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Agronomic performance and adaptation of the CROPGRO - Perennial Forage Model to predict growth of three tropical forage grasses under irrigated and rainfed conditions

Diego Noleto Luz Pequeno

Thesis presented to obtain the degree of Doctor in Science. Area: Animal Science and Pastures

Piracicaba
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RESUMO

Respostas agronômicas e adaptação do modelo CROPGRO - Perennial Forage para predição de crescimento de três genótipos forrageiros tropicais sob condição irrigada e não-irrigada

As gramíneas do gênero *Brachiaria* e *Cynodon* são algumas das pastagens cultivadas introduzidas no Brasil de maior importância. Convert HD 364, um novo híbrido de *Brachiaria*, foi lançado como uma opção para uso numa ampla gama de condições ambientais, com alto valor nutritivo e produção de forragem. Sistemas pecuários em pastagens são complexos e as interações entre os animais, as plantas e o meio ambiente existem em vários níveis de complexidade, que podem ser avaliados utilizando modelagem computacional. Acúmulo de forragem, proteína bruta (PB), fibra em detergente neutro (FDN), digestibilidade *in vitro* da matéria orgânica (DIVMO), a composição morfológica da planta, fotossíntese foliar, índice de área foliar (IAF) e interceptação luminosa (IL) foram avaliados em resposta à duas frequências de colheita (28 e 42 dias), irrigada e não irrigada, em um estudo com parcelas colhidas mecanicamente a partir de abril de 2011 até abril de 2013, contrastando os capins Convert HD 364® (*Brachiaria* híbrida CIAT 36061), Marandu {*Brachiaria brizantha* (Hochst. ex A. Rich.) RD Webster [syn. *Urochloa brizantha* (A. Rich.) Stapf]; CIAT 6297} e Tifton 85 (*Cynodon* spp.). O delineamento experimental utilizado tanto para o irrigado quanto para o não irrigado foi de blocos casualizados, com quatro repetições. Convert HD 364 teve acúmulo de forragem anual, produção sazonal de forragem e taxa de acúmulo de forragem semelhante ou superior ao Marandu e Tifton 85, (acúmulo de forragem 15% maior do que Marandu e 12% maior do que o Tifton 85, quando irrigado e colhido em intervalos de rebrotação mais curtos). Convert HD 364 teve boa distribuição sazonal de forragem total do ano, produzindo cerca de 30% da massa total de forragem durante a estação fria, em Piracicaba, semelhante ao Marandu. Tifton 85 produziu cerca de 20% do seu rendimento médio anual durante a estação fria. Tifton 85 teve PB maior do que as outras duas gramíneas, quando colhidas em intervalos mais curtos e quando irrigadas. A concentração de FDN em Convert HD 364 foi menor do que nas outras gramíneas, independentemente da irrigação, da frequência de colheita e das estações do ano, resultando em alta DIVMO (mais de 650 g kg^{-1}), semelhante à do capim Marandu. Em relação à calibração do CROPGRO, em geral, o desempenho do modelo foi bom para as três gramíneas. Simulações de massa de folha e colmo foram melhoradas para os capins, devido ao aumento na partição de assimilados direcionados para colmo em condição de baixa freqüência de colheita. O IAF e IL foram bem simulados pelo modelo, mostrando aumento com a diminuição da freqüência de colheita, com exceção do Tifton 85. Em condição não irrigada, as simulações utilizando o método de Penman -Monteith - FAO 56 deram respostas mais realistas de estresse hídrico do que usando o método de Priestley e Taylor. Os resultados da calibração sugerem que o modelo CROPGRO – forragem perene pode ser usado para simular adequadamente o crescimento de Marandu, Convert HD 364 e Tifton 85 sob condições irrigadas e não irrigada, sendo capaz de simular diferentes manejos de frequência de desfolhação.

Palavras-chave: Acúmulo de forragem; Digestibilidade i*n vitro* da matéria orgânica; DSSAT; Fibra em detergente neutro; Marandu; Mulato II; Proteína bruta; Tifton 85; Valor nutritivo

ABSTRACT

Agronomic performance and adaptation of the CROPGRO - Perennial Forage Model to predict growth of three tropical forage grasses under irrigated and rainfed conditions

Grasses of the genera *Brachiaria* and *Cynodon* are some of the most important pasture introductions in Brazil. Convert HD 364 brachiariagrass, a new *Brachiaria* hybrid, was released as an option for a broad range of environmental conditions, high nutritive value and forage production. Forage-based livestock systems are complex and interactions among animals, plants, and the environment exist at several levels of complexity, which can be evaluated using computer modeling. Herbage accumulation, crude protein (CP), neutral detergent fiber (NDF), *in vitro* organic matter digestibility (IVOMD), plant-part composition, leaf photosynthesis, leaf area index (LAI), and light interception (LI) were evaluated as affected by two harvest frequency (28 and 42-days), irrigated and rainfed in a clipping study from April 2011 to April 2013, contrasting Convert HD 364® brachiariagrass (*Brachiaria* hybrid CIAT 36061), Marandu palisadegrass {*Brachiaria brizantha* (Hochst. ex A. Rich.) R. D. Webster [syn. *Urochloa brizantha* (A. Rich.) Stapf]; CIAT 6297}, and Tifton 85 bermudagrass (*Cynodon* spp.). The experimental design for both the irrigated and the rainfed trials was a randomized complete block with four replications. Convert HD 364 had similar or higher annual herbage accumulation, seasonal yield and herbage accumulation rate than Marandu and Tifton 85, (15% more herbage accumulation than Marandu and 12% more than Tifton 85 when irrigated and when harvested at shorter regrowth intervals). Convert HD 364 had good seasonal distribution of total annual herbage produced and accumulates about 30% of the total herbage mass during the cool season in Piracicaba, similar to Marandu. Tifton 85 produced around 20% of its average annual yield during dry season. Tifton 85 forage had higher CP concentration than the other two grasses when harvested at shorter intervals and when irrigated. The NDF concentration in Convert HD 364 was lower than in the other grasses regardless of irrigation treatment, harvest frequency, and season of the year, resulting in high IVOMD (more than 650 g kg^{-1}), similar to that of Marandu. Regard to CROPGRO calibration, in general the model performance was good for the three grasses. Leaf and stem weight simulations were improved, due to increase partitioning to stem for low harvest frequencies. The LAI and LI were well performed by the model, showing increase for lower harvest frequency, with exception to Tifton 85. Under rainfed conditions, the simulations using the Penman-Monteith-FAO 56 method gave more realistic water stress responses than using the Priestley and Taylor method. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Marandu, Convert HD 364, and Tifton 85 under irrigated and rainfed conditions, being able to simulate different harvest frequency managements.

Keywords: Crude protein; DSSAT; Herbage accumulation; *In vitro* organic matter digestibility; Marandu; Mulato II; Neutral detergent fiber; Nutritive value; Tifton 85

1 INTRODUCTION

Mathematical modeling for decision support in the Brazilian livestock industry is a topic of increasing interest to plan the feed supply throughout the year and to evaluate different market strategies (BARIONI et al., 2006). Several approaches have been used to simulate pasture growth and biomass production, most of them using meteorological variables. However, most approaches have been developed under optimal conditions with no water stress and with good nutrient supply. Cruz (2010) used the CROPGRO model to simulate rainfed Marandu palisadegrass {*Brachiaria brizantha* (Hochst. ex A. Rich.) R. D. Webster [syn. *Urochloa brizantha* (A. Rich.) Stapf]; CIAT 6297} in São Carlos, state of São Paulo, Brazil, and reported an underestimation of the biomass production attributed to water and nutritional stress. Pedreira (2009) reported the same underestimation of biomass production, leaf area index, and light interception simulations of rainfed Xaraes palisadegrass [*Brachiaria brizantha* (Hochst ex A. RICH.) STAPF. cv. Xaraes] growth in Piracicaba, state of São Paulo, Brazil. Tonato et al. (2010) studied the effect of photoperiod, temperature, and solar radiation on forage accumulation of *Cynodon*, *Brachiaria*, and *Panicum* grasses, irrigated and well fertilized, in Piracicaba, and pointed out that the use of dataset from experiments on ideal conditions of water and nutrient supply can limit the application of the models when applied to rainfed and/or non-fertilized conditions.

There is an increasing need to evaluate crop productivity under limited or uncertain water supply scenarios using simple models (KREMER et al., 2008). A common approach to solve for water stress effect on plant growth is the hydric restriction factor (HF) which is calculated based on the ratio between reference (RET) and potential evapotranspiration (PET), taking into account the crop coefficient (kc) of the pasture species (BARIONI et al., 2006). This approach considers that the biomass accumulation is reduced linearly when RET:PET is less than 0.5, with magnitude defined according to HF, calculated according to the equation 1.

$$HF = 1 \ if \ \frac{RET}{PET} \geq 0.5 \ or \ HF = \left[2 * \left(\frac{RET}{PET}\right)\right] \ if \ \frac{RET}{PET} < 0.5$$

(eq. 1)

Tonato et al. (2010) tested the effect of photoperiod, temperature, and solar radiation on forage accumulation of *Cynodon*, *Brachiaria*, and *Panicum* grasses using empirical models and reported that the model with minimum temperature as independent variable had best values of determination coefficient, Akaike, and Bayesian criteria, under irrigated and well fertilized conditions. The authors pointed out, however, that the calibration of the models for broader site-specific conditions is needed for practical application in large scale.

Cruz et al. (2011) studied empirical models to simulate herbage accumulation rate of rainfed Marandu palisadegrass using minimum, maximum and average temperatures, global radiation, growing degree-days, actual and potential evapotranspiration, photothermal units, and the climatic growth index. The best results were for the multivariate regression, with minimum temperature, global radiation, and actual evapotranspiration. They also observed that the use of the RET:PET ratio enhanced the dry matter accumulation simulations.

Pezzopane et al. (2012) studied climatic variables to simulate forage production of Tanzania guineagrass [*Panicum maximum* Hochst. ex A. Rich (Syn. *Megathyrsus maximus* (Jacq.) B.K. Simon & S.W.L. Jacobs.)]. The authors reported that thermal and water availability effects combined, such as actual evapotranspiration, accumulation of degree-days corrected for water availability, and the climatic growth index, based on average temperature, solar radiation, and water availability, was the best approach to simulate forage production of Tanzania guineagrass.

