



Adapting the CROPGRO perennial forage model to predict growth of *Brachiaria brizantha*

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ABSTRACT

Warm-season grasses are economically important for cattle production in tropical regions, and tools to aid in management and research of these forages would be highly beneficial. Crop simulation models synthesize numerous physiological processes and are important research tools for evaluating production of warm-season grasses. This research was conducted to adapt the perennial CROPGRO Forage model to simulate growth of the tropical species palisadegrass [*Brachiaria brizantha* (A. Rich.) Stapf. cv. Xaraes] and to describe model adaptation for this species. In order to develop the CROPGRO parameters for this species, we began with values and relationships reported in the literature. Some parameters and relationships were calibrated by comparison with observed growth, development, dry matter accumulation and partitioning during a 2-year experiment with Xaraes palisadegrass in Piracicaba, SP, Brazil. Starting with parameters for the bahiagrass (*Paspalum notatum* Flugge) perennial forage model, dormancy effects had to be minimized, and partitioning to storage tissue/root decreased, and partitioning to leaf and stem increased to provide for more leaf and stem growth and less root. Parameters affecting specific leaf area (SLA) and senescence of plant tissues were improved. After these changes were made to the model, biomass accumulation was better simulated, mean predicted herbage yield per cycle was 3573 kg ha⁻¹, with a RMSE of 538 kg DM ha⁻¹ (D -Stat = 0.838, simulated/observed ratio = 1.028). The results of the adaptation suggest that the CROPGRO model is an efficient tool to integrate physiological aspects of palisadegrass and can be used to simulate growth.

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1. Introduction

Livestock production is a major agricultural enterprise in Brazil, as the country has the world's largest beef cattle number (204.5 million head), and major beef export status globally (FAO, 2010). The beef cattle industry is essentially forage-based and is supported by 197 million ha of improved pastures (FAO, 2010). Of those, approximately 35–40 million ha are currently established with grasses of the genus *Brachiaria* (Miles et al., 1996), an introduced, African, C₄ grass that has shown excellent adaptation to most of Brazil, although management of this grass is largely empirical. Most recommendations do not take into account physiological aspects commonly used for establishing harvest management of high technology row crops. Harvesting and grazing schedules of forages are often established at the convenience of the producer, often using fixed time periods between harvests. This results in variable amounts and quality of forage available for

grazing or clipping as the season progresses and the environment changes, even in the low latitudes of the tropics (Pedreira et al., 2009).

Systems modeling is a highly useful tool for understanding the relationships among soil, plants, and other components in agricultural systems, particularly for studying the relationships between system components over time. Agricultural models have been developed not only to understand the processes and interactions involving system components and their effects upon overall production but for their usefulness as decision support tools for evaluating management options (Zamora et al., 2009). CROPGRO is a mechanistic model (implemented in FORTRAN) that predicts dynamic growth and composition of crops based on plant, soil, management and weather inputs (Boote et al., 1998a). The ability of the CROPGRO model to simulate soil water and N balances, soil organic matter, residue dynamics and pest/disease damage increases its usefulness (Jones et al., 2003; Rymph, 2004). The model is generic in the sense that it uses the same common FORTRAN code to predict the growth of a number of different grain legumes such as soybean [*Glycine max* (L.) Merr.], peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.) (Boote et al., 1998a, 1998b), faba bean (*Vicia faba* L.) (Boote et al., 2002), and velvet bean (*Mucuna pruriens*) (Hartkamp et al., 2002a, 2002b), as well as other

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crops including tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997). This is possible because the internal code of CROPGRO model is generic; and the model uses input files that define species traits and cultivar attributes to represent genetic differences among species and cultivars. These models are part of the DSSAT (Decision Support System for Agrotechnology Transfer) software which provides a user-friendly interface, allowing users to simulate options for crop management over a number of years to assess the risks associated with each option (Jones et al., 2003).

CROPGRO has one generic code that can be used for various crop species, and variation among crop species is described with parameters input in the species file (Boote et al., 1998a). For each species, the CROPGRO species file specifies base temperature (TB) and optimum temperature (Topt) for developmental processes (such as rate of emergence and rate of leaf appearance) and growth processes (photosynthesis, leaf expansion, N mobilization, etc.). In the cultivar file, daylength effect is created with two parameters that define critical daylength and slope of daylength sensitivity, which slows or accelerates development depending on daylength. The species file also includes coefficients and other relationships for photosynthesis, N fixation, tissue composition, growth and maintenance respiration (Boote et al., 2002).

In the 1990s, the “annual” CROPGRO model was adapted to simulate bahiagrass (*Paspalum notatum* Flugge) as a component of a crop rotation system for simulating peanut cropping systems in Florida (Kelly, 1995) and an “annual” *Brachiaria* model was parameterized by Giraldo et al. (2001). The species, cultivar and ecotype files developed were released as “pasture” models in DSSAT v. 3.5 (ICASA, 1998) and later releases. However, these simple “annual” versions of the model were unreliable, particularly for the cooler months when they consistently over-predicted dry matter yields, in part because code limitations did not allow for winter dormancy or re-growth after 100% foliage harvest or freeze-damage (Rymph et al., 2004). The desire for more rigorous applications and use of the model under varying re-growth situations required more realistic representation of the seasonal and rapid patterns of regrowth, including a storage organ for reserves (Rymph, 2004). For these reasons, Rymph (2004) added code to the model to create a true perennial CROPGRO bahiagrass model which included a perennating storage organ (rhizome/stolon) for re-fill of reserves and use of carbohydrate and N reserves for re-growth, as well as dormancy and partitioning that responded to daylength. This coding and more vigorous parameterization and testing was done with the CROPGRO v4.0 growth simulation model, thus conferring the ability to predict growth and tissue N composition of bahiagrass in response to daily weather, N fertilizer and harvest management. The source code for this perennial forage model differs from the standard “annual” CROPGRO model, and the perennial CROPGRO-Forage model developed by Rymph (2004) was used in this study because it includes storage organs, which allows for a better representation of carbon and N partitioning, and consequently patterns of regrowth.

Starting with the perennial CROPGRO Forage model previously calibrated for bahiagrass (Rymph, 2004), our primary objective was to adapt it to simulate the growth and composition of *B. brizantha*, a tropical forage grass of major economic importance in many tropical forage-livestock systems. Our second objective was to describe the process of adapting the model for this new species and genotypes.

