivity to daylength was performed in several steps throughout the modeling exercise (Table 4; Figure 1), and improved aboveground live biomass accumulation simulation, especially for Tanzânia (Figure 5a).

The CROPGRO approach for shifting the photosynthate allocation from the shoot toward the storage organ, for example, the stem base and root, under short days, has been used successfully to simulate seasonal growth dynamics and winter dormancy of other tropical perennial grasses including bahiagrass, palisadegrass, and the prior version of guineagrass (Lara et al., 2012; Pedreira et al., 2011; Rymph, 2004). After parameterization, the simulations show long-term stability of storage organ and root biomass over years (Figure 8), which allows for the perennation of the plant and facilitates long-term simulations for model applications.

### 3.2.5 | Parameters for N stress effect on shifting partitioning from shoot to root and on leaf area expansion

The simulated N stress was relatively severe (Figure 9) for Tanzânia, whereas there was no simulated N stress for Mombaça (data not shown). Thus, the Tanzânia experiment brought the need of parameterizing conditions under N stress, which



**FIGURE 9** Nitrogen stress factor simulated with the parameterized version as a function of date for Tanzânia in Piracicaba

has a significant impact on warm-season grass growth. Mombaça simulated no N stress due to the high levels of both nitrate and ammonium that were present at the start of the experiment and defined in the initial conditions (Table 2). In contrast, the smaller amount of initial nitrate and ammonium, total soil C as well as low prior crop residue resulted in simulated N stress for Tanzânia.

The effect of N stress on shifting the partitioning from shoot to root is controlled by a new parameter (NSTFAC), which was set to 0.8 (the prior value was hard-coded at 0.7 in the model). The effect of increasing the partitioning to roots whenever N stress occurred in the Tanzânia trial, provided a better fit to Tanzânia aboveground live biomass simulation (Figure 5a). Additionally, the CROPGRO-PFM has a parameter that allows N stress effect to reduce leaf expansion (NSLA). This parameter was reduced from the default value of 1.0 to 0.7 (Table 5), decreasing the effect of N stress on

reducing LAI expansion, which improved the simulation of LAI for Tanzânia (Figure 7a).

### 3.2.6 | Parameters affecting prediction of specific leaf area and leaf area index

Specific leaf area (SLA) was not considered in optimization because SLA of Mombaça showed unusual patterns of thin leaves early during each cycle with subsequent thickening, whereas this did not occur for Tanzânia (SLA data are not shown). Simulated SLA with the original parameters showed an underestimation for both cultivars during all regrowth cycles. To increase SLA and thus LAI, the SLAMIN, SLAREF, and the cultivar-specific SLA (SLAVR) parameters were all set at  $180 \text{ cm}^2 \text{ g}^{-1}$  (Table 5), which provided simulations with a higher specific leaf area, and, consequently, a higher LAI under good conditions when compared to the simulations with original model parameters. This allowed for a better fit of LAI for Tanzânia and Mombaça (Figure 7). The changes were made from steps 2 to 4 and 29 (Table 5), and the final values (set on step 29), resulted in a considerable decrease in RMSE of LAI (Figure 1c).

The effect of cool temperature on leaf expansion and the effect of low radiation regime can affect seasonal SLA and LAI during the cool months. The temperature effect on SLA of newly produced leaves (XSLATM and YSLATM, Table 5) was optimized. The threshold temperature (XSLATM) at which maximum reduction of SLA occurs and the degree of reduction (YSLATM) on leaf expansion was increased. This allowed for a larger effect of cool temperature to reduce SLA and LAI. Furthermore, the thinnest leaf under very low light

**TABLE 5** Initial (Lara et al., 2012) and parameterized values of parameters affecting leaf area index (LAI) modified in species (SPE), ecotype (ECO), and cultivar (CUL) genetics files of guineagrass for the simulation of the Tanzânia and Mombaça cultivars and the steps at which the parameters were modified throughout the parameterization