Araujo et al. (2012) tested three empirical agro-climatic models (a cumulative degree-day, a photothermal units, and a climatic growth index) and one bio-physical simulation model, the APSIM-Growth model to simulate growth of Mombaça guineagrass (*Panicum maximum* Jacq. cv. ‘Mombaça’). The authors pointed out that, even though the empirical models had good performance in the simulations, their use is limited to regions that have similar soil and climatic characteristics. The biophysical model approach is more indicated because it takes into account a broader range of climatic, soil, and management conditions.

Another particularity of models based on climatic variables is the limited number of physiological studies in tropical conditions that have considered the effect of temperature on forage growth and the choice of method to calculate base temperature (Tb) (BARIONI et al., 2006). Base-temperature is defined as the temperature below which plant growth ceases or is negligible (McWILLIAM, 1978). Moreno et al. (2014) studied the use of different methods to calculate Tb of five guineagrasses (*Panicum* spp.) grasses, as Tb is widely used in several degree-day-based sub-models to simulate plant growth. The authors observed significant differences among methods, the best being (in decreasing order) iteration, coefficient of variation of accumulated degree-days, and the b-coefficient method. They also observed variation in Tb among grasses within the genus, from as low as 7ºC for Tanzânia to higher than 15ºC for Massai and Atlas.

The CROPGRO model is a mechanistic model that predicts production and crop tissue composition based on plant, climate, and soil management information, enabling the simulation of water and nitrogen balance, organic matter and residue dynamics in the soil, as well as damage by pests and diseases, which results in numerous application possibilities (BOOTE et al., 2002; JONES et al., 2003). In 1995, the CROPGRO model was adapted as an annual version for bahiagrass (*Paspalum notatum* Flugge) in order to simulate pasture growth as a rotation component with peanut (*Arachis hypogaea* L.), in Florida, which was used in systems of crop rotation with corn (*Zea mays* L.) in the previous version (KELLY, 1995). The results of these simulations were inserted in an economic model to predict the sustainability and viability of the peanut crop. The species, cultivar, and ecotype files were released later as a model of "grazing" in the DSSAT models (the Decision Support System for Agrotechnology Transfer) version 3.5 (INTERNATIONAL CONSORTIUM FOR AGRICULTURAL SYSTEMS APPLICATIONS - ICASA, 1998). In addition to estimating the production of *P. notatum*, DSSAT later included an "annualized" version adapted for *Brachiaria decumbens* Stapf. (GIRALDO et al., 2001), using data from the international network of Tropical Pasture evaluation, CIAT, Colombia.

This "annualized" version of the model was used to simulate hay production of *P. notatum*, but revealed a consistent overestimation of dry matter production, particularly in the colder months. Thus, in 2004 this aspect was evaluated by Rymph et al. (2004) by means of model calibration and adjustments to parameters, getting more realistic representations of seasonal growth and *P. notatum* growth rate. Rymph et al. (2004) concluded that a true perennial version was needed that included a state variable for storage of reserves by the plant. For these reasons, Rymph (2004) developed a true perennial version of the model by adding a state variable for storage of C and N reserves, along with rules for use of those reserves for regrowth even after complete defoliation or surface winter-kill (which the annualized version would not tolerate). In addition to the new code, Rymph developed the parameterization and released the CROPGRO Perennial Forage model (for DSSAT version 4.0), giving it the ability to estimate the regrowth and nitrogen concentration of the tissues of *P. notatum* in response to daily variations in climate, fertilization and crop management. These improvements have not yet been incorporated into the publicly-released DSSAT models, but the model code has been improved and used in adaptations of parameters to allow prediction of several other tropical forages. More recently, using the CROPGRO Perennial

Forage developed for *P. notatum* as starting point, the model was successfully adapted to estimate the growth of *B. brizantha* and *P. maximum* for some locations in Brazil (PEDREIRA et al., 2011; LARA et al., 2012).

Pedreira (2009) used the CROPGRO perennial forage model to simulate biomass production, leaf area index, and light interception of rainfed Xaraes palisadegrass in Piracicaba, state of São Paulo, Brazil, and reported an underestimation in plant growth, which was attributed to water and nutritional stress. Cruz (2010) made a similar observation in rainfed Marandu palisadegrass simulated accumulation in São Carlos, state of São Paulo, Brazil, also using CROPGRO. These results showed the need for calibrating the CROPGRO perennial forage model to rainfed conditions for palisadegrass.

In the CROPGRO soil-plant-atmosphere module, potential transpiration is a function of the leaf area index and potential evapotranspiration. The model calculates potential evapotranspiration (PET) using one of two current options: the default Priestley and Taylor (1972) method, which requires only daily solar radiation and temperature, described in detail by (Richie, 1972); or the Penman-Montieth FAO 56 method (ALLEN et al., 1998) which uses windspeed and dewpoint temperature data in the weather data file to calculate PET (JONES et al., 2003). CROPGRO calculates water stress by the ratio of root supply to transpiration demand, via two different ratios (SWFAC for photosynthesis, and TURFAC for expansive processes of water stress signs). When SWFAC is less than 1.0, root depth progression is accelerated, leaf senescence is more rapid, and crop phenology may be delayed or accelerated depending on the crop growth phase. When TURFAC is less than 1.0, the expansion of new leaves and internode elongation (height and width increase) are reduced. A TURFAC less than 1.0 reduces leaf appearance rate (V-stage), specific leaf area of new leaves, the increase in height and width, and shifts allocation from leaf and stem toward root (BOOTE et al., 2008).

$$SWFAC = \frac{TRWU}{EP_o}\ limited\ to\ a\ maximum\ of\ 1.0$$

(eq. 2)

$$TURFAC = \frac{TRWU}{(EP_o \times 1.5)}\ limited\ to\ a\ maximum\ of\ 1.0$$

(eq. 3)

Where the TRWU is the total potential root water uptake and EP_o is the potential plant transpiration.

The present study was conducted in order to discuss agronomic performance and nutritive value of Marandu palisadegrass, Convert HD364 Brachiariagrass (*Brachiaria* hybrid CIAT 36061) and Tifton 85 Bermudagrass (*Cynodon* spp.) and as an attempt to contribute to the improvement of the CROPGRO Perennial Forage model, with regard to simulating the growth and physiology responses of the forage grasses under irrigated and rainfed conditions, as affected by harvest management.

1.1 Hypothesis

This study started with the hypothesis that the plant physiological processes, growth and nutritive value of pastures of Marandu palisadegrass, Convert HD364 Brachiariagrass and Tifton 85 Bermudagrass are affected by irrigation and harvest frequency.

The following hypothesis was that the CROPGRO – Perennial Forage Model can be calibrated to simulate accurately physiological processes and the growth of the three forage grasses.

1.2 Objectives

The general objective of this study was to describe and explain, based on a modeling approach, the effect of harvest frequency and irrigation on the growth and nutritive value of Marandu palisadegrass, Convert HD364 brachiariagrass and Tifton 85 bermudagrass. To achieve the main objective we described the process of CROPGRO – Perennial Forage Model calibration and evaluation for each pasture genotypes.

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2 HERBAGE YIELD AND NUTRITIVE VALUE OF BRACHIARIAGRASSES AND TIFTON 85 BERMUDAGRASS AS AFFECTED BY HARVEST FREQUENCY AND IRRIGATION

Abstract

Grasses of the genera *Brachiaria* and *Cynodon* are some of the most important pasture introductions in Brazil. Convert HD 364 brachiariagrass, a new *Brachiaria* hybrid, was released as an option for a broad range of environmental conditions, high nutritive value and forage production. Herbage accumulation, crude protein (CP), neutral detergent fiber (NDF), and *in vitro* organic matter digestibility (IVOMD) were evaluated as affected by two harvest frequency (28 and 42-days), irrigated and rainfed in a clipping study from 2011 to 2013, contrasting Convert HD 364® brachiariagrass (*Brachiaria* hybrid CIAT 36061), Marandu palisadegrass {*Brachiaria brizantha* (Hochst. ex A. Rich.) R. D. Webster [syn. *Urochloa brizantha* (A. Rich.) Stapf]; CIAT 6297}, and Tifton 85 bermudagrass (*Cynodon* spp.). The experimental design for both the irrigated and the rainfed trials was a randomized complete block with four replications. Convert HD 364 had similar or higher annual herbage accumulation, seasonal yield and herbage accumulation rate than Marandu and Tifton 85 (15% more herbage accumulation than Marandu and 12% more than Tifton 85 when irrigated and when harvested at shorter regrowth intervals). Convert HD 364 had good seasonal distribution of total annual herbage produced and accumulates about 30% of the total herbage mass during the cool season in Piracicaba, similar to Marandu. Tifton 85 produced around 20% of its average annual yield during dry season. Tifton 85 forage had higher CP concentration than the other two grasses when harvested at shorter intervals and when irrigated. The NDF concentration in Convert HD 364 was lower than in the other grasses regardless of irrigation treatment, harvest frequency, and season of the year, resulting in high IVOMD (more than 650 g kg^{-1}), similar to that of Marandu. The results suggest that Convert HD 364 can be used in moderately- to highly-intensive livestock enterprises, as it has the desirable combination of high forage production and nutritive value when harvested every 28 days and irrigated. Although under rainfed condition Convert HD 364 had higher forage yield when harvested every 42 days, it has lower CP, NDF and IVOMD.

Keywords: Crude protein; *In vitro* organic matter digestibility; Mulato II; Neutral detergent fiber; Pasture

2.1 Introduction

The Brazilian livestock industry is highly dependent on grazed pastures. The country has around 196 million ha of pastures (23% of its total land area) (FAO, 2013) of which 100 million ha are of cultivated pastures (EUCLIDES et al., 2010). About 40 to 60% of the improved pasture area shows some sign of degradation (BODDEY et al., 2004; DIAS-FILHO, 2011), which is associated with decreased in animal production, low soil fertility and problems related to soil conservation, weed encroachment, pests and diseases, environmental problems and overall declining sustainability. This is mainly due to errors in management, including wrong stocking rates and insufficient soil nutrient replenishment (BODDEY et al., 2004). In many cases, a forage genotype is not well adapted to the environmental condition where it is to be used, and this hinders pasture persistence and longevity (GOMIDE; GOMIDE, 2007).