2. Materials and methods

2.1. Field data on yield and growth analysis of *Brachiaria brizantha*

The dataset used in this adaptation was collected in a *Brachiaria* spp. genotype field trial conducted at the University of Sao Paulo

“Luiz de Queiroz” College of Agriculture (USP-ESALQ), in Piracicaba, state of Sao Paulo, Brazil (22°42'S, 47°30'W, 546 m asl). Irrigated ‘Xaraes’ palisadegrass plots were periodically clipped over two calendar years, from October 2005 to September 2006 and from October 2007 to September 2008. Plots were harvested to 15 cm stubble height every 28 d from October through March and every 42 d from April through September for a total of 11 growth cycles each year. Plots were 9 by 4 m, replicated four times in the field, on a high-fertility Kandiuclafic Eutrudo soil. Plots were fertilized immediately after each harvest, totaling 220 kg N ha⁻¹ year⁻¹ and 185 kg K ha⁻¹ year⁻¹ applied as (NH₄)₂SO₄ and KCl, respectively. Sprinkler irrigation was supplied (4–12 mm) whenever soil water tension reached 0.30 kPa, as determined by tensiometers at 25 cm depth.

To quantify forage accumulation during regrowth in each plot, forage mass (FM) was sampled at the end of each regrowth by clipping the forage above the 15-cm stubble inside three 0.5-by-2 m quadrats. The two re-growth cycles that occurred around the longest (December 21) and shortest (June 21) days of the year were considered as a representative of spring/summer (“spring/summer cycle”) and autumn/winter (“autumn/winter cycle”), respectively. To facilitate modeling, the stubble mass below 15-cm height was quantified twice per year (spring/summer cycle and autumn/winter cycle) by clipping the stubble mass to soil level, after one of the regular 15-cm harvests. Also each year, the FM harvested during the regrowth of the “spring/summer cycle” and the “autumn/winter cycle” was hand separated into leaf and stem fractions. Leaf area index (LAI) was measured weekly during each regrowth in each plot, including immediately before and after harvest, using a model LAI 2000 plant canopy analyzer (LI-COR, Lincoln, Nebraska, EUA) (Welles and Norman, 1991).

2.2. Model adaptation

The perennial CROPGRO Forage Model adapted and calibrated for bahiagrass (Rymph, 2004), including specific changes to simulate pasture growth, was used as the starting point to this study. The code was considered a reasonable starting point because bahiagrass is a C₄ grass grown in tropical and sub-tropical regions, and the parameters in the species file were initially thought to be similar to those of palisadegrass. The CROPGRO model can be calibrated using parameters listed in species, cultivar and ecotype files. To develop these parameters, we used values and relationships reported in the literature and compared simulated growth with observed values from the above described 2-year experiment in Piracicaba, state of Sao Paulo, Brazil.

Weather data (daily solar radiation, maximum and minimum temperature and rainfall) were collected at a station located 1 km from the experimental site, entered on a daily basis in the weather file for the model, and, are presented here as monthly averages (Table 1). Soil data (clay and silt percentage, and organic carbon) from the experimental area was input in DSSAT and a specific file (.soil) was created using the ‘Sbuild’ default equations (Table 2). The experimental data used in the simulation, including location and crop establishment, were described and entered into an experimental “management” file called “File X”. Planting age (150 days) and transplanting weight (2000 kg ha⁻¹) were adjusted to better characterize pasture initial conditions. Different from row crops, the forage model can be run using transplanting rather than sowing seed, which allows starting a simulation with an already established plant stand.

For this forage model version, we improved the method (and code) for defining forage harvest conditions. A new input file was created, which defines the dates of harvest, the MOW parameter (amount of stubble remaining after harvest), the leaf fraction (in the stubble; RSPLF), corresponding to the time when top growth

Table 1

Monthly weather data at the experimental site during the first (2005–2006) and second (2007–2008) years in Piracicaba, SP, Brazil.

Weather Variable	October	November	December	January	February	March	April	May	June	July	August	September
2005–2006												
Solar radiation (MJ/m ² d)	16.7	21.1	21.4	22.0	18.9	18.9	17.3	14.4	13.8	13.4	17.2	18.3
<i>T</i> _{max} (°C)	30.0	29.1	29.2	30.8	29.8	30.4	27.9	24.9	25.7	26.4	28.6	27.6
<i>T</i> _{min} (°C)	18.2	17.0	17.9	19.6	19.7	19.3	15.9	10.8	10.4	10.8	12.0	13.7
Rain and irrigation (mm)	147.5	128.1	158.4	279.2	234.0	223.3	70.3	77.4	62.6	42.1	89.2	142.8
2007–2008												
Solar radiation (MJ/m ² d)	17.5	19.9	19.5	14.2	13.7	12.4	15.4	16.3	18.7	18.6	21.8	22.4
<i>T</i> _{max} (°C)	31.7	28.5	30.4	28.4	30.2	29.1	27.2	24.3	24.9	26.4	27.5	26.8
<i>T</i> _{min} (°C)	17.4	17.3	18.7	18.7	19.1	18.3	17.0	12.4	12.5	9.8	13.4	13.1
Rain and irrigation (mm)	111.8	157.1	204.1	416.7	191.5	187.7	196.1	118.7	108.6	98.3	133.5	128.4

harvest is simulated. The MOW was set at 2042, 2554, 1672, 1979 kg DM ha⁻¹ and RSPLF 36.0, 56.0, 39.3, 53.2%, respectively, for summer and winter of the first and second years, based on collected data. The measured stubble mass (MOW) characterizes the non-harvestable mass that remains in the field. For palisade-grass, we used different MOW values for the different harvest dates based on observed data because the stubble mass changed over the duration of the experimental period. In addition to MOW and leaf fraction, one other parameter was entered: the MVS parameter (number of leaves left on a primary tiller axis after harvest). This provides the leaf number per main tiller at harvest, which in this study was set at three leaves, based on published data (Alexandrino et al., 2004; Martuscello et al., 2005). The CROPGRO model predicts daily assimilate production based on hourly leaf-level photosynthesis for sunlit and shaded leaf area by simulating the dynamics of Rubisco activity and electron transport, and integrates them within the hourly canopy assimilation approach to yield a daily assimilation rate (Boote and Pickering, 1994). The simulated photosynthesis is sensitive to current temperature, CO₂ concentration, and leaf N concentration. The leaf-level photosynthesis was used in this paper because it is more mechanistic, and it allows for comparison with field measurements of one of the input parameters such as single leaf light-saturated photosynthesis rate (Pedreira and Pedreira, 2007).