Parameter (and step)	Description (and parameter's file)	Initial value	Parameterized value
SLAVR <sup>a</sup> (4, 29)	Specific leaf area of cultivar under standard growth conditions, $\text{cm}^2 \text{ g}^{-1}$ (CUL)	175	180
SLAREF (2, 29) <sup>a</sup>	Specific leaf area of standard cultivar, $\text{cm}^2 \text{ g}^{-1}$ (SPE)	166	180
SLAMIN (3, 29) <sup>a</sup>	The thickest leaves under high light, $\text{cm}^2 \text{ g}^{-1}$ (SPE)	137	180
SLAMAX (28, 29) <sup>a</sup>	The thinnest leaves under low light, $\text{cm}^2 \text{ g}^{-1}$ (SPE)	356	320
XSLATM (5, 25) <sup>a</sup>	Relative effect of temperature on specific leaf area of newly formed leaves, °C (X vs. Y pair) (SPE)	11.8, 26.6	12.7, 26.6
YSLATM (6)	Relative effect of temperature on specific leaf area of newly formed leaves, fraction reduction (X vs. Y pair) (SPE)	0.39, 1.00	0.30, 1.00
NSLA(28)	N effect on specific leaf area (SPE)	1	0.75

<sup>a</sup>Parameters with more than one step are due to iteration. The final values were set in the final steps of each parameter, while the intermediate values (not given) were set in the preceding steps.



(SLAMAX) was decreased (Table 5), which also reduced SLA under the low light conditions of winter. The parameterization of low temperature and low radiation effects on leaf expansion allowed for a better fit of LAI for Tanzânia during cool months (Figure 7a). The changes of these parameters were done iteratively throughout parameterization (Table 5) and resulted in an improvement of model performance (Figure 1), mainly due to the seasonality on LAI in the Tanzânia trial.

### 3.3 | The importance of model improvements for applications

The flexibility in harvest date for perennial forages allows for different harvest frequencies and intensities when compared to annual crops. Harvest may occur at different frequencies, that is, regrowth durations, and intensities, that is, portion harvested/total biomass available, depending on the manager's goal and technology available. In pasture-based livestock systems, green leaf accumulation is preferred to stem accumulation, as greater leaf proportions favor enhanced grazing efficiency and forage nutritive value (Gontijo Neto et al., 2006). In practice, regrowth duration varies considerably despite recommendations to set optimum harvest time to avoid excess stem accumulation (Carnevali et al., 2006; Congio et al., 2018). The forage availability for the animals varies throughout the year and between years as a consequence of edapho-climatic conditions (Brunetti et al., 2020) and stocking rate. Adjusting the stocking rate is not an easy task and, therefore, variations in the harvest frequency occur and, thus, the pasture may be harvested during several phenological stages. These variations, in turn, have consequences on animal performance and composition of the stubble, with further consequences for the next regrowth. On the other hand, some management practices may benefit from longer regrowth cycles. For silage, longer regrowth cycles are advisable as longer cycles increase the dry matter and soluble carbohydrate concentration, which, in turn, favors the development of lactic acid bacteria and silage fermentation process (Santos et al., 2014), despite causing negative effects for the forage nutritive value (Vasconcelos et al., 2009). Additionally, there is a growing interest for use of highly productive grasses as guineagrass in long regrowth cycles as bioenergy source (Jank et al., 2013). Thus, the model with robust biomass partitioning in long cycles including early, mid- and late cycle, and better representation of self-shading effects caused by high LAIs which is common in long cycles on leaf and stem senescence will aid planning and decision-making for diverse harvesting practices and understanding animal and plant responses.