Grasses of the genus *Brachiaria* (syn. *Urochloa*) are widely used in planted pastures by the livestock industry in Brazil, totaling 80% of cultivated pasture area (FONSECA et al., 2006). Marandu palisadegrass was released in 1984 and it is the most common planted pasture grass in Brazil and is widely used in forage-livestock operations in the country due to its tolerance to low soil fertility, resistance to spittlebugs [*Deois flavopicta* (Stal), and *Zulia entreriana* (Berg)], high forage production and nutritive value (when well fertilized and managed), and high viable seed production (NUNES; BOOK; PENDEADO, 1984). Out of 100 million hectares of cultivated pastures in Brazil, 45 million hectares are established with Marandu. In addition, this grass provides about 60% of the forage seed market in the country (EUCLIDES et al., 2010). Despite its importance Marandu palisadegrass has recently shown problems relative to monoculture of this cultivar known as “Marandu Death Syndrome” (DIAS-FILHO, 2005). The causes for the decline have not been completely elucidated, but are thought to be the result of the combined effects of poor soil drainage, low soil fertility and possibly pests and diseases.

‘Mulato’ brachiariagrass (*Brachiaria* hybrid CIAT 36061) was the first *Brachiaria* hybrid originated from the cross between ruzigrass [*Brachiaria ruziziensis* (R. Germ. & C. M. Evrard)] Crins (syn. *Urochloa ruziziensis* Germain and Evrard); clone 44-6] and palisadegrass [*Brachiaria brizantha* (A. Rich.) Stapf, CIAT 6297]. (INYANG et al., 2010a). ‘Mulato II’ brachiariagrass (Convert HD 364®) was later developed from three generations of hybridization between ruzigrass (clone 44-6) and signalgrass [*Brachiaria decumbens* (Stapf) R. D. Webster (syn. *Urochloa decumbens* (Stapf) R. D. Webster)] (cv. Basilisk), where the first generation was exposed to open pollination from lines of *B. brizantha*, including cv. Marandu (ARGEL et al., 2007). This genotype was subsequently identified as *Brachiaria* hybrid accession CIAT 36087 and it was released in 2005 as cv. Mulato II by Semillas Papalotla S.A., Mexico. ‘Mulato II’ was developed to have a broad range of adaptation (including acid soils of low fertility and moderate moisture saturation), high nutritive quality and forage production, and good-quality seed (ARGEL et al., 2007) as well as an option to be used in replacement of Marandu palisadegrass in some degraded pasture areas affected with Marandu death syndrome (DIAS-FILHO, 2005). ‘Mulato II has been commercialized as Convert HD 364® by Dow AgroSciences, Brazil, in 2009.

For very intensive livestock production systems, Tifton 85 bermudagrass (*Cynodon* spp.), among the other *Cynodon* cultivars, is one of the most productive and with a remarkably high nutritive value (HILL et al., 1993). Tifton 85 is a hybrid strain of bermudagrass released by the University of Georgia and the USDA-ARS in 1992, and has been successfully adopted as a pasture grass in tropical and subtropical areas. It is a F1 hybrid between PI 290884 from South Africa (*Cynodon dactylon* [L.] Pers) and Tifton 68 stargrass (*Cynodon nlemfuensis* Vanderyst). It is taller, has larger stems, broader leaves and a darker green color than other bermudagrass hybrids. It also has has large rhizomes, crowns, and large, rapidly-spreading stolons (BURTON et al., 1993).

New forage genotypes should only be adopted commercially and widely established after sufficient experimental information is gathered from research, with regard to responses to harvest frequency, defoliation intensity, fertilization, irrigation and other management factors and environments, when compared to well known standard genotypes (INYANG et al., 2010a). Seasonal forage production patterns throughout the year should be assessed so that yield potential is known for various regions, even in tropical and subtropical areas where winter temperatures are mild, but where there can be variations in quality and quantity of herbage produced (MORENO et al., 2014). Information on the agronomic and forage nutritive value responses of ‘Mulato II’ brachiariagrass to management are scarce and needed if this grass is to be adopted in high-scale forage-livestock operations.

The objective of this study was to evaluate and describe the effect of harvest frequency and irrigation on forage production and nutritive value of Convert HD 364® brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass.

2.2 Materials and Methods

A field trial was carried out at University of Sao Paulo “Luiz de Queiroz” College of Agriculture (USP-ESALQ) in Piracicaba, state of São Paulo, Brazil (22º42’ S, 47º30’ W, 546 m altitude a.s.l.). Weather data for the experimental period (Table 1) were obtained from a weather station distant about 1.8 km from the experimental area. Two identical experiments were conducted simultaneously and adjacent to each other, one irrigated and another rainfed.

The grasses were established in October 2010 in 4 x 5 - m plots separated by 1-m alleys. The experimental design for both trials was a randomized complete block in a factorial arrangement (3 x 2), and four replications, with treatments corresponding to all possible combinations among three grasses, Marandu palisadegrass, Convert HD364 brachiariagrass and Tifton 85 bermudagrass, and two harvest frequencies, 28 and 42-days. The plots were mechanically harvested to a 10-cm stubble height during two years (from April 2011 to April 2013). The soil was a Kandiudalfic Eutrudox, with no need for fertility correction (Table 2). Nitrogen was split-applied after each harvest, at 400 kg ha^{-1} yr^{-1} as NH_4NO_3.

Table 1 - Monthly weather data at the experimental site during the evaluation period in Piracicaba, SP, Brazil

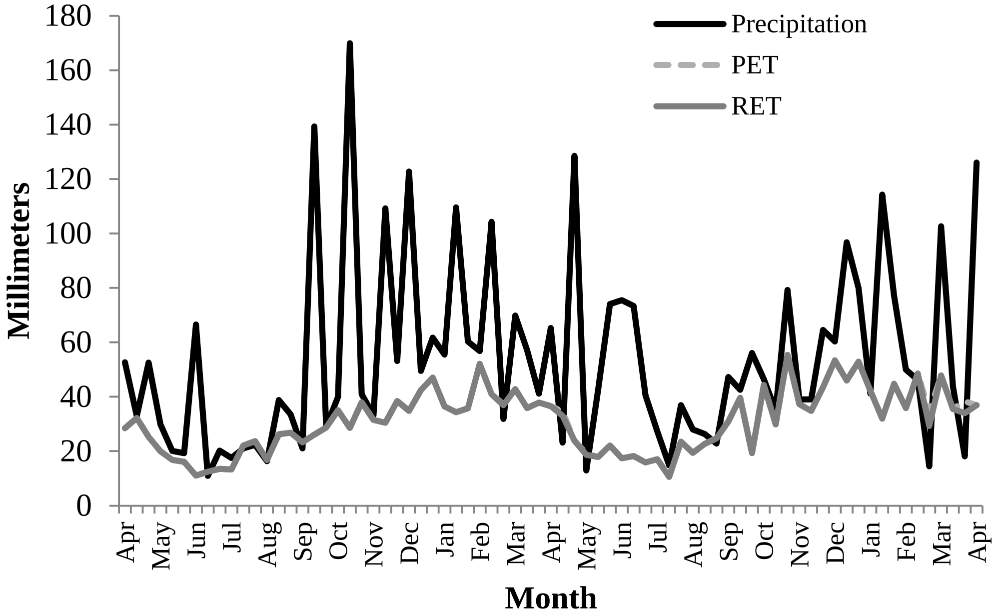
Weather Variable	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
						2011-2012						
Solar Radiation (MJ $m^{-2}d^{-1}$)	16.1	14.9	13.8	14.7	16.9	23.4	21.3	24.9	25.4	21.7	24.6	23.7
Max. Temperature (ºC)	29.2	25.9	24.6	27.0	28.1	30.3	29.6	29.4	30.7	29.2	33.1	31.6
Min. Temperature (ºC)	17.5	12.5	9.3	12.8	13.2	12.9	17.1	16.6	18.6	18.5	20.1	18.8
Rainfall (mm)	131.2	29.0	48.8	3.0	30.8	1.7	193.9	155.3	153.4	214.9	138.7	61.5
						2012-2013						
Solar Radiation (MJ $m^{-2}d^{-1}$)	18.3	16.7	11.9	16.7	21.1	21.2	23.7	24.1	24.6	21.0	22.4	19.4
Max. Temperature (ºC)	29.8	26.2	24.5	26.4	28.7	30.6	33.0	30.9	33.1	30.3	32.6	31.6
Min. Temperature (ºC)	18.0	13.9	14.0	11.2	11.9	14.6	17.9	18.1	21.3	19.4	20.4	20.0
Rainfall (mm)	159.2	57.8	158.0	24.7	0.0	40.9	70.3	97.9	191.4	224.7	110.7	135.8

Table 2 - Chemical and physical soil analysis of the experimental area (0 to 20-cm) before plot establishment (October 22nd, 2010) in Piracicaba, SP, Brazil

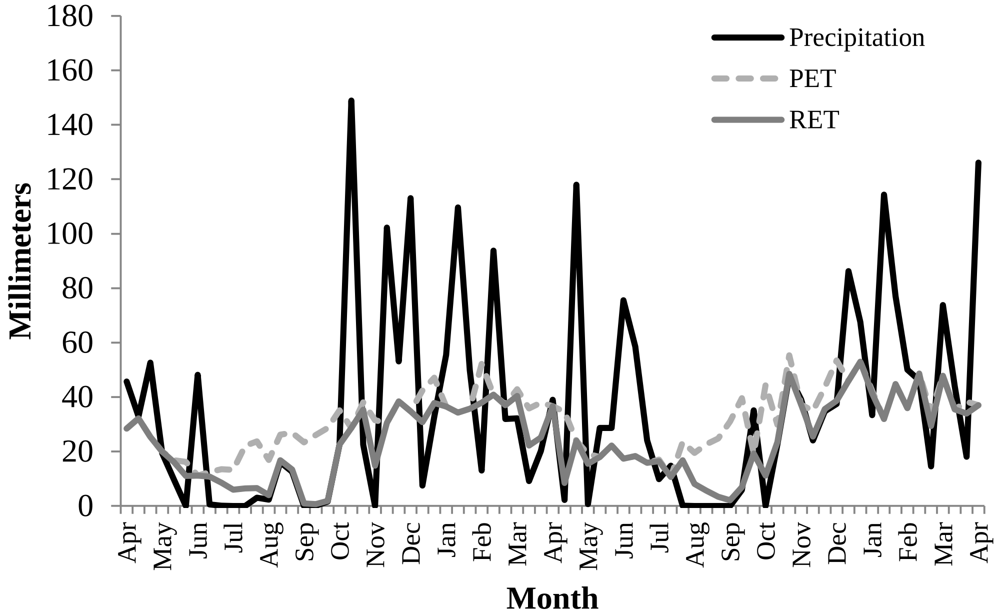
pH	O.M.	P	K	Ca	Mg	H+Al	SB	C.E.C.	BS	SO_4	Clay	Silt	Sand
($CaCl_2$)	g dm^{-3}	mg dm^{-3}	------------ $mmol_c$ dm^{-3} ------------						%	mg dm^{-3}	------ g kg^{-1} ------		
5.5	24	38	6	75	25	34	106	140	76	8	431	199	370

O.M. = Soil organic matter; P = Phosphorus ion-exchange resin extraction method; S.B. = Sum of bases; C.E.C. = Soil cation exchange capacity; BS = Soil base saturation

Sprinkler irrigation was used to eliminate water stress effect in the irrigated experiment, by supplying 8 to 12-mm rainfall equivalent when soil water tension reached 0.30 kPa, as measured by tensiometers at 30-cm depth. The soil-water balance (Figure 1) was calculated for both experiments.