The DSSAT crop simulation models include two options for simulating soil organic matter (SOM) and residue dynamics: (1) the PAPRAN model (Godwin and Jones, 1991; Seligman and Van Keulen, 1988) and (2) the CENTURY model (Parton et al., 1988). The CENTURY model converted to daily time step and linked to DSSAT models by Gijsman et al. (2002) was used because it is more flexible in handling different agricultural systems including decomposition of plant litter that falls on the soil during the season and it gave good results when simulating the time-course of the SOM content for long-term experiments as is the case of perennial forage species simulations, the focus of our study. The CENTURY model requires separation of the SOM into three SOM pools; this was done with equations reported by Porter et al. (2009), based on soil clay and silt percent and soil organic carbon from the experimental site. Three soil organic matter (SOM) pools were calculated (SOM 1 = 0.01, SOM 2 = 0.42, and SOM 3 = 0.57) and entered into the SOM fraction file.

Table 2

Soil profile created with the "Sbuild" DSSAT program for the experimental site in Piracicaba, SP, Brazil.

Depth (cm)	Clay (%)	Silt (%)	Organic matter (%)	Lower limit (v/v)	Drained upper limit	Saturated upper limit	Bulk density (g cm ⁻³)	Sat. hydraulic conduct (cm h ⁻¹)	Root growth factor
5	40	22	1.74	0.242	0.366	0.48	1.37	0.38	1.00
15	40	22	1.74	0.242	0.366	0.48	1.37	0.38	1.00
25	40	22	1.10	0.242	0.366	0.48	1.37	0.38	0.87
40	44	22	0.70	0.242	0.366	0.48	1.35	0.40	0.79
55	61	4	0.40	0.24	0.34	0.48	1.15	0.40	0.7
75	61	4	0.40	0.24	0.34	0.49	1.15	0.40	0.62
85	61	4	0.36	0.24	0.34	0.49	1.13	0.40	0.55
200	59	10	0.36	0.25	0.35	0.49	1.13	0.36	0.31

2.3. Statistical evaluation of model performance

Predicted photosynthesis, biomass accumulation and leaf area index (LAI) were compared with observed values, running the model with actual weather, soil and management input data and then parameterizing partitioning and leaf growth parameters for best fit of biomass, leaf, stem, LAI and SLA. For evaluating model performance we used the ratio observed/simulated, root mean square error (RMSE) and the Willmott agreement index (*D*-Stat) (Willmott, 1981; Willmott et al., 1985). Better model prediction is characterized by an observed/simulated ratio close to 1, smaller RMSE and *D*-Stat values also close to 1.

Some parameters were optimized using the generalized likelihood uncertainty estimation (GLUE) method, which consists of a Bayesian method that is useful for analyzing the uncertainty about parameter values (Makowski et al., 2002). The procedure is based on making a large number of simulations with different sets of parameter values and comparing the predicted and observed values for each simulation. Each set of parameter values was assigned a likelihood value indicating the goodness of fit of model performance (Wang et al., 2005). Such representation of the parameter uncertainty can be useful for taking into account risk in model based decision-making (Makowski et al., 2002). Thus, for each parameter for which the GLUE method was used, we took into account the fundamental understanding of how the parameter drives the model as well as the possible parameter range based on the literature or previous knowledge.

3. Results and discussion

3.1. Model adaptation based on the *Brachiaria* dataset

Ideally, model parameterization to estimate potential growth should be done in the absence of water and nitrogen stress allowing for the understanding of the uncontrollable environmental effects (temperature, daylength, soil characteristics, etc.) on biomass accumulation. The soil water balance simulated in CROPGRO did not show that water stress affected photosynthesis, when irrigation and rainfall datasets were entered. Simulated nitrogen stress was not significant for a long-term simulation (simulations not shown),

Table 3

Plant composition, phenology and productivity (photosynthesis and respiration) parameter names, definitions, initial values (bahiagrass) and optimized values (palisadegrass).

Name	Definition	Initial	Optimized values
PRO_G	"Normal growth" protein concentrations of tissue (leaf = LF, root = RT, stem = ST, storage organ = SR).	0.110, 0.040, 0.070, 0.064	0.110, 0.040, 0.070, 0.064
PRO_L	"Maximum" protein concentrations of tissue (leaf = LF, root = RT, stem = ST, storage organ = SR).	0.220, 0.110, 0.101, 0.092	0.220, 0.110, 0.101, 0.092
TB, TO1, TO2, TM	Base temperature (TB), first optimum (TO1), second optimum (TO2), and maximum temperature for vegetative development (TM) (°C)	9.0, 32.0, 40.0, 45.0	10.0, 32.0, 40.0, 45.0
RES30C	Constant (g CH ₂ O per g of dry weight/h) describing maintenance respiration as a function of total crop dry weight (minus oil, protein, and starch in the seed). Temperature dependent	3.5E–05	3.0E–04
MRSWITCH	Respiration: M = Mass-based/original CROPGRO code or P = Protein-based	P	M
LFMAX	Maximum leaf photosynthetic rate at 30 °C, 350 ppm CO ₂ , and high light	1.76	1.89
FNPGN (1–2)	Leaf nitrogen effect on PG or FNPGN (4) and TYPPGN—A two-sided quadratic curve describing leaf photosynthesis response to leaf N concentration. Increases from zero at the minimum leaf N concentration to maximum at the maximum leaf N concentration.	0.75, 3.00	0.80, 4.00
SLWREF	Specific leaf weight at which LFMAX is defined (g m ^{–2})	0.0100	0.0078
R30C2	Constant, g CH ₂ O per g of photosynthate CH ₂ O per hour describing maintenance respiration as a function of canopy photosynthesis. Temperature dependent	0.0029	0.0024

and this is probably related to the high soil organic matter (1.74%) and the nitrogen supplied after each harvest (20 kg ha^{–1}).

We accepted bahiagrass plant composition parameters values (Table 3) which give simulated crude protein (CP) concentrations from 7 to 11% in vegetative tissues, and between 9 and 15% in leaf tissue. These simulations are close to values reported by Nave et al. (2010), who studied palisadegrass nutritive value under 28-d cycles, and found that CP concentrations in above-stubble forage (above 15 cm) and leaves ranged between 9.3 and 13.4% and 10.3 and 15.5%, respectively. Therefore, no changes were needed for composition parameters.

Phenology is driven in the model by a set of four temperature (°C) parameters: base temperature (TB), first optimum (TO1), second optimum (TO2), and maximum temperature for vegetative development (TM). We increased TB from 9 to 10 °C. The other temperature parameters (TO1, TO2 and TM) were maintained similar to those of bahiagrass (Table 3).