The previous versions of CROPGRO-PFM were parameterized for data collected only at the harvest date, and, thus were lacking data on partitioning to leaf and stem during

early regrowth starting immediately after cutting (Lara et al., 2012; Pedreira et al., 2011; Pequeno, 2014; Pequeno et al., 2018). Additionally, the cycles of those previous studies were "short", ranging from 28 to 42 d during warm months and 65 d during cooler months, and probably the forages barely approached stem elongation and extreme self-shading by high LAIs. By contrast, the cycles of Mombaça in the present study extended 70–98 d and the plants approached stem elongation/flowering and high self-shading. Therefore, the detailed time-series data on forage mass and partitioning from very early to very late cycle for Mombaça, allowed for a more robust parameterization of biomass accumulation in long cycles along with partitioning to leaf and stem during cycles of varying durations, as shown by the major improvement in statistics. Detailed time-series data on forage regrowth immediately after cutting, while useful, are scarce in forage experiments, because taking frequent destructive samples down to the soil surface affects pasture regrowth, thus requiring that those sampled areas are excluded during any later sampling.

In this study we were also able to improve parameterization of the seasonality of production, for example, cool temperature and daylength effects, based on the Tanzânia experiment. This is important for the parameterization of guineagrass as it is usually grown year-round in the tropics, but the decrease in forage supply to feed the animals during the winter often has to be complemented with other feeding sources (Brunetti et al., 2020). Thus, the model sensitivity to temperature and daylength is important for planning of pasture-based systems and for model use considering diverse locations within warm-season non-freezing climates. Additionally, we parameterized the two new parameters related to N stress (NSTFAC and NSLA) that were not present in the version used by Lara et al. (2012), and now better represent the N stress effects on guineagrass growth. This aspect is particularly important, as N is the nutrient with the greatest effect on pasture growth and, consequently, the most used for increasing biomass accumulation.

### 3.4 | Future model improvements

At the midpoint to end of the second cycle in the Mombaça experiment, the plants flowered. Guineagrass is a short-day species (Felippe, 1978; Loch, 1980) with approximate critical daylength of 11.8 h, when floral initiation can be seen in reproductive tillers (Araujo et al., 2018). This occurs between the months of April–September in the latitude of Mombaça and Tanzânia experiments (the sites are similar in latitude). The occurrence of the first reproductive tillers (observation of flower primordia) for the Mombaça trial was on 4 Apr. 2018. Thereafter, the number of tillers with flower primordia increased for about 15 d until the panicles finally started to emerge. Floral initiation (and flowering) terminates leaf

initiation and markedly stimulates subsequent stem elongation which raises the apical meristems in conjunction with shifting partitioning from leaves to stem. In addition, the new leaves that had been initiated inside the whorl of leaf sheaths (boot stage) before differentiation of apical meristem from vegetative to reproductive, are shorter (smaller) than vegetative leaves, which also decreases leaf accumulation. It is unclear, however, whether the stem elongation in long cycles is necessarily a prelude to flowering or occurs irrespective of flowering stimulus during long vegetative growth. In the present study, no reproductive meristems were observed in the first and third cycles of Mombaça even with the presence of high stem elongation (and accumulation), as corroborated by Araujo et al. (2018). More studies are needed to elucidate stem elongation, flowering, and their interactions in tropical forage grasses growth.

Despite the observation of floral buds in the meristems exclusively in the second cycle of Mombaça, and the uncertainties underlying stem elongation and flowering in the other two cycles, the parameterized model showed good performance for simulating stem and biomass accumulation in the three cycles (Figures 5b and 6b). The present CROPGRO-PFM, however, does not simulate flowering, which may be needed in other studies, depending on the objectives of those studies. Therefore, model changes are needed to simulate floral initiation and its relationship to daylength and associated stem elongation, seed growth, and seed maturation. These processes were uncoupled with the transition of CROPGRO from annual to perennial species. The issues are not simple, because the model will need to re-initiate the juvenile vegetative state either on an annual basis or after harvesting of the reproductive tissues.