(A)



(B)

Figure 1 - Soil-water balance (ROLIM et al., 1998; THORNTHWAITE; MATHER, 1955) with irrigation (A) and under rainfed conditions (B) from April 2011 to April 2013 in Piracicaba, SP, Brazil. PET: Potential evapotranspiration; RET: Reference evapotranspiration; Water holding capacity of 40 mm

Herbage mass above the 10-cm stubble was quantified every 28 and 42 days using two 0.75 m^2 – quadrats per plot. The forage inside the quadrats was clipped, weighed fresh in the field and sub-sampled. Subsamples were weighed in the field (300 g, approximately) and subsequently dried in a forced-draft oven at 60ºC for at least 72 h and then weighed again to calculate dry matter concentration. The DM concentration of the subsamples was extrapolated to the sample to determine sample dry weight. Sample dry weight was assumed to be the herbage accumulation per unit area since the previous harvest. Herbage accumulation rate was calculated as the amount of herbage accumulated divided by the length of the regrowth cycle. After samples were taken, the entire plot was mechanically staged to a 10-cm stubble height and fertilized to start a new regrowth cycle.

Samples for nutritive value were taken from the regrowth cycles in which the harvest dates were coincident for both 28- and 42-days treatments (7-Apr. 2011; 30-Jun. 2011; 22-Sept. 2011; 12-Jan. 2012; 5-Apr. 2012; 28-Jun. 2012; 20-Sept. 2012; and 10-Jan. 2013), and were assumed to be representative of each season of the year. For this purpose, the same dried subsamples used to estimate DM concentration on those dates were combined, ground in a Wiley mill to pass a 1-mm screen, and taken to the laboratory for chemical analyses.

Nitrogen (N) concentration was measured using a modification of the aluminum block digestion technique (GALLAHER et al., 1975); NH_3 in the digestate was determined by semiautomated colorimetry (HAMBLETON, 1977). Concentration of crude protein (CP) in the herbage dry matter was calculated as N × 6.25. *In vitro* digestible organic matter concentration (IVOMD) was determined by the two-stage procedure of Tilley and Terry (1963) modified by Moore and Mott (1974). Neutral detergent fiber (NDF) concentration in the forage samples was determined according to the A2000 Filter Bag Technique - Method 13 (Ankom Technology, Macedon, NY) (ANKOM, 2013).

Data were analyzed using a multi-site experiment analysis (NOGUEIRA; GOMES, 1978) with PROC MIXED of SAS (SAS INSTITUTE, 2013). Both years were divided into a "dry season" (April 6 to Sept. 20) and a "rainy season" (Sept. 21 to April 5). This grouping was based on the soil water balance, in order to separate the periods when there were environmental constraints to growth and periods when there were not (Figure 1). Annual herbage accumulation was analyzed as the sum of all herbage accumulated in all regrowths each year. Seasonal yield was calculated as the sum of herbage accumulated during the dry season and the rainy season during each year. Herbage accumulation rate was analyzed as the average of all means within the dry season and rainy season, during each year. Crude protein, neutral detergent fiber, and *in vitro* organic matter digestibility were the weighted means across sampling dates within dry season and rainy season, for each year [(Σ seasonal herbage accumulation × CP or IVOMD or NDF concentration)/total herbage accumulation].

Response variables studied were annual herbage accumulation (total yield per year), seasonal yield, herbage accumulation rate, crude protein, neutral detergent fiber, and *in vitro* organic matter digestibility. Grass, harvest frequency, and their interactions were considered fixed effects, and, because it was assumed that there was no relevant carry-over effect from year 1 to year 2, and years were used so as to allow for broader inference, year and block were considered random effects (LITTELL et al., 2006). Seasons within years were analyzed as repeated measures. Treatments were compared using PDIFF ($P < 0.05$) and means are reported as least squares means.

2.3 Results and Discussion

2.3.1 Annual herbage accumulation, seasonal herbage accumulation and herbage accumulation rate

There was a grass × frequency × irrigation interaction for annual herbage accumulation (P=0.0091), and for herbage accumulation rate (P=0.0005). In the rainfed experiment, when harvested every 42 days, Convert HD 364 had higher annual herbage accumulation, and herbage accumulation rate than Marandu and Tifton 85. There was no difference among grasses in the rainfed experiment for 28-d treatment (Table 3). In the rainfed experiment, 42-d treatment resulted in higher annual herbage accumulation, and herbage accumulation rate than 28 days only for Convert HD 364, with no effect of harvest frequency on Marandu and Tifton 85. Under rainfed conditions, Convert HD 364 probably had the same growth rate of Marandu and Tifton 85 until about 28 days of regrowth, and had higher growth rate after that. In the irrigated experiment, under the 28-d harvest frequency, Convert HD 364 had higher annual herbage accumulation, and herbage accumulation rate than Marandu and Tifton 85. In the irrigated experiment, with 42 days of harvest frequency, there was no difference on annual herbage accumulation among grasses, but the herbage accumulation rate was lower for Tifton 85. Marandu had higher annual herbage accumulation, and herbage accumulation rate when irrigated and harvested every 42 days, compared to 28 days. It is possible that irrigation allowed for higher growth rate in Convert HD 364 until 28 days of regrowth, but after 28 days this advantage probably disappeared. High regrowth vigor is related to (i) shoot apex survival, (ii) residual leaf area, (iii) carbohydrate reserves, and (iv) tillering potential (GOMIDE, 1989). Pedreira et al. (2000) studied persistence of Florakirk bermudagrass [*Cynodon dactylon* (L.) Pers.] affected by grazing frequency (7, 21, and 35 days) and post-grazing stubble heights (8, 16 and 24 cm) and stated that the high remaining leaf area after defoliation can reduce the need for reserves storage and mobilization for regrowth. Convert HD 364 stubble has higher leaf area than the other two grasses studied (Chapter 4 of this dissertation, table 4 and 5), but this advantage seems to disappear by the 28th day of regrowth. Vendramini et al. (2012) compared persistence and productivity between Mulato II and Tifton 85 clipped every 5 to 6 weeks with 10-cm stubble height and found no difference in herbage yield during the warm season (5.2 and 4.9 Mg DM ha^{-1} in the first year, and 11.3 and 10.7 in the second year, respectively). Demski (2013) compared Convert HD 364 and Marandu in a grazing study and did not find differences in herbage accumulation and herbage accumulation rate during the warm season (8.1 and 8.6 Mg DM ha^{-1}, for herbage accumulation, and 89 and 93 kg DM ha^{-1} for herbage accumulation rate, respectively). Teodoro (2011) studied three stubble heights (10, 20 and 30 cm) of Convert HD 364 and Marandu, clipped every 28 days and also did not find differences in yield between grasses.

Table 3 - Annual herbage accumulation, and herbage accumulation rate of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass rainfed and irrigated, harvested each 28- and 42-days from April 2011 to April 2013 in Piracicaba, SP, Brazil

	Rainfed		Irrigated	
Grass	28-days	42-days	28-days	42-days
	---------------- Annual herbage accumulation (Mg DM ha^{-1} yr^{-1}) ----			
Convert HD 364	17.9 Ca	20.2 Ba	22.2 ABa	22.8 Aa
	(0.86)	*(0.86)*	*(0.86)*	*(0.86)*
Marandu	17.8 BCa	16.3 Cb	19.3 Bb	23.0 Aa
	(0.86)	*(0.86)*	*(0.86)*	*(0.86)*
Tifton 85	18.7 Ba	17.9 Bb	19.7 ABb	21.1 Aa
	(0.86)	*(0.86)*	*(0.86)*	*(0.86)*
	----------- Herbage accumulation rate (kg DM ha^{-1} d^{-1}) -----------			
Convert HD 364	46.7 Ca	51.9 Ba	63.9 Aa	60.9 Aa
	(1.61)	*(1.61)*	*(1.61)*	*(1.61)*
Marandu	44.8 Ca	40.9 Cb	54.8 Bb	60.7 Aa
	(1.61)	*(1.61)*	*(1.61)*	*(1.61)*
Tifton 85	47.4 Ba	45.0 Bb	55.5 Ab	54.0 Ab
	(1.61)	*(1.61)*	*(1.61)*	*(1.61)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

A grass × season interaction affected seasonal yield (P<0.0001). Convert HD 364 yielded 7% more than Marandu in the rainy season, but did not differ from Tifton 85 (Table 4). In the dry season, however, Convert HD 364 plots produced 13% more herbage than those of Marandu and 44% more than those of Tifton 85. Similar results were reported by Peters et al. (2003) who found that Convert HD364 is 25% more productive than Marandu palisadegrass under similar management practices.

Convert HD 364 had higher herbage accumulation rate during the dry season than Marandu, which had a higher rate than Tifton 85 (Table 4). For the rainy season, there was no difference between Convert HD 364 and Tifton 85, both with higher herbage accumulation rates than Marandu. Convert HD 364 produced 28% of its total annual yield during the dry season. Marandu and Tifton 85 produced 27 and 21% of their average annual yields during dry season, respectively. This can be partially explained by an atypically high rainfall in June of 2012 (the second experimental year) in the dry season (Table 1). According to Argel et al. (2007), an important characteristic of Convert HD 364 is its tolerance to prolonged periods of drought (up to 6 months) which can provide up to 20% of its forage production during the dry season, a trait that is consistent with the findings of the present study.