Parameters that influence productivity were also adjusted (Table 3). One of these parameters refers to maintenance respiration as a function of total crop dry weight (RES30C), which was increased. Respiration options can be set to either mass- or protein-based, and we decided to simulate mass-based instead of protein-based respiration, because there is limited nitrogen information for palisadegrass. Maximum leaf photosynthetic (LFMAX) was increased slightly to match field-measured values. The leaf photosynthesis response to leaf N concentration (FNPGN) was modified, increasing the N concentration for maximum photosynthesis to 4.0%. Specific leaf weight at which LFMAX is defined (SLWREF) and maintenance respiration as a function of canopy

photosynthesis (R30C2) was reduced based on GLUE optimization with biomass and leaf photosynthesis data (Table 3). This allowed the model to simulate higher leaf and canopy photosynthesis and, consequently, more accurate higher productivity.

3.1.1. Senescence parameters

A set of senescence parameters was modified to improve simulations (Table 4). According to Silveira et al. (2010), the leaf life span of four cultivars of palisadegrass was between 45 and 74 days under free growth. However, when life span was measured under different grazing managements, it resulted in values around 35–40 days (Marcelino et al., 2006). Thus, natural leaf senescence rate (LFSEN) was increased to 0.02, which means that a leaf has approximately 50 (physiological) days of lifespan unless accelerated by self-shading (discussed later). Similarly, stems, roots and storage tissues also senesce as the plant ages. The senescence rate of leaves, stems, roots, and storage organs (SENSR) is a function of age/temperature (physiological days). Root senescence (RTSEN) was kept at 0.008 (0.8% per day), but SENSR was increased to 0.11% per day to increase storage tissue turnover and reduce total storage tissue mass.

In addition, other senescence parameters including stem senescence as a function of the senesced leaf mass (PORPT), light compensation point for senescence of lower leaves (ICMP), and a time constant for senescence of lower leaves (TCMP) when under shade stress (<ICMP), were all optimized based on the GLUE method (Table 4). The PORPT can be considered equivalent to the amount of leaf sheath that senesces when a given mass of leaf blade senesces.

Table 4

Senescence parameter names, definitions, initial values (bahiagrass) and optimized values (palisadegrass).

Name	Definition	Initial	Optimized values
LFSEN	Natural leaf senescence rate/photothermal day (0.02 means 50 d of life span)	0.01	0.02
RTSEN	Root senescence (fraction per physiological day)	0.008	0.008
ICMP	Light compensation point (mol PPFD m ^{–2} d ^{–1}) for senescence of lower leaves because of excessive self-shading by the crop canopy.	0.80	1.17
TCMP	Time constant (days) for senescence of lower leaves because of excessive self-shading by the crop canopy.	25.0	13.1
PORPT	Stem senescence as a function of the senesced leaf mass (fraction)	0.02	0.27
SENSR	Senescence rate of storage organ tissue (proportion of cumulative storage mass lost/physiological day).	0.007	0.011

Table 5
Vegetative partitioning, specific leaf area, temperature and photoperiod parameter names, definitions, initial values (bahiagrass) and optimized values (palisadegrass).

Name	Definition	Initial	Optimized values
XLEAF VALUES	Leaf number or vegetative stage at which the partitioning is defined	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0, 40.0	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0, 40.0
YLEAF VALUES	Describes dry matter partitioning to leaf among vegetative tissue only, as a function of vegetative stage (fraction)	0.60, 0.40, 0.30, 0.25, 0.20, 0.20, 0.20, 0.20	0.80, 0.80, 0.80, 0.75, 0.50, 0.40, 0.40, 0.40
YSTEM VALUES	Describes dry matter partitioning to stem among vegetative tissue only, as a function of vegetative stage (fraction)	0.10, 0.10, 0.10, 0.10, 0.05, 0.05, 0.05, 0.05	0.10, 0.10, 0.17, 0.17, 0.15, 0.16, 0.16, 0.16
YSTOR VALUES	Describes dry matter partitioning to storage among vegetative tissue only, as a function of vegetative stage (fraction)	0.15, 0.20, 0.30, 0.40, 0.45, 0.50, 0.50, 0.50	0.01, 0.01, 0.01, 0.02, 0.02, 0.03, 0.03, 0.03
SLAVR	Specific leaf area of cultivar under standard growth conditions ($\text{cm}^2 \text{g}^{-1}$)	100	170
SLAMAX	SLAMAX is the (thinnest) leaves under low light ($\text{cm}^2 \text{g}^{-1}$)	200	358
SLAMIN	SLAMIN is the (thickest) leaves under high light ($\text{cm}^2 \text{g}^{-1}$)	100	130
FNPGL (1–2)	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) ($^{\circ}\text{C}$)	7.0, 22.0	7.6, 20.9
XLMAXT (2–3)	Relative rate of photosynthetic electron-transport in response to temperature, linear from base (0.0) to maximum (1.0) ($^{\circ}\text{C}$)	12.0, 45.0	10.4, 38.0
XSLATM (3–4)	Relative temperature effect on specific leaf area of newly formed leaves ($^{\circ}\text{C}$, X vs. Y pair)	10.0, 30.0	11.0, 26.0
YSLATM (3–4)	Relative temperature effect on specific leaf area of newly formed leaves (fraction reduction, X vs. Y pair)	0.25, 1.00	0.29, 1.00
FNPTD (2–3)	Daylength effect on partitioning (h)	10.5, 12.5	10.3, 15.2
FNPMD (1–3)	Daylength effect on mobilization (h)	10.5, 12.5, 0.10	10.1, 14.5, 0.46
RDRMT	Relative dormancy sensitivity of this cultivar—daylength effect on partitioning	1.000	0.405
RDRMM	Relative dormancy sensitivity of this cultivar—daylength effect on mobilization	1.000	0.532

3.1.2. Partitioning of dry matter to leaf, stem and root

Initial simulations with palisadegrass showed the need to modify partitioning parameters (YLEAF, YSTEM and YSTOR values, Table 5) to increase allocation to leaf and stem growth (Table 6), while allocating less to storage organ growth. During the initial seedling growth phase, bahiagrass parameters prioritized partitioning to leaf, and so did palisadegrass. As plant age increases (in bahiagrass), partitioning shifts to increase storage/rhizome mass, while stem proportion remains low and varies little. Palisadegrass is different from bahiagrass, however, in that it has a tufted, upright growth habit (Pedreira et al., 2007) and has considerable vegetative stem elongation, combined with high amounts of leaf mass (Pedreira et al., 2009). This results in considerable accumulation of stem as well as leaf tissue during regrowth, resulting in increases in herbage mass and sward height (Braga et al., 2006, 2008).