Future model evaluation against independent experimental data collected at other locations is recommended to confirm the performance of CROPGRO-PFM for these guineagrass cultivars grown under both long and short regrowth cycles. An improvement needed in the DSSAT in general for all crops, is the creation of automated calibration software that makes use of time-series data that are typical for both perennial and annual crops. Automated calibration was not possible because the existing automated calibration software in DSSAT only uses end-of season grain yield, biomass, and phenological observations, but does not use the time-series data typical of perennial forages (He et al., 2010; Hunt et al., 1993). While unpublished partially automated software using time-series data was used for some prior studies using CROPGRO-PFM (Malik et al., 2018; Pequeno et al., 2018), that software is no longer functional or useable for the version 4.7.5 of DSSAT used in this study. However, with the addition of automated calibration software programs that work for CROPGRO-PFM, an improved calibration of the parameters resulting from this study may be possible. Various new tools for using time-series data for model calibration

and evaluation are currently under development (Alderman, 2020; Memic et al., 2021).

## 4 | CONCLUSION

The original model CROPGRO-PFM showed a good performance for simulating growth of Tanzânia but a relatively poor but acceptable performance for simulating Mombaça growth. After parameterization, the model had good performance for predicting aboveground biomass accumulation and partitioning to leaf and stem during varying phenological phases. The parameterized set of genetic parameters worked well to simulate both Tanzânia and Mombaça (no cultivar-specific parameters were required). For other cultivars, small adjustments to the ecotype and cultivar parameters may be needed to achieve good simulations. This model improvement for guineagrass will be included in future versions of DSSAT and will facilitate further use for evaluating pasture utilization strategies with harvesting at widely varying times during the regrowth cycles.

## CONFLICT OF INTEREST

The authors have no conflict of interest to disclose.

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## AUTHOR CONTRIBUTIONS

Henrique Brunetti: Conceptualization; Formal analysis; Investigation; Methodology; Visualization; Writing-original draft; Writing-review & editing. Ken Boote: Conceptualization; Formal analysis; Methodology; Software; Supervision; Visualization; Writing-original draft; Writing-review & editing. Patricia Menezes Santos: Conceptualization; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Writing-review & editing. José Ricardo Macedo Pezzopane: Conceptualization; Funding acquisition; Investigation; Methodology; Resources; Writing-review & editing. Carlos G. S. Pedreira: Investigation; Resources; Writing-review & editing. Márcio André Stefanelli Lara: Investigation; Resources; Writing-review & editing. Leonardo S. B. Moreno: Investigation; Resources; Writing-review & editing. Gerrit Hoogenboom: Methodology; Software; Writing-review & editing