Table 4 - Seasonal yield and herbage accumulation rate of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass during dry (April to September) and rainy (September to April) season from April 2011 to April 2013 in Piracicaba, SP, Brazil

Grass	Dry season	Rainy season
	----------- Seasonal yield (Mg DM ha^{-1}) -----------	
Convert HD 364	5.8 Ba	14.9 Aa
	(0.29)	*(0.29)*
Marandu	5.2 Bb	13.9 Ab
	(0.29)	*(0.29)*
Tifton 85	4.1 Bc	15.2 Aa
	(0.29)	*(0.29)*
	----------- Herbage accumulation rate (kg DM ha^{-1} d^{-1}) ---------	
Convert HD 364	39.6 Ba	72.1 Aa
	(1.19)	*(1.19)*
Marandu	35.1 Bb	65.5 Ab
	(1.19)	*(1.19)*
Tifton 85	28.6 Bc	72.4 Aa
	(1.19)	*(1.19)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

There was an irrigation × season interaction effect on seasonal yield, and herbage accumulation rate (P<0.0001). Irrigation increased seasonal yield, and herbage accumulation rate during the rainy and dry seasons (Table 5). There were short periods of water stress during rainy season, which could be supplied through irrigation, increasing herbage production (Figure 1). Oliveira Filho et al. (2011) evaluated fertilization and irrigation effects on Xaraes palisadegrass pastures and reported increased yield with irrigation compared to the rainfed treatment during the dry season.

Table 5 - Seasonal yield, and herbage accumulation rate of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass during dry (April to September) and rainy (September to April) season, as affected by irrigation, from April 2011 to April 2013 in Piracicaba, SP, Brazil

Irrigation	Dry season	Rainy season
	----------- Seasonal yield (Mg DM ha^{-1}) -----------	
Irrigated	5.5 Ba	15.8 Aa
	(0.25)	*(0.25)*
Rainfed	4.6 Bb	13.4 Ab
	(0.25)	*(0.25)*
	----------- Herbage accumulation rate (kg DM ha^{-1} d^{-1}) ---------	
Irrigated	38.5 Ba	78.1 Aa
	(1.02)	*(1.02)*
Rainfed	30.3 Bb	61.9 Ab
	(1.02)	*(1.02)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05).

The 42-d harvest frequency resulted in higher seasonal yield, and herbage accumulation rate during the rainy season (Table 6). Similar results were reported by Inyang et al. (2010b) with Mulato II. Longer regrowth intervals are often reported to result in higher herbage yield, mainly associated with stem elongation and decrease in leaf:stem proportion (OLIVEIRA et al., 2000; PEDREIRA et al., 2009). In the dry season the 28-d frequency resulted in higher seasonal yield and herbage accumulation rate. During rainy season, the 42-d schedule resulted in lower post-harvest leaf area, which made for slow post-harvest growth, resulting in lower initial growth rate for this treatment. In the subsequent dry season, the time spent in the initial part of sigmoidal growth curve is increased. This probably contributed to lower seasonal yield in the 42-d treatment. Lara and Pedreira (2011) evaluated leaf and sward photosynthesis of five *Brachiaria* genotypes and found that around 53% of the sward carbon assimilation in summer regrowths came from shaded leaves which remained from the previous regrowth. This is important because according to Pedreira and Pedreira (2007), longer regrowth intervals can result in lower leaf photosynthesis due to higher stem elongation and greater amount of dead material, decreasing the post-harvest leaf area. This is partly explained by the fact that the lower leaves remain self-shaded for longer periods of time due to higher defoliation intervals.

Table 6 - Seasonal yield, and herbage accumulation rate of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass during dry (April to September) and rainy (September to April) season, as affected by harvest frequency, from April 2011 to April 2013 in Piracicaba, SP, Brazil

Harvest frequency	Dry season	Rainy season
	----------- Seasonal yield (Mg DM ha^{-1}) -----------	
28 days	5.4 Ba	13.8 Ab
	(0.25)	*(0.25)*
42 days	4.7 Bb	15.5 Aa
	(0.25)	*(0.25)*
	----------- Herbage accumulation rate (kg DM ha^{-1} d^{-1}) ---------	
28 days	38.2 Ba	66.2 Ab
	(1.02)	*(1.02)*
42 days	30.7 Bb	73.8 Aa
	(1.02)	*(1.02)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

2.3.2 Nutritive value

There was a grass × irrigation interaction (P=0.0144) for crude protein (CP) concentration in the forage. Forage produced in the irrigated experiment had lower crude protein concentration than in the rainfed experiment (Table 7). This is probably related to a dilution effect, as more forage was produced with irrigation (Table 3). Similar results were reported by Inyang et al. (2010b) with Mulato II. Under rainfed conditions there was no difference in CP concentration among grasses. When irrigated, Tifton 85 forage had higher CP concentration than that of Marandu and Convert HD 364.

There was also an irrigation × season interaction (P<0.0001; SE=1.6) for CP. During the dry season, irrigation decreased forage CP from 152 to 147 g kg^{-1}, and during rainy season from 139 to 118 g kg^{-1}, compared with the rainfed plots. This can also be partly attributed to a dilution effect, as during the rainy season there was higher seasonal yield than in the dry season (Table 4). Forage N concentrations, however, never decreased below the critical level necessary for minimum crude protein requirements of 70 g kg^{-1} for rumen digestion (MILFORD; HAYDOCK, 1965).

Table 7 - Forage crude protein (CP) concentration of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass, rainfed and irrigated, from April 2011 to April 2013 in Piracicaba, SP, Brazil

Grass	Rainfed	Irrigated
	- - - - - - - g kg^{-1} - - - - - - -	
Convert HD 364	147 Aa	132 Bb
	(2.0)	*(2.0)*
Marandu	144 Aa	126 Bb
	(2.0)	*(2.0)*
Tifton 85	146 Aa	140 Ba
	(2.0)	*(2.0)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

A grass × frequency interaction affected CP concentration (P=0.0131). Tifton 85 had higher CP under the 28-d harvest frequency, followed by Convert HD 364 and Marandu (Table 8). There was no difference among cultivars in CP concentration in the 42-d harvest frequency. Vendramini et al. (2012) compared Mulato II and Tifton 85 clipped every 5 to 6 weeks with 10-cm stubble height and found no difference in CP (131 and 137 g kg^{-1} in the first year, and 100 and 107 g kg^{-1} in the second year, respectively). Lower harvest frequency (42 days between harvests) resulted in lower CP concentration in all grasses. According to Peyraud and Astigarraga, (1998), the increase of N fertilizer on crude protein reaches its maximum soon after application, then decreases rapidly as growth progresses. Vendramini et al. (2008), studied the effects of regrowth intervals and nitrogen fertilization levels (0, 80, and 160 kg ha^{-1} yr^{-1}) on cool- and warm-season grasses and reported lower CP concentration in rye (*Secale cereale* L.)–annual ryegrass (*Lolium multiflorum* Lam.) mixtures when the regrowth interval increased from 3 to 6 weeks. The authors attributed the CP reduction to a higher stem/leaf ratio in more mature forage. In the same study the authors reported lower CP concentration in Tifton 85 forage when the regrowth interval was increased from 2 to 4 weeks at all N fertilization levels tested. Nave et al. (2010) studied the effect of grazing frequencies on Xaraes palisadegrass and stated that stem crude protein concentration can be decreased not only by higher stem proportion in lower grazing frequencies, but by the maturity of the stem as the regrowth period increases.

Table 8 - Forage crude protein (CP) concentration of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass, harvested each 28- and 42-days, from April 2011 to April 2013 in Piracicaba, SP, Brazil

Grass	28-days	42-days
	------- g kg^{-1} -------	
Convert HD 364	147 Ab	132 Ba
	(2.0)	*(2.0)*
Marandu	139 Ac	132 Ba
	(2.0)	*(2.0)*
Tifton 85	153 Aa	134 Ba
	(2.0)	*(2.0)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

There was frequency × season interaction on CP concentration (P<0.0001; SE=1.6). The lower harvest frequency (42 d) resulted in lower CP only in the rainy season (142 and 116 g kg^{-1}, for 28 d and 42 d, respectively), with no differences during the dry season (mean=149 g kg^{-1}). Johnson et al. (2001) found the same N depression due to longer regrowths for Tifton 85 and other tropical grasses during the summer months. The stage of maturity at harvest, or harvest frequency, has been shown to be the main factor affecting nutritive value of forage plants (MANDEBVU et al., 1998). Pedreira et al. (1999) studying productivity and nutritive value of Florakirk bermudagrass [*Cynodon dactylon* (L.) Pers.] affected by grazing frequency (7, 21, and 35 days) and post-grazing stubble heights (8, 16 and 24 cm) found that from short (7 d) to intermediate (21 d) levels of grazing cycle, there was a slightly increase in CP followed by a decline in CP reaching a minimum at 35-d frequency.

There was a cultivar × irrigation × season interaction (P=0.0044) on neutral detergent fiber (NDF) concentration. During the rainy season, irrigation increased NDF in Convert HD 364 and Marandu, but there was no effect on Tifton 85 (Table 9). In the dry season, irrigation did not change NDF in Marandu and Tifton 85, but slightly decreased Convert HD 364 NDF. Convert HD 364 had the lowest NDF concentration, regardless of irrigation or season, followed by Marandu and Tifton 85 (Table 9). For Convert HD 364 and Marandu the NDF values were not higher than 600 g kg^{-1}, which was similar to those found by Demski (2013), who compared Convert HD 364 and Marandu in a grazing study (612 and 619 g kg^{-1} NDF, respectively). Neutral detergent fiber of Tifton 85 was higher than that of those grasses, but was consistent with what has been reported in other studies (GALDÁMEZ-CABRERA et al., 2003; HILL et al., 1993; MANDEBVU et al., 1998).

Table 9 - Neutral detergent fiber (NDF) concentration in Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass, rainfed and irrigated, during dry and rainy season, from April 2011 to April 2013 in Piracicaba, SP, Brazil

	Dry season		Rainy season	
Grass	Rainfed	Irrigated	Rainfed	Irrigated
	- - - - - - - - - - - - - -	g kg^{-1}	- - - - - - - - - - - - - -	
Convert HD 364	533 Bc	524 Cc	530 BCc	562 Ac
	(8.7)	*(8.7)*	*(8.7)*	*(8.7)*
Marandu	543 Cb	549 BCb	556 Bb	588 Ab
	(8.7)	*(8.7)*	*(8.7)*	*(8.7)*
Tifton 85	657 ABa	653 Ba	659 ABa	665 Aa
	(8.7)	*(8.7)*	*(8.7)*	*(8.7)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

The 42-d harvest frequency, during the rainy season, resulted in higher forage NDF concentration in all grasses (P=0.0065). Longer regrowth periods probably resulted in more stem elongation, a plant fraction that has higher levels of cell wall components than leaves. In the dry season, the 42-d harvest schedule resulted in lower NDF than in the 28-d frequency, in Convert HD 364 and Marandu (Table 10). This is coupled with the level of seasonal yield, which was lower for 42-d treatment during dry season (Table 6). When there is environmental constraints to growth, NDF is kept in low concentration in the forage mass because cell wall deposition and lignification are not primary sink of assimilates, once their primary function is to strengthen the plant structure in well-developed canopies (TAIZ; ZEIGER, 2004). Convert HD 364 had the lower NDF concentration, regardless of harvest frequency or season, followed by Marandu and Tifton 85. Costa et al. (2007) evaluated harvest frequency effects on Xaraes palisadegrass and reported increasing levels of NDF as growth progressed, which was attributed to deposition of lignin and increasing of cellulose and hemicellulose concentration in the plant cell wall. The chemical composition of the NDF (proportions of cellulose, hemicellulose, and lignin) affects the digestibility of the NDF fraction (NRC, 2001), mainly due to lignification of cellulose and hemicellulose, which decreases the nutritional availability (digestibility) of NDF (VAN SOEST, 1994). According to Oba and Allen (1999), NDF digestibility can vary widely among forage genotypes, affecting fiber digestibility, rumen retention time, and dry matter intake.