3.1.3. Prediction of specific leaf area and leaf area index

Simulated and observed specific leaf area for palisadegrass showed annual variation associated with seasonal variation in light and temperature (Fig. 1). The SLAVR (Table 5) was set to $170 \text{ cm}^2 \text{g}^{-1}$ for the standard reference cultivar at peak early vegetative phase, under standard growth conditions (optimum temperature, water, and high light). In addition, simulated SLA is reduced by cool temperature or water deficit and increased under low light. The thinnest (SLAMAX) and thickest (SLAMIN) leaves under low and high light, respectively, and the temperature effect on SLA (XSLATM and YSLATM, Table 5) of newly produced leaves were optimized using the GLUE method relative to the data in Fig. 1. The rate of leaf appearance on the main stem (TRIFL) was kept at 0.15 leaves per thermal day because it was similar to val-

ues reported in the literature for palisadegrass (Alexandrino et al., 2004; Marcelino et al., 2006; Rodrigues et al., 2008; Sbrissia and Da Silva, 2008).

Leaf area index cycled during successive regrowths (Fig. 2), indicating a reasonably good prediction of the regrowth of LAI during each cycle. In the winter, the simulated LAI was not as well predicted as during the growing season, and this can be associated with large amounts of dead material on pastures during the cool season. This is probably associated with the equipment used in these measurements (LAI-2000 canopy analyzer) which can overestimate LAI due to its reading of high amounts of dead material that register as leaf area.

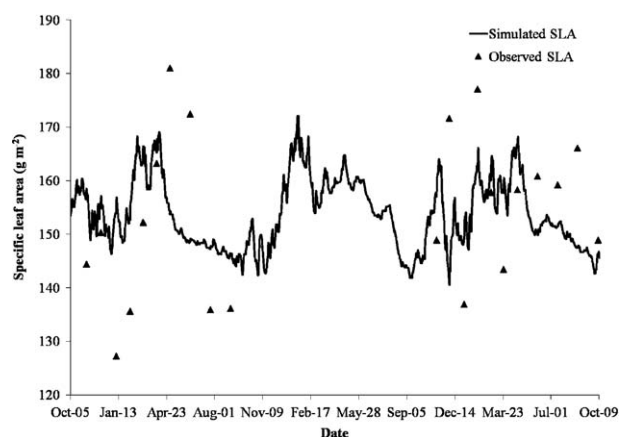


Fig. 1. Specific leaf area simulated as a function of date over 3 years for palisadegrass in Piracicaba, SP, Brazil.

Table 6

Comparison of mean values of observed and simulated leaf and stem percentage on the first and last day of the regrowth cycle, during the first (2005–2006) and second (2007–2008) experimental years, as a function of date for palisadegrass in Piracicaba, SP, Brazil.

Season		Date	Leaf (%)		Stem (%)	
			Observed	Simulated	Observed	Simulated
Summer	Post-harvest	8 December 2005	39.3	38.9	60.7	61.0
	Pre-harvest	8 January 2006	62.1	65.5	37.9	34.5
Winter	Post-harvest	12 June 2006	55.5	56.0	44.5	44.0
	Pre-harvest	23 July 2006	57.6	58.6	42.4	42.4
Summer	Post-harvest	3 December 2007	37.9	39.3	62.1	60.7
	Pre-harvest	2 January 2008	69.1	47.8	30.9	34.0
Winter	Post-harvest	4 June 2008	51.9	53.2	48.1	46.8
	Pre-harvest	15 July 2008	59.6	61.0	40.4	39.0

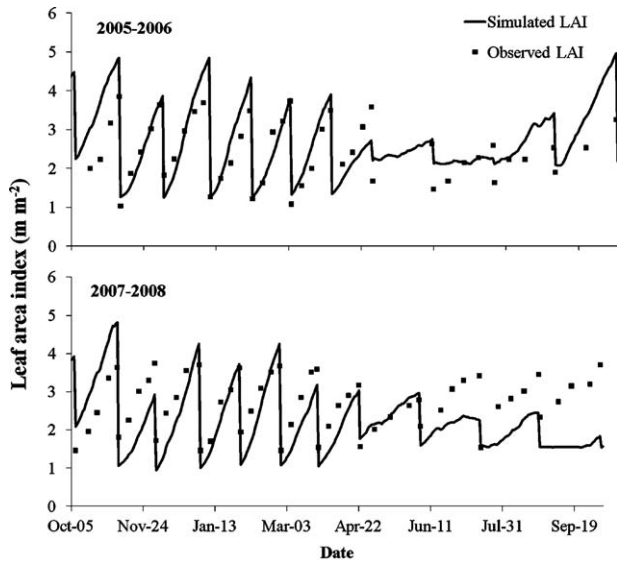


Fig. 2. Leaf area index simulated vs. observed during the first (2005–2006) and second (2007–2008) experimental years, as a function of date for palisadegrass in Piracicaba, SP, Brazil.

In the model calculations, LAI is a cumulative result of daily assimilate from photosynthesis, the fraction of assimilate partitioned to leaves, and the resulting SLA under those conditions. Adjustments of the leaf fraction in the stubble (RSPLF) affected the percentage of leaf as well. The optimization of SLA and partitioning parameters improved the statistical indices in Table 7.

Shifts in photosynthate partitioning to storage organs are triggered by decreased photoperiod and temperature in many tropical grasses such as *Cynodon* spp. (Pedreira et al., 2000), *Pennisetum* spp. (Macon et al., 2002), *Hemarthra altissima* (Newman and Sollenberger, 2005), and *Andropogon gerardii* Vitman (Mousel et al., 2005). Other species such as ryegrass (*Lolium perenne* L.) (Lee et al., 2008; Ourry et al., 1988, 1990, 1994) and palisadegrass (Miles et al., 1996; Rodrigues et al., 2007) are not rhizomatous, and thus do not allocate significant amounts of photosynthate to specific storage organs. Instead, reserves are normally found in tiller bases and roots, and can be remobilized to fuel leaf regrowth after defoliation.

Table 7

Comparison of mean values of observed and simulated growth variables and their statistics for palisadegrass in Piracicaba, SP, Brazil during two years (2005–2006, 2007–2008).