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## REFERENCES

- Alderman, P. D. (2020). A comprehensive R interface for the DSSAT Cropping System Model. *Computers and Electronics in Agriculture*, 172, 105325. <https://doi.org/10.1016/j.compag.2020.105325>
- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration-Guidelines for computing crop water requirements* (FAO Irrigation and drainage paper 56, Vol. 300(9), p. D05109). Rome, Italy: FAO.
- Araujo, L. C. D.e, Santos, P. M., Rodriguez, D., & Pezzopane, J. R. M. (2018). Key factors that influence for seasonal production of Guinea grass. *Scientia Agricola*, 75(3), 191–196. <https://doi.org/10.1590/1678-992x-2016-0413>
- Araujo, L. C., Santos, P. M., Rodriguez, D., Pezzopane, J. R. M., Oliveira, P. P. A., & Cruz, P. G. (2013). Simulating guinea grass production: Empirical and mechanistic approaches. *Agronomy Journal*, 105(1), 61–69. <https://doi.org/10.2134/agronj2012.0245>
- Boote, K. J., Jones, J. W. & Hoogenboom, G. (2021). Incorporating realistic trait physiology into crop growth models to support genetic improvement. *in silico Plants*, 3(1), <https://doi.org/10.1093/insilicoplants/diab002>
- Boote, K. J., Jones, J. W., Hoogenboom, G., & Pickering, N. B. (1998). The CROPGRO model for grain legumes. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production. Systems approaches for sustainable agricultural development* (pp. 99–128). Dordrecht, the Netherlands: Kluwer Academic Publishers.
- Bosi, C., Sentelhas, P. C., Pezzopane, J. R. M., & Santos, P. M. (2020). CROPGRO-Perennial Forage model parameterization for simulating Piatã palisade grass growth in monoculture and in a silvopastoral system. *Agricultural Systems*, 177, 102724. <https://doi.org/10.1016/j.agsy.2019.102724>
- Brunetti, H. B., Cavalcanti, P. P., Dias, C. T. S., Pezzopane, J. R. M., & Santos, P. M. (2020). Climate risk and seasonal forage production of Marandu palisadegrass in Brazil. *Anais da Academia Brasileira de Ciências*, 92(3). <https://doi.org/10.1590/0001-3765202020190046>
- Carnevali, R. A., Da Silva, S. C., Bueno, A. D. O., Uebele, M. C., Bueno, F. O., Hodgson, J., Silva, G. N., & Morais, J. P. G. (2006). Herbage production and grazing losses in *Panicum maximum* cv. Mombaça under four grazing managements. *Tropical Grasslands*, 40(3), 165.
- Congio, G. F. S., Batalha, C. D. A., Chiavegato, M. B., Berndt, A., Oliveira, P. P. A., Frighetto, R. T. S., Maxwell, T. M. R., Gregorini, P., & Da Silva, S. C. (2018). Strategic grazing management towards sustainable intensification at tropical pasture-based dairy systems. *Science of the Total Environment*, 636, 872–880. <https://doi.org/10.1016/j.scitotenv.2018.04.301>
- Felippe, G. M. (1978). Effects of photoperiod, GA3 and CCC on flowering of *Panicum maximum*. *Hoehnea*, 7, 11–16.
- Fernandes, F. D., Ramos, A. K. B., Jank, L., Carvalho, M. A., Martha Jr., G. B., & Braga, G. J. (2014). Forage yield and nutritive value of *Panicum maximum* genotypes in the Brazilian savannah. *Scientia Agricola*, 71(1), 23–29. <https://doi.org/10.1590/S0103-90162014000100003>