Table 10 - Neutral detergent fiber (NDF) concentration in Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass, harvested each 28- and 42-days, during dry and rainy season, from April 2011 to April 2013 in Piracicaba, SP, Brazil

	Dry season		Rainy season	
Grass	28-days	42-days	28-days	42-days
	- - - - - - - - - - - -	g kg^{-1}	- - - - - - - - - - - -	
Convert HD 364	534 Bc	523 Cc	531 BCc	561 Ac
	(8.7)	*(8.7)*	*(8.7)*	*(8.7)*
Marandu	558 Bb	535 Cb	555 Bb	589 Ab
	(8.7)	*(8.7)*	*(8.7)*	*(8.7)*
Tifton 85	659 Ba	651 Ba	653 Ba	671 Aa
	(8.7)	*(8.7)*	*(8.7)*	*(8.7)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

There was a grass × irrigation interaction (P=0.0030) on *in vitro* organic matter digestibility (IVOMD). Irrigation decreased IVOMD of Convert HD 364 and Marandu, but had no effect on Tifton 85 (Table 11). The absence of response of Tifton 85 IVOMD to irrigation may be partially due to its higher-than-average fiber digestibility, with less lignification of cell wall components, even with irrigation (HILL et al., 1993). Tifton 85 had lower IVOMD than Convert HD 364 and Marandu, the latter two not differing from each other, regardless of irrigation (Table 11). Comparing three stubble heights (2.5, 7.5 and 12.5 cm) and two harvest frequencies (2 and 4 weeks), Vendramini et al. (2013) reported higher IVOMD for Convert HD 364 than Tifton 85 (670 and 630 g kg^{-1}, respectively). Vendramini et al. (2012) also compared Mulato II and Tifton 85 clipped every 5 to 6 weeks with 10-cm stubble height, and found higher IVOMD in Mulato II than in Tifton 85 (669 and 632 g kg^{-1} in the first year, and 652 and 560 g kg^{-1} in the second year, respectively).

Table 11 - *In vitro* organic matter digestibility (IVOMD) of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass, rainfed and irrigated, from April 2011 to April 2013 in Piracicaba, SP, Brazil

Grass	Rainfed	Irrigated
	- - - - - - - - - - g kg^{-1}	- - - - - - - - - -
Convert HD 364	676 Aa	659 Ba
	(3.6)	*(3.6)*
Marandu	677 Aa	652 Ba
	(3.6)	*(3.6)*
Tifton 85	612 Ab	613 Ab
	(3.6)	*(3.6)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different (P>0.05)

During the rainy season, Convert HD 364 and Marandu had lower IVOMD ($P<0.0001$) while Tifton 85 had higher IVOMD compared to the dry season (Table 12). The higher NDF concentration during the rainy season for Convert HD 364 and Marandu probably contributed to lower IVOMD, since higher NDF during the rainy season most of time is related to lignification of cell wall constituents. According to Nussio et al. (2011), the first limitation for rapid fiber digestion is physical, rather than chemical, and refers to the presence of lignin in the cell wall tissue structure. However, contrasting with other grasses, Tifton 85 had higher IVOMD in the rainy season. Hill et al. (1993) reported that even though NDF concentration of Tifton 85 can be quite high (reaching more than 700 g kg^{-1}), the digestibility of the forage is not greatly depressed by that, with more than 600g kg^{-1} IVDMD.

Table 12 - *In vitro* organic matter digestibility (IVOMD) of Convert HD 364 brachiariagrass, Marandu palisadegrass, and Tifton 85 bermudagrass, during dry and rainy season, from April 2011 to April 2013 in Piracicaba, SP, Brazil

Grass	Dry season	Rainy season
	- - - - - - - - - - g kg^{-1}	- - - - - - - - - -
Convert HD 364	674 Aa	661 Ba
	(3.6)	*(3.6)*
Marandu	675 Aa	654 Ba
	(3.6)	*(3.6)*
Tifton 85	599 Bb	626 Ab
	(3.6)	*(3.6)*

Means within rows followed by the same uppercase letter and within columns followed by the same lowercase letter are not different ($P>0.05$)

There was an irrigation × season interaction ($P<0.0001$; SE=3.0) for IVOMD. Irrigation decreased IVOMD concentration only during the rainy season (662 and 632 g kg^{-1}, for rainfed and irrigated, respectively), with no differences during the dry season (mean=649 g kg^{-1}). Irrigation probably contributed to stem elongation and increased stem/leaf proportion, mainly during rainy season, and this contributed to decreased digestibility, as stems have lower digestibility than leaves (NAVE et al., 2010). The cell wall deposition and the lignification of cellulose and hemicellulose were probably increased by irrigation, as well. As the water enters the cell, the cell wall is stretched by the contents of the enlarging protoplast. The wall resists such stretching by pushing back on the cell (TAIZ; ZEIGER, 2004). As a result, turgor pressure increases the mechanical rigidity of cells and tissues, increasing lignin content, which has negative correlation with digestibility (CARMI et al., 2006).

Lower harvest frequency (42 d), in the rainy season, decreased IVOMD ($P<0.0001$; SE=3.0) compared to the 28-d frequency (659 and 635 g kg^{-1}, respectively). Longer regrowth probably allowed for higher stem elongation which has lower digestibility than leaves. Pedreira et al. (1999) studying productivity and nutritive value of Florakirk bermudagrass [*Cynodon dactylon* (L.) Pers.] affected by grazing frequency (7, 21, and 35 days) and post-grazing stubble heights (8, 16 and 24 cm) found that lower concentrations of CP and IVOMD were generally associated with longer grazing cycles and, consequently with older regrowth. The authors also reported that grazing managements that cause a greater proportion of the regrowth directed to stem can reduce digestibility. In the dry season, there was an increase in IVOMD with longer harvest interval (641 and 657 g kg^{-1}, for 28-d and 42-d concentration, respectively). During dry season, even 42-d treatment probably did not result in high cell wall deposition due to environmental constraints to growth (Figure 1).

2.4 Summary and Conclusions

Convert HD 364 may be a viable forage option to intensify pasture-based animal production systems and for diversification of pasture grasses in tropical areas due to its high forage yield and good nutritive value when well fertilized and well managed. Considering the differences in yield among the three grasses studied, Convert HD 364 can be superior to Marandu and Tifton 85 (15% more herbage accumulation than Marandu and 12% more than Tifton 85 when irrigated and when harvested at shorter regrowth intervals), resulting in forage of high nutritive value. It is suggested that this grass be used in moderately- to highly-intensive livestock enterprises. Convert HD 364 has good seasonal distribution of total annual herbage produced and accumulates about 30% of the total herbage mass during the cool season in Piracicaba, similar Marandu. Tifton 85 has higher CP concentration than the other two grasses when harvested at shorter intervals and when irrigated. The NDF concentration in Convert HD 364 was lower than in the other grasses regardless of irrigation treatment, harvest frequency, and season of the year, resulting in high IVOMD (more than 650 g kg^{-1}), similar to that of Marandu. The use of Convert HD 364 under rainfed conditions can be a good option for high-input livestock systems in warm areas, although irrigation resulted in 18 to 20% more forage yield with higher NDF and lower CP and IVOMD. Thus, the decision about the use of irrigation and harvest frequency will depend on the economical and practical aspects of the livestock enterprise.

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3 CALIBRATION OF THE CROPGRO – PERENNIAL FORAGE MODEL TO SIMULATE GROWTH OF MARANDU PALISADEGRASS UNDER IRRIGATED AND RAINFED CONDITIONS

Abstract

Forage-based livestock systems are complex and interactions among animals, plants, and the environment exist at several levels of complexity, which can be evaluated using computer modeling. Pastures are key to livestock production in Brazil because they allow low feeding costs and, more recently, have been regarded to promote higher marketability to the final animal products than a grain-based diet. Despite the importance of grasslands for livestock production in Brazil, tools that assist producers to make decisions in forage-livestock systems are scarce. The objective of this research was to use the CROPGRO – Perennial Forage Model to simulate the irrigated and rainfed growth of Marandu palisadegrass [*Brachiaria brizantha* (A. Rich.) Stapf. cv. Marandu], the most widely grown forage in Brazil, using the model previously calibrated for the tall-growing Xaraes cultivar of the same species, under non-limiting water conditions. Our null hypothesis was that the forage model previously calibrated for a given cultivar of a species, can accurately simulate the growth and forage yield of a new cultivar of the same species under irrigated and rainfed conditions. Data used to calibrate the model included forage production, plant-part composition, leaf photosynthesis, leaf area index, specific leaf area, light interception and plant nitrogen concentration from a field experiment conducted in 2011, 2012 and 2013 in Piracicaba, SP, Brazil. Agronomic and morpho-physiological differences between the two grasses, such as maximum leaf photosynthesis, nitrogen concentration and temperature effect on growth rate, were considered in the calibration. Under rainfed conditions, the simulations using Penman-Monteith FAO 56 method gave more realistic water stress response than using the Priestley and Taylor method. After model adjustments, the mean simulated herbage yield was 4582, and 5249, for 28-d and 42-d irrigated, and 4158 and 4735 kg ha^{-1}, for 28-d and 42-d rainfed, respectively. The RMSE ranged from 464 to 526 kg ha^{-1} and D-Stat from 0.907 to 0.962. The simulated/observed ratio were from 0.977 to 1.001. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Marandu palisadegrass under irrigated and rainfed conditions.