Parameter	Observed	Simulated	RMSE	Ratio	D-Stat
Leaf weight (kg DM ha ⁻¹)	1431	1581	291	1.098	0.953
Stem weight (kg DM ha ⁻¹)	1080	1167	144	1.076	0.824
Biomass (kg DM ha ⁻¹)	3358	3573	538	1.070	0.838
SLA (cm ² g ⁻¹)	153.7	154.0	15.5	1.040	0.386
LAI (m ² m ⁻²)	2.58	2.47	0.70	0.965	0.816

Based on the contrasting characteristics between palisadegrass and bahiagrass, changes were made in the model partitioning parameters to allow for more stems but less root and storage, while keeping the leaf portion high. Allocation of reserves to storage organs is driven by dormancy functions that increase partitioning of assimilate to stolon and reduce mobilization from stolon and roots under short daylengths. These are features found necessary to simulate seasonal growth dynamics and winter dormancy of bahiagrass (Rymph, 2004).

It is important to emphasize that, in order to mimic lower palisadegrass seasonal production in this tropical latitude, in relation to decreased mean temperature and daylength during the “winter” months (April–September), similar “dormancy” adjustments were needed in some parameters although not as strongly as for bahiagrass (Table 5). Thus, the GLUE optimization was used to solve for sensitivity of single-leaf light-saturated photosynthesis rate to minimum night temperature (FNPGI, Table 5), and the function describing relative rate of photosynthetic electron-transport in response to current temperature (XLMAXT). These parameter adjustments to temperature sensitivity of photosynthesis (FNPGI and XLMAXT) and SLA of newly formed leaves (XSLATM and YSLATM) resulted in improvements to the prediction of winter versus summer season biomass regrowth dynamics.

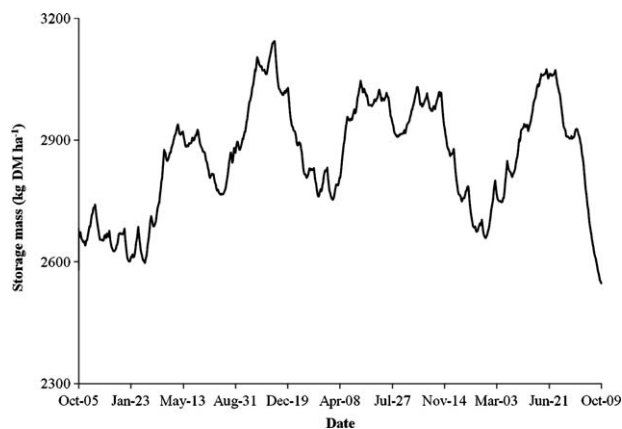
Changes were made to the daylength effect on mobilization and partitioning (FNPMMD, FNPTD), and relative dormancy sensitivity of this species to daylength affecting partitioning (RDMRT) and mobilization (RDRMM), to make palisadegrass less sensitive to photoperiod (Table 5). This was done by reducing the relative sensitivity (smaller RDMRT and RDRMM) and increasing the range of daylengths over which mobilization and partitioning are affected. The simulated stolon/rhizome (Fig. 3) and root (Fig. 4) tissues show cycling in response to annual daylength variations. *Brachiaria* genotypes do not have rhizomes or stolons; rather organic reserves as total non-structural carbohydrates (TNC) and nitrogen (N) are stored in stem bases and roots (Reis et al., 1985; Rodrigues et al., 2007). We assumed that the storage organ in this simulation was in the stem bases and roots (but in the model the simulated storage organ has no positional location and is not removed by harvesting).

If grazing or harvesting allows more residual leaf area, regrowth will be less dependent on reserves because the remaining leaf area provides photosynthate to synthesize new tissue from current photosynthesis. On the other hand, when grazing is severe and little or no leaf area is left, new growth will depend on the existence of

Table 8

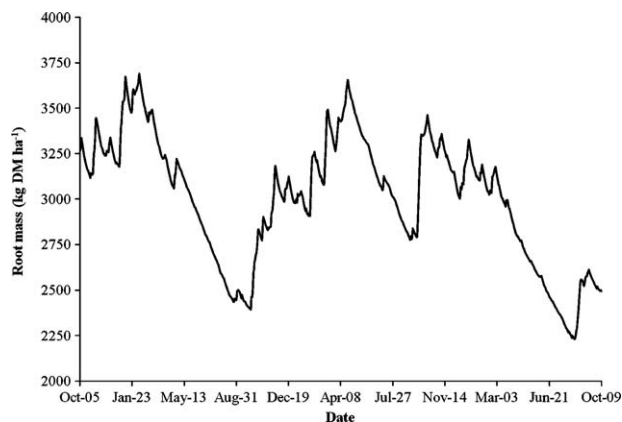
Carbohydrate and nitrogen mobilization and refill parameter names, definitions, initial values (bahiagrass) and optimized values (palisadegrass).

Name	Definition	Initial	Optimized values
CMOBSRN	Minimum daily rate of CH ₂ O mobilization from storage (fraction)	0.020	0.020
CMOBSRX	Maximum daily rate of CH ₂ O mobilization from storage (fraction)	0.050	0.050
NMOBSRN	Minimum daily rate of N mobilization from storage (fraction)	0.010	0.010
NMOBSRX	Maximum daily rate of N mobilization from storage (fraction)	0.060	0.060
ALPHSR	Fraction of new storage tissue growth that is available CH ₂ O (fraction)	0.30	0.20
CADPV	Maximum fraction of photoassimilate available that can be allocated to CH ₂ O refill during non-stress conditions	0.07	0.437
LRMOB (3–4)	LAI effect on mobilization	0.5, 1.50	0.44, 1.03
CRREF (2–4)	Carbohydrate status effect on refilling of storage tissue CH ₂ O pool	0.25, 0.75, 0.25	0.30, 0.77, 0.29
LRREF (2–3)	LAI effect on refilling of storage tissue CH ₂ O pool	0.50, 3.00	0.65, 2.41
PRREF (1–2)	Canopy photosynthesis effect on refilling of storage tissue CH ₂ O	0.20, 0.45	0.30, 0.45
CMOBMX	Maximum mobilization of CH ₂ O from vegetative tissues, fraction of available CH ₂ O pool per day	0.025	0.050
NMOBMX	Maximum mobilization of protein from vegetative tissues, fraction of available protein pool per day	0.02	0.088

**Fig. 3.** Stolon/rhizome weight simulated as a function of date over 3 years for palisadegrass in Piracicaba, SP, Brazil.

organic reserves, with slow initial regrowth rates (Donaghy and Fulkerson, 2002; Rodrigues et al., 2007).