- Gijsman, A. J., Hoogenboom, G., Parton, W. J., & Kerridge, P. C. (2002). Modifying DSSAT crop models for low-input agricultural systems using a soil organic matter–Residue module from CENTURY. *Agronomy Journal*, 94(3), 462–474. <https://doi.org/10.2134/agronj2002.4620>
- Godwin, D. C., & Allan Jones, C. (1991). Nitrogen dynamics in soil-plant systems. *Modeling Plant and Soil Systems*, 31, 287–321. <https://doi.org/10.2134/agronmonogr31.c13>
- Gontijo Neto, M. M., Euclides, V. P. B., Nascimento Júnior, D. D.o, Miranda, L. F., Fonseca, D. M. D.a, & Oliveira, M. P. D.e (2006). Consumo e tempo diário de pastejo por novilhos Nelore em pastagem de capim-tanzânia sob diferentes ofertas de forragem. (In Portuguese, with English abstract.) *Revista Brasileira de Zootecnia*, 35(1), 60–66. <https://doi.org/10.1590/S1516-35982006000100007>
- He, J., Jones, J. W., Graham, W. D., & Dukes, M. D. (2010). Influence of likelihood function choice for estimating crop model parameters using the generalized likelihood uncertainty estimation methods. *Agricultural Systems*, 103, 256–264. <https://doi.org/10.1016/j.agsy.2010.01.006>
- Hoogenboom, G., Porter, C. H., Boote, K. J., Shelia, V., Wilkens, P. W., Singh, U., White, J. W., Asseng, S., Lizaso, J. I., Moreno, L. P., Pavan, W., Ogoshi, R., Hunt, L. A., Tsuji, G. Y., & Jones, J. W. (2019). The DSSAT crop modeling ecosystem. In K. J. Boote (Ed.), *Advances in crop modeling for a sustainable agriculture* (pp. 173–216). Cambridge, UK: Burleigh Dodds Science Publishing.
- Hoogenboom, G., Porter, C. H., Shelia, V., Boote, K. J., Singh, U., White, J. W., Hunt, L. A., Ogoshi, R., Lizaso, J. I., Koo, J., Asseng, S., Singels, A., Moreno, L. P., & Jones, J. W. (2019). *Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7*. Gainesville, FL: DSSAT Foundation.
- Hunt, L. A., Pararajasingham, S., Jones, J. W., Hoogenboom, G., Ima-mura, D. T., & Ogoshi, R. M. (1993). GENCALC - Software to facilitate the use of crop models for analyzing field experiments. *Agronomy Journal*, 85(5), 1090–1094. <https://doi.org/10.2134/agronj1993.00021962008500050025x>
- Jank, L., De Lima, E. A., Simeão, R. M., & Andrade, R. C. (2013). Potential of *Panicum maximum* as a source of energy. *Tropical Grasslands-Forrajes Tropicales*, 1(1), 92–94. [https://doi.org/10.17138/TGFT\(1\)92-94](https://doi.org/10.17138/TGFT(1)92-94)
- Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., Wilkens, P. W., Singh, U., Gijsman, A. J., & Ritchie, J. T. (2003). DSSAT Cropping System Model. *European Journal of Agronomy*, 18, 235–265. [https://doi.org/10.1016/S1161-0301\(02\)00107-7](https://doi.org/10.1016/S1161-0301(02)00107-7)
- Kelly, T. C. (1995). *Bioeconomic systems approach to sustainability analysis at the farm level* (PhD dissertation, University of Florida).
- Lara, M. A. S., Pedreira, C. G. S., Boote, K. J., Pedreira, B. C., Moreno, L. S. B., & Alderman, P. D. (2012). Predicting growth of *Panicum maximum*: An adaptation of the CROPGRO–Perennial forage model. *Agronomy Journal*, 104(3), 600–611. <https://doi.org/10.2134/agronj2011.0272>