Keywords: *Brachiaria brizantha*; DSSAT; Pasture model; Tropical grass; *Urochloa brizantha*

3.1 Introduction

Grasses of the genus *Brachiaria* (syn. *Urochloa*) are widely used in planted pastures by the livestock industry in Brazil, totaling 80% of cultivated pasture area (FONSECA et al., 2006). Marandu palisadegrass {*Brachiaria brizantha* (Hochst. ex A. Rich.) R. D. Webster [syn. *Urochloa brizantha* (A. Rich.) Stapf]; CIAT 6297} was released in 1984 and it is the most common pasture grass in Brazil and is widely used in forage-livestock operations in the country due to its tolerance to low soil fertility, resistance to spittlebugs, high forage production and nutritive value (when well fertilized and managed), and high viable seed production (NUNES; BOOK; PENDEADO, 1984). Out of 100 million hectares of cultivated pastures in Brazil, 45 million hectares are established only with Marandu. In addition, this grass provides about 60% of the forage seed market in the country (EUCLIDES et al., 2010).

Despite the importance of pasture-based systems for livestock production in Brazil, intensive pasture management has been a challenge, because stocking rates should ideally be adjusted based on the carrying capacity of the pasture so as to achieve high grazing efficiency (SOLLENBERGER et al., 2005). Forage production and sward characteristics are very sensitive to environmental conditions, such as rainfall, air temperature and incoming solar radiation (TAIZ; ZEIGER, 2004). The pasture management aspects, such as the amount of fertilizer applied (WOODARD; SOLLENBERGER, 2011), and the harvest management with the frequency and intensity of defoliation (PEDREIRA et al., 2009) play an important role in the sward morphology, chemical composition, and in the forage production as well. Thus, mechanistic models can be used to integrate plant responses based on site-specific aspects, and have been useful as decision support tools (BOOTE et al., 1998). For this purpose, models should be extensively calibrated and validated to exhibit reasonable accuracy under a wide range of management practices and environmental conditions (HOOGENBOOM et al. 1994).

When physiological processes are well understood, they can be synthesized using crop models, which can become an important tools in research, allowing simulations of scenarios and assisting decisions in genetic improvement programs, in strategies of soil and cultural management, besides being useful in future climate change simulations (BOOTE et al., 1998; ASSENG et al., 2013). The CROPGRO model is a mechanistic model that predicts production and crop tissue composition based on the plant, climate information, and soil management, enabling the simulation of water and nitrogen balance, organic matter and dynamics of residues into the soil, and damage by pests and/or diseases, which results in numerous applications (BOOTE et al., 2002; JONES et al., 2003).

In 1995, the CROPGRO model was initially adapted as an annual version for *Paspalum notatum* Flugge in order to simulate the growth of pasture as a rotation component of the crop cultivation with peanut in Florida, which was used in systems of crop rotation with corn in the previous version (KELLY, 1995). The results of these simulations were inserted in an economic model to predict the sustainability and viability of the crop peanuts. The species, cultivar, and ecotype files were released later as a model of "grazing" in the DSSAT models (the Decision Support System for Agrotechnology Transfer) version 3.5 (ICASA, 1998). In addition to estimating the production of *P. notatum*, the DSSAT later included an “annualized” version adapted for *Brachiaria decumbens* (GIRALDO et al., 2001), using data from the international network of Tropical Pasture evaluation, CIAT, Colombia.

This “annualized” version of the model was used to simulate hay production of *P. notatum*, but revealed a consistent overestimation of dry matter production, particularly in the colder months. Thus, in 2004 this aspect was evaluated by Rymph et al. (2004) by means of model calibration and adjustments to parameters, getting more realistic representations of seasonal growth and *P. Notatum* growth rate.

Nevertheless, Rymph et al. (2004) concluded that a true perennial version was needed that included a state variable for storage of reserves by the plant. For these reasons, Rymph (2005) developed a true perennial version of the model by adding a state variable for storage of C and N reserves, along with rules for use of those reserves for re-growth even after complete defoliation or surface winter-kill (which the annualized version would not tolerate). In addition to new code, Rymph developed parameterization and released the CROPGRO Perennial Forage model (for version 4.0), giving it the ability to estimate the re-growth and nitrogen concentration of the tissues of *P. notatum* in response to daily variations in climate, fertilization and crop management. These improvements have not yet been incorporated into the publically-released DSSAT models, but the model code has been improved and used in adaptations of parameters to allow prediction of several other tropical forages. More recently, using as a basis the CROPGRO Perennial Forage developed for *P. notatum*, efforts were successful in adapting the model to estimate the growth of *Brachiaria brizantha* and *Panicum maximum* for Brazilian locations (PEDREIRA et al., 2011; LARA et al., 2012).

The objective of this research was to evaluate the CROPGRO – Perennial Forage Model for simulating the irrigated and rainfed growth of Marandu palisadegrass, using the model previously calibrated for Xaraes palisadegrass under non-limiting water conditions (PEDREIRA et al., 2011). Our null hypothesis was that the forage model previously calibrated by Pedreira et al., (2011) when used for different pasture cultivars within the same species, can accurately simulate growth and forage yield under irrigated and rainfed conditions. Failure to accurately predict growth and forage yield could be attributed to requirement for parameterization of cultivar specific traits when using the model for this purpose.

3.2 Materials and Methods

3.2.1 Field data used for model calibration

The data used in the model adaptation were collected in a field trial at the University of São Paulo, "Luiz de Queiroz" College of Agriculture (USP-ESALQ) in Piracicaba, state of São Paulo, Brazil (22º42' S, 47º30' W, 546 m a.s.l.). Weather data for the experimental period (Table 2) were obtained from a weather station about 1.8 km distant from the experimental area. Two identical experiments were conducted simultaneously, one irrigated and another rainfed. The treatments were harvest intervals of 28 and 42 days. Plots were 4 by 5 m and the experimental design was a randomized block with four replications. The plots were mechanically harvested to a 10-cm stubble during two years, from April 2011 to April 2013. The fertilization consisted of 400 kg N ha^{-1} yr^{-1}, applied as a NH_4 NO_3 split-applied after each harvest. Sprinkler irrigation was used to eliminate water stress in the irrigated experiment, by supplying 8-12 mm when soil water tension reached 0.30 kPa, as measured by ceramic tensiometers installed at 30-cm depth. The soil was a Kandiudalfic Eutrudox soil, without necessity of soil fertility correction (Tables 1 and 3).

Table 1 - Chemical and physical soil analysis of the experimental area (0 to 20-cm) before plot establishment (October 22nd, 2010) in Piracicaba, SP, Brazil

pH	O.M.	P	K	Ca	Mg	H+Al	SB	C.E.C.	BS	SO_4	Clay	Silt	Sand
($CaCl_2$)	g dm^{-3}	mg dm^{-3}	------------ mmol$_c$ dm^{-3} ------------						%	mg dm^{-3}	------ g kg^{-1} ------		
5.5	24	38	6	75	25	34	106	140	76	8	431	199	370

O.M. = Soil organic matter; P = Phosphorus ion-exchange resin extraction method; S.B. = Sum of bases; C.E.C. = Soil cation exchange capacity; BS = Soil base saturation.

Table 2 - Monthly weather data at the experimental site during the evaluation period in Piracicaba, SP, Brazil

Weather Variable	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
						2011-2012						
Solar Radiation (MJ $m^{-2}d^{-1}$)	16.1	14.9	13.8	14.7	16.9	23.4	21.3	24.9	25.4	21.7	24.6	23.7
Max. Temperature (ºC)	29.2	25.9	24.6	27.0	28.1	30.3	29.6	29.4	30.7	29.2	33.1	31.6
Min. Temperature (ºC)	17.5	12.5	9.3	12.8	13.2	12.9	17.1	16.6	18.6	18.5	20.1	18.8
Rainfall (mm)	131.2	29.0	48.8	3.0	30.8	1.7	193.9	155.3	153.4	214.9	138.7	61.5
						2012-2013						
Solar Radiation (MJ $m^{-2}d^{-1}$)	18.3	16.7	11.9	16.7	21.1	21.2	23.7	24.1	24.6	21.0	22.4	19.4
Max. Temperature (ºC)	29.8	26.2	24.5	26.4	28.7	30.6	33.0	30.9	33.1	30.3	32.6	31.6
Min. Temperature (ºC)	18.0	13.9	14.0	11.2	11.9	14.6	17.9	18.1	21.3	19.4	20.4	20.0
Rainfall (mm)	159.2	57.8	158.0	24.7	0.0	40.9	70.3	97.9	191.4	224.7	110.7	135.8

Table 3 - Soil profile created with the DSSAT Sbuild program for the experimental site in Piracicaba, SP, Brazil

Depth	Clay	Silt	Organic C	Lower limit	Drained upper limit	Saturated upper limit	Bulk density	Sat. Hydraulic conductivity	Root growth factor
cm	--------------------	%	-----	--------------------	v/v	-------------------	g cm^{-3}	cm h^{-1}	
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	0.240	0.340	0.48	1.15	0.40	0.70
75	61	4	0.40	0.240	0.340	0.49	1.15	0.40	0.62
85	61	4	0.36	0.240	0.340	0.49	1.13	0.40	0.55
200	59	10	0.36	0.250	0.350	0.49	1.13	0.36	0.31

Herbage mass was quantified at pre-harvest dates (at 28- and 42-day frequencies) using two 0.75 m^2 – quadrats clipped 10 cm above ground level, weighed in the field and sub-sampled. Sub-samples were hand dissected into live leaf (lamina), live stem (leaf sheath + stem) and dead material. The area of live leaf was measured using a leaf area meter (model LAI-3100 - LI-COR, Lincoln, NE, USA) to obtain the leaf area index. Leaf mass and other components was dried separately in a forced-draft oven at 60ºC for 72 h and then weighed. Herbage dry matter content and its morphological composition were calculated from the dry weights of sub-samples and their components, and then estimated to the whole sample. Then, the LAI was obtained as a result of dividing the leaf area of the sample by the 0.75 m^2 metallic rectangle area.

Dry samples were weighed, ground in a Wiley mill to pass a 1-mm screen, and taken to the laboratory for chemical analyses. Nitrogen concentration was determined using a micro-Kjeldahl method, a modification of the aluminum block digestion technique described by Gallaher et al. (1975) using aliquots of 0.25-g. Catalyst used was 1.5 g of 9:1

K_2SO_4:$CuSO_4$, and digestion was conducted for at least 4h at 375°C using 6 ml of H_2SO_4 and 2 ml H_2O_2. Nitrogen in the digestate was determined by semiautomated colorimetry (Hambleton, 1977). Nitrogen (N) is reported as elemental N as a percentage of DM.