In order to ensure the dynamics of regrowth patterns, some parameters for carbohydrate and nitrogen mining (Table 8) were kept similar to those of bahiagrass, including minimum and maximum rates of carbon and nitrogen mobilization from storage (CMOBSRN, CMOBSRX, NMOBSRN and NMOBSRX, respectively). Other parameters, however, were optimized (Table 8) using the GLUE method, to adjust the concentration of carbohydrate in newly produced storage tissue (ALPHSR), the fraction of daily assimilation that can be allocated to storage tissues (CADPV), and the LAI effect

**Fig. 4.** Root weight simulated as a function of date over 3 years for palisadegrass in Piracicaba, SP, Brazil.

on mobilization (LRMOB). For example, mobilization from reserves (to drive re-growth) is accelerated above a base rate, if LAI is less than the upper threshold (1.03 value in LRMOB in Table 8). Carbohydrate status, LAI and canopy photosynthesis effects on routine refilling of mobile carbohydrates (CRREF, LRREF and PRREF, respectively) were also optimized. These three enhance refill of storage tissue as a function of lower current storage reserve level, greater LAI, and greater canopy photosynthesis. Maximum rate (fraction per day) of mobilization of carbohydrate (CMOBMX) and protein (NMOBMX) from non-storage vegetative tissues was adjusted to allow for leaf, stem and root concentration dynamics during the cycles.

The model modifications reported above allowed for improved regrowth patterns as shown in Fig. 5. During the spring, when the growing season starts and the environmental conditions are favorable, the simulation shows a more rapid increase in biomass along with increase in root tissue but relatively stable storage tissue (Fig. 5a). Conversely, in autumn, biomass increases at lower rates while root is reduced and storage tissue is maintained (Fig. 5b). In both spring and autumn cycles, the storage tissue shows small cycling effects of decline in storage tissue for 2 weeks after harvest followed by storage tissue growth in the subsequent 2–4 weeks as LAI and photosynthesis increase.

3.1.4. Biomass accumulation

The default parameters of the perennial CROPGRO Forage model were modified from bahiagrass values in order to simulate more leaf and stem growth, along with less root growth. At the same time improvements were made in simulation of SLA, as well as senescence of various plant organs (leaf, stem, root, and storage). After these changes, biomass accumulation was better simulated (Fig. 6) with better ratio and *d*-statistics index (Table 7), despite the fact that observed and predicted values were quite different from each other in the second winter. Observed field data values in the second winter were lower than those of the first winter, which decreased model precision, but simulated biomass values were close to expected. Because the plots were harvested using a mower, stubble mass (mainly stems and dead material) increased from the first to the second year of data collection. This may have been magnified by the fact that between the end of the first and the beginning of the second experimental years, plots were kept under the same clipping schedule for a whole year, without data collection. This may have had a negative impact on regrowth in the second winter, reducing light penetration into the canopy and reducing basal tillering, ultimately decreasing forage accumulation. In early spring, when environmental conditions improved, plants were expected to re-establish rapid growth patterns, but this did not happen. It seems that even under good conditions, there is a lag

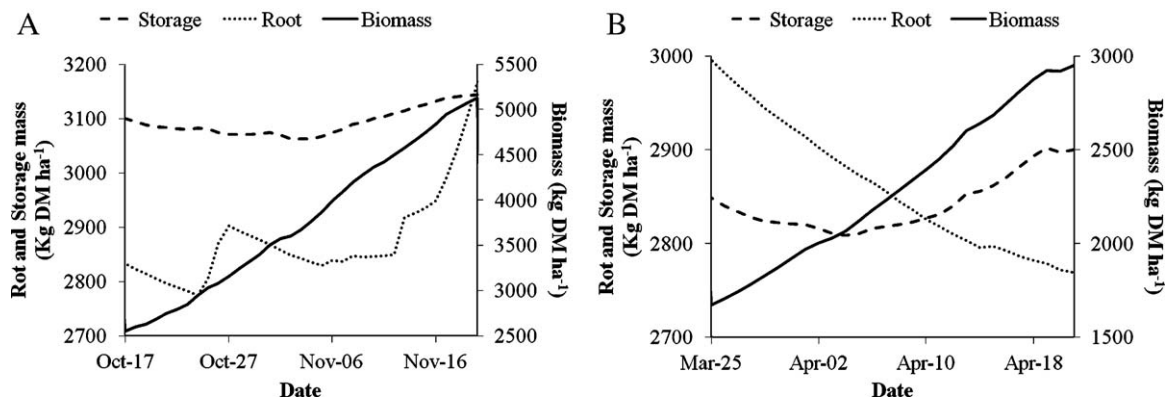


Fig. 5. Dynamics of biomass, storage and root, during single spring (A) and autumn (B) regrowth cycles, as a function of time for palisadegrass in Piracicaba, SP, Brazil.

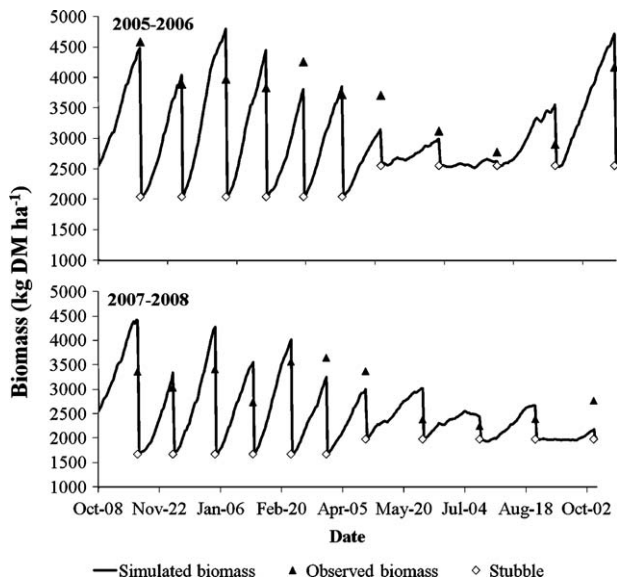


Fig. 6. Biomass simulated vs. observed, during the first (2005–2006) and second (2007–2008) experimental years, as a function of time for palisadegrass in Piracicaba, SP, Brazil.

between the onset of favorable weather for vegetative growth and resumption of growth. The cause of this delay is unknown, but may involve carbon partitioning during that transition stage, possibly to roots, particularly if root senescence during winter is substantial (and more than we simulated).