- Loci, D. (1980). Selection of environment and cropping system for tropical grass seed production. *Tropical Grasslands*, 14(3), 159.
- Malik, W., Boote, K. J., Hoogenboom, G., Caverio, J., & Dechmi, F. (2018). Adapting the CROPGRO model to simulate alfalfa growth and yield. *Agronomy Journal*, 110(5), 1777–1790. <https://doi.org/10.2134/agronj2017.12.0680>
- Memic, E., Graeff, S., Boote, K. J., Hensel, O., & Hoogenboom, G. (2021). Cultivar coefficient estimator for the cropping system model based on time-series data - A case study for soybean. *Transactions of the ASABE*, (Accepted for publication).
- Moreno, L. S. B., Pedreira, C. G. S., Boote, K. J., & Alves, R. R. (2014). Base temperature determination of tropical *Panicum* spp. grasses and its effects on degree-day-based models. *Agricultural and Forest Meteorology*, 186. <https://doi.org/10.1016/j.agrformet.2013.09.013>
- Muir, J. P., & Jank, L. (2004). Guineagrass. In L. E. Moser, B. L. Burson, & L. E. Sollenberger (Eds.), *Warm-season (C4) grasses* (pp. 589–621). Madison, WI: ASA, CSSA, and SSSA. <https://doi.org/10.2134/agronmonogr45.c17>
- Pearcy, R. W., & Ehleringer, J. (1984). Comparative ecophysiology of C3 and C4 plants. *Plant, Cell & Environment*, 7(1), 1–13. <https://doi.org/10.1111/j.1365-3040.1984.tb01194.x>
- Pedreira, B. C., Pedreira, C. G. S., Boote, K. J., Lara, M. A. S., & Alderman, P. D. (2011). Adapting the CROPGRO perennial forage model to predict growth of *Brachiaria brizantha*. *Field Crops Research*, 120(3), 370–379. <https://doi.org/10.1016/j.fcr.2010.11.010>
- Pequeno, D. N. L. (2014). *Agronomic performance and adaptation of the CROPGRO-Perennial Forage Model to predict growth of three tropical forage grasses under irrigated and rainfed conditions* (PhD dissertation, Universidade de São Paulo). <https://www.teses.usp.br/teses/disponiveis/11/11139/tde-21032014-151530/pt-br.php> <https://doi.org/10.11606/T.11.2014.tde-21032014-151530>
- Pequeno, D. N. L., Pedreira, C. G. S., & Boote, K. J. (2014). Simulating forage production of Marandu palisade grass (*Brachiaria brizantha*) with the CROPGRO-Perennial Forage model. *Crop and Pasture Science*, 65(12), 1335–1348. <https://doi.org/10.1071/CP14058>
- Pequeno, D. N. L., Pedreira, C. G. S., Boote, K. J., Alderman, P. D., & Faria, A. F. G. (2018). Species-genotypic parameters of the CROPGRO Perennial Forage Model: Implications for comparison of three tropical pasture grasses. *Grass and Forage Science*, 73(2), 440–455. <https://doi.org/10.1111/gfs.12329>
- Pezzopane, J. R. M., Santos, P. M., Cruz, P. G. D.a, Bosi, C., & Sentelhas, P. C. (2018). An integrated agrometeorological model to simulate Marandu palisade grass productivity. *Field Crops Research*, 224, 13–21. <https://doi.org/10.1016/j.fcr.2018.04.015>
- Rymph, S. J. (2004). *Modeling growth and composition of perennial tropical forage grasses* (PhD dissertation, University of Florida). [http://etd.fcla.edu/UF/UFE0006608/rymph\\_s.pdf](http://etd.fcla.edu/UF/UFE0006608/rymph_s.pdf)
- Santos, P. M., Corsi, M., & Balsalobre, M. A. A. (1999). Efeito da frequência de pastejo e da época do ano sobre a produção e a qualidade em *Panicum maximum* cvs. Tanzânia e Mombaça. (In Portuguese, with English abstract.) *Revista Brasileira de Zootecnia*, 28(2), 244–249. <https://doi.org/10.1590/S1516-35981999000200004>
- Santos, E. M., Pereira, O. G., Garcia, R., Ferreira, C. L. L. F., Oliveira, J. S., & Silva, T. C. (2014). Effect of regrowth interval and a microbial inoculant on the fermentation profile and dry matter recovery of guinea grass silages. *Journal of Dairy Science*, 97(7), 4423–4432. <https://doi.org/10.3168/jds.2013-7634>
- Silva, S. C. D.a, & Nascimento Júnior, D. D.o (2007). Avanços na pesquisa com plantas forrageiras tropicais em pastagens: Características morfofisiológicas e manejo do pastejo. (In Portuguese, with English abstract.) *Revista Brasileira de Zootecnia*, 36, 122–138. <https://doi.org/10.1590/S1516-35982007001000014>
- Silveira, M. C. T. D.a, Nascimento Júnior, D. D.o, Silva, S. C. D.a, Euclides, V. P. B., Montagner, D. B., Sbrissia, A. F., Rodrigues, C. S., Sousa, B. M. D.e L., Pena, K. D.a S., & Vilela, H. H. (2010). Morphogenetic and structural comparative characterization of tropical forage grass cultivars under free growth. *Scientia Agricola*, 67(2), 136–142. <https://doi.org/10.1590/S0103-90162010000200002>
- Vasconcelos, W. A. D., Santos, E. M., Zanine, A. D. M., Pinto, T. F., Lima, W. C., Edvan, R. L., & Pereira, O. G. (2009). Valor nutritivo de silagens de capim-mombaça (" *Panicum maximum*" Jacq.) colhido em função de idades de rebrotação. (In Portuguese, with English abstract.) *Revista Brasileira de Saúde e Produção Animal*, 10(4).
- Welles, J. M., & Norman, J. M. (1991). Instrument for indirect measurement of canopy architecture. *Agronomy Journal*, 83(5), 818–825. <https://doi.org/10.2134/agronj1991.00021962008300050009x>
- Willmott, C. J., Ackleson, S. G., Davis, R. E., Feddema, J. J., Klink, K. M., Legates, D. R., O'donnell, J., & Rowe, C. M. (1985). Statistics for the evaluation and comparison of models. *Journal of Geophysical Research: Oceans*, 90(C5), 8995–9005. <https://doi.org/10.1029/JC090iC05p08995>

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