In addition, adjustments were needed in temperature and photoperiod effects. Our results indicate that palisadegrass growth and

composition can be simulated using the perennial CROPGRO Forage Model, although additional validation should be done using independent datasets before the model is released for general use.

3.2. Sensitivity analysis: temperature, daylength, solar radiation, and rainfall

The model showed sensitivity to temperature (-2 and $+2$ °C; Table 9) throughout the year. In general, when temperature was reduced by 2 °C, biomass accumulation decreased, mainly during the winter and autumn. The forage accumulation was decreased on average by 840 kg DM ha $^{-1}$ or 43% in each of the two cool seasons. When temperature was increased by 2 °C, the simulated biomass accumulation increased, although in the summer and second spring, biomass decreased because of increased simulated water deficit.

Studies under controlled environments have shown that grass growth responds to daylength (Marousky et al., 1992). In addition, sensitivity to daylength can have a great impact on the relative growth of grasses under natural conditions. When daylength was increased ($+1$ h, super-imposed on the natural yearly cycle of daylength in the model) simulated biomass yield was enhanced throughout the year (Table 9). Biomass yield was increased by 1230 kg DM ha $^{-1}$ per season on average under simulated longer days. When daylength was shortened (-1 h) yields decreased by a similar magnitude (Table 9). The shorter daylength has the effect of causing more partitioning to storage organ and slower use of reserves for regrowth which would lead to less production. Increasing solar radiation ($+1$ MJ m $^{-2}$ d $^{-1}$) increased production by 110 kg DM ha $^{-1}$ per season on average, while reduction of solar radiation decreased yields by about the same magnitude. The smaller response to 1 MJ m $^{-2}$ d $^{-1}$ of solar radiation should not be

Table 9

Temperature, daylength, solar radiation, and rainfall sensitivity analyses for herbage dry matter production^a (total kg DM ha $^{-1}$ per season) of palisadegrass in Piracicaba, SP, Brazil.

Year	Season ^b	Standard conditions (kg DM ha $^{-1}$)	Temperature (°C)		Daylength (h)		Solar radiation (MJ m $^{-2}$ d $^{-1}$)		Rainfall (%)	
			-2	$+2$	-1	$+1$	-1	$+1$	-10	$+10$
2005–2006	Spring	5453	−1022	244	−1199	774	−271	233	63	−27
	Summer	6814	−434	−284	−1704	1605	−70	196	−34	18
	Autumn	2293	−874	660	−1053	1190	−58	77	−16	67
	Winter	1870	−1039	840	−1887	1198	−67	32	11	8
2007–2008	Spring	5120	−325	−186	−1447	1380	−151	66	−80	62
	Summer	6938	−173	−203	−1671	1544	−272	224	36	−7
	Autumn	2963	−866	355	−1277	1382	−115	56	−39	6
	Winter	773	−584	734	−518	811	−11	8	14	5

^a Growing cycles were 28-d long in Spring/Summer and 42-d long in Autumn/Winter.

^b Spring (September 21 to December 21), Summer (December 21 to March 21), Autumn (March 21 to June 21), and Winter (June 21 to September 21).

taken as insensitivity, because this is a small step that amounts to less than a 5% change in solar radiation. When rainfall was increased by 10%, herbage production did not change significantly, because this was an irrigated trial without water deficit. In addition, there are some negative values, caused by simulated water excess in the soil. When rainfall was reduced (–10%), biomass production decreased at times when there was higher growth with possibility of water deficit (first summer and second spring) or only when water deficit was possible (autumn). These tests show that the model is sensitive to solar radiation and rainfall, which are very important for biomass accumulation. The variation in biomass caused by temperature and daylength changes shows the sensitivity of these variables on the model performance.

3.3. Adaptation process: advantages and difficulties

Changes in rate of herbage biomass production by perennial grasses during the transition from summer to winter in tropical areas are likely influenced by fall dormancy and relate to shifts in daylength and temperature regimens. In the spring, regrowth under favorable environmental conditions in tropical grasses is also triggered by daylength and temperature. Daylength sensitivity in the model may require improvement to achieve better simulation during winter. Even grasses that have low sensitivity to daylength show reduction in forage accumulation during the short-daylength months (Sinclair et al., 2001). The decrease in growth occurs despite the fact that there appears to be adequate soil moisture, soil fertility, and sufficiently high temperatures that would allow for substantially greater yields (Sinclair et al., 2003).

Early in the growing season (September–October), simulated values were higher than observed data. Marousky et al. (1992) demonstrated that longer days increased leaf length but did not increase stolon number or plant dry weight. This is likely the case with palisadegrass in early spring, when environmental conditions are favorable (increasing temperature, longer daylength, higher available soil moisture) but plants do not respond in terms of biomass accumulation. The model already accounts equally for short daylength or cool temperature effects on shortening or rising daylengths, so there may be some “carry-over” effect of winter dormancy that limits the forage re-growth potential in early spring (September–October) that the model is not accounting for. This may require new thinking as to how to create this carry-over effect on regrowth and production potential. In order to better mimic the biology of perennial tropical grasses, such modifications may be needed in the current crop model concepts and codes.

In addition, well defined initial conditions are an important aspect when working with forages, as one will often start using an already established stand and thus want to simulate growth in the model from that point onwards. The use of new code for herbage harvest, for direct parameterization of proportion of leaf fraction remaining (RSPLF), in addition to the ability to define the residual stubble mass (MOW) itself, improved the ability to simulate post-harvest condition, compared to the previous model version.

4. Conclusion

The results of the adaptation indicate that the CROPGRO-Perennial Forage Model is effective in integrating the knowledge about physiology of *B. brizantha* and can be used to simulate growth with acceptable accuracy. The model is sensitive to temperature, daylength, solar radiation, and rainfall. Additional data collection and validation should be carried out to test these results, so that the model may be used as a decision-making tool in production and research, simulating seasonal forage production, predicting response patterns to water and fertilizer, and supporting recom-

mendations as to whether a specific forage genotype is adapted to a set of environmental conditions. Areas of the model that need to be further improved for palisadegrass include the productivity and herbage composition response to N fertilization, because this trial was conducted under reasonably high N fertility. In addition, additional data on leaf and stem mass is needed for improving partitioning, and data on root mass is needed to verify partitioning to root. Senescence rates of leaf blade, leaf sheath, stem, root, and storage organs need to be verified.

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