Canopy light interception (LI) was measured immediately before harvest in each regrowth, using a LI-COR model LAI 2000 plant canopy analyzer (LI-COR, Lincoln, NE, USA). In each plot, one reading was taken above the canopy and eight at ground level (optical sensor placed at the mid distance between tussocks).

Rates of net photosynthesis of individual leaves were measured at pre harvest condition in May 4th, 2011, July 28th, 2011, Oct. 21st 2011, and Feb. 8th, 2012, using a system portable photosynthesis meter, model LI-6400 (LI-COR, Lincoln Nebraska, USA). Rates were measured in three leaves per plot, following a visual criterion of evaluation to select the best leaves present (the youngest expanded, with a minimum of leaf blade, green and clean), between 8 and 11h in the morning. The intensity of light in the leaf chamber was 2000 μmol photons m^{-2} s^{-1}, and CO_2 concentration was 385 μmol mol^{-1}.

3.2.2 Model calibration

The CROPGRO – Perennial Forage model developed for *Brachiaria brizantha* cv. Xaraes (PEDREIRA et al., 2011) was used as the starting point under the hypothesis that both genotypes of the same species have similar parameterization of the species, cultivar, and ecotype files in the model.

The CROPGRO model can be adapted 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 to observed values from the above described two-year experiment.

The experimental data used in the simulation, including location, soil, weather, and crop establishment, were described and entered into an experimental “Management” file, called “File X”. Planting age and transplanting weight were adjusted to better characterize pasture initial conditions. Different from row crops, the forage model can be run using transplanting rather than sowing, which allows starting a simulation with an already established plant stand, as often happens with perennial pastures or for those forages established by sprigging, as is the case of some tropical grasses such as hybrid bermudagrass (*Cynodon* spp.).

Another characteristic specific to the forage model is the MOW parameter, which is used to define the harvest date, the amount of forage mass remaining (stubble mass), percentage leaf of the stubble (RSPLF), and a "re-staged" leaf number (MVS) when top growth harvest is simulated. The measured stubble mass is entered as the MOW value in the simulations and characterizes the non-harvestable mass that remains in the field. The MVS parameter (hypothetical number of leaves left on a primary tiller axis after harvest) in the MOW file was kept at 3 (PEDREIRA et al., 2011).

In the DSSAT soil-plant-atmosphere module, potential transpiration is a function of the leaf area index and potential evapotranspiration. The model calculates potential evapotranspiration (ET) using one of two current options: The default Priestley and Taylor (1972) method which requires only daily solar radiation and temperature, described in detail by (Richie, 1972); and the Penman-Montieth FAO 56 method (ALLEN et al., 1998) which uses windspeed and humidity (actually dewpoint temperature) data in the weather data file to calculate potential ET (JONES et al., 2003). The Penman-Montieth FAO 56 method was used to calculate potential ET because, according to Saseendran et al. (2008), Priestley and Taylor tends to over predict ET slightly in cooler but relatively arid locations.

The DSSAT crop models include a module for simulating soil organic matter (SOM) and dynamics of a residue layer on top of the soil, with two different options: the PAPRAN model (GODWIN; JONES, 1991; SELIGMAN; VAN KEULEN, 1988) and the CENTURY model (PARTON et al., 1988). The main differences are that the CENTURY-based module (i) divides the SOM in more fractions, each of which has a variable C:N ratio and can mineralize or immobilize nutrients, (ii) it has a residue layer on top of the soil, and (iii) the decomposition rate is texture dependent. The CENTURY model converted to daily 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 during the season and root/rhizome/stolon mass that senesces in the soil during the long multi-year growth of perennial crops. Additionally, 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 CENTURY-based module distinguishes three types of SOM: (1) easily decomposable (microbial) SOM1, (2) recalcitrant SOM2, which contains lignin and cell walls, and (3) an almost inert SOM3. Three SOM pools were calculated (SOM1=0.01, SOM2=0.42, and SOM3=0.57) and entered into the SOM fraction file (PEDREIRA et al., 2011).

3.2.3 Statistical evaluation of model performance

Predicted biomass accumulation, leaf area index (LAI), leaf weight, stem weight, specific leaf area, leaf photosynthesis, and nitrogen concentration were compared to observed values, running the model with actual weather, soil and management input data and parameterizing partitioning and leaf growth parameters for best fit. Many of these parameters were optimized using the generalized likelihood uncertainty (GLUE) method (MAKOWSKI et al., 2002). The main steps of the GLUE procedure in the DSSAT are based on Beven and Binley (1992) and it follows this procedure: 1) Develop prior parameter distributions; 2) Generate random parameter sets from the prior parameter distributions; 3) Run the model with the randomly generated parameter sets; 4) Calculate the likelihood values; and 5) Construct posterior distribution and statistics (JONES et al., 2011). It consists of creating a set of large number of parameters by randomly generating cultivar-specific parameter values between the "assigned" minimum and maximum values across an expected range or the range of all cultivars previously calibrated for a given crop. The model is then simulated with the parameters sets generated and the likelihood value is computed for each generated parameter vector, used to construct the posterior distribution and to compute the mean and variance of the selected parameters used to compare predicted and observed values for each simulation (JONES et al., 2011). When GLUE was used, we took into account knowledge of how the parameter drives the model and if the resulting parameter fits the range of values reported in the literature or previous knowledge.

For evaluating model performance we used the observed/simulated ratio, root mean square error (RMSE) and the Willmott agreement index (D-Stat) (WILLMOTT, 1981; WILLMOTT et al., 1985).

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}$$

Where N is the total number of data points for comparison, Y_i is a given observed value, and $\hat{Y}_i$ is the corresponding value predicted by the model. A better model prediction will produce a smaller RMSE. The Willmott agreement index is given by

$$d = 1 - \left[\frac{\sum_{i=1}^{N}(Y_i - \hat{Y}_i)^2}{\sum_{i=1}^{N}(|\hat{Y}_i - \bar{Y}| + |Y_i - \bar{Y}|)^2}\right], 0 \le d \le 1$$

Where N is the number of observed data points, Y_i is a given observed value, $\hat{Y}_i$ is the corresponding value predicted by the model, and $\bar{Y}$ is the mean of the observed data. The d index near to 1 indicates good model prediction.

3.3 Results and Discussion

3.3.1 Simulation of irrigated and rainfed palisadegrass using original *B. brizantha* adaptation

For the irrigated dataset, the *Brachiaria brizantha* version of CROPGRO Perennial Forage model adapted by Pedreira et al., (2011) for Xaraes palisadegrass simulated both harvest frequency of 28 and 42 days quite well, using the Marandu palisadegrass dataset (Table 4). To the extent that Marandu and Xaraes are genotypes within the same species, this is not surprising, although they have distinct agronomic and morphological characteristics. The rainfed simulation, on the other hand, showed a reasonable underestimation for biomass, stem weight, LI and N concentration, which was due to an overestimation of water and N stress (Table 5).

Table 4 - Means and statistics for simulations of irrigated Marandu palisadegrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, simulated using the original *Brachiaria brizantha* adaptation by Pedreira et al. (2011)

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4566	4666	706.5	1.01	0.844
Leaf weight (kg DM ha^{-1})	1632	1746	493	1.05	0.916
Stem weight (kg DM ha^{-1})	2606	2557	245	0.98	0.949
LAI (m^2 m^{-2})	2.1	2.5	0.69	1.19	0.930
LI (% of incident light)	90.7	87.4	6.50	0.96	0.714
SLA (cm^2 g^{-1})	161.8	150.2	19.55	0.93	0.411
N (% on DM basis)	1.39	1.39	0.234	1.01	0.515
			42-days		
Biomass (kg DM ha^{-1})	5350	5018	846.9	0.94	0.915
Leaf weight (kg DM ha^{-1})	2119	2007	362	0.95	0.976
Stem weight (kg DM ha^{-1})	2776	2535	508	0.92	0.887
LAI (m^2 m^{-2})	3.63	3.12	0.797	0.88	0.961
LI (% of incident light)	93.9	92.1	5.179	0.98	0.555
SLA (cm^2 g^{-1})	183.6	154.5	32.38	0.84	0.391
N (% on DM basis)	1.38	1.47	0.233	1.08	0.588

Table 5 - Means and statistics for simulations of rainfed Marandu palisadegrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, simulated using the original *Brachiaria brizantha* adaptation by Pedreira et al. (2011)

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4229	3426	1112	0.82	0.741
Leaf weight (kg DM ha^{-1})	1539	1638	629	1.08	0.807
Stem weight (kg DM ha^{-1})	2259	1753	695	0.81	0.522
LAI (m^2 m^{-2})	2.37	2.40	0.789	1.02	0.879
LI (% of incident light)	86.3	79.7	12.6	0.92	0.679
SLA (cm^2 g^{-1})	190.6	144.6	53.01	0.77	0.461
N (% on DM basis)	2.97	1.39	1.7	0.49	0.323
			42-days		
Biomass (kg DM ha^{-1})	4835	3526	1619	0.74	0.632
Leaf weight (kg DM ha^{-1})	1819	1790	561	0.96	0.914
Stem weight (kg DM ha^{-1})	2610	1710	1078	0.68	0.460
LAI (m^2 m^{-2})	2.38	2.67	0.886	1.22	0.886
LI (% of incident light)	90.4	83.8	12.0	0.93	0.687
SLA (cm^2 g^{-1})	146.3	145.8	24.49	1.02	0.430
N (% on DM basis)	2.89	1.40	1.5	0.50	0.299

3.3.2 Model calibration for irrigated and rainfed Marandu palisadegrass

The irrigated experiment did not show any water and nitrogen stress. The absence of water and nitrogen deficit in the irrigated experiment allowed for calibration of the model parameters for ideal conditions. In this situation the uncontrollable environment factors (daylength, temperature, solar radiation, etc.) can be calibrated in the model. On the other hand, the rainfed experiment, with some short-term water and nitrogen limitation, allows for potential calibration of some parameters relative to water and nitrogen stress.

We changed the evapotranspiration method to Penman-Monteith-FAO 56, from the Priestley and Taylor method. This gave a more realistic estimation of evapotranspiration, which decreased water and nitrogen stress overestimation. Additionally, we decreased soil runoff from 0.76 to 0.70 due to unrealistic low water infiltration, and we decreased the computation of the potential evapotranspiration at LAI of 6 (EORATIO) from 1.0 to 0.9 based on water stress vs. field simulation growth data graphics. Marin et al. (2011), parameterizing the DSSAT/CANEGRO model for irrigated and rainfed sugarcane (*Saccharum* spp.) also in Southern Brazil stated that some potential reasons for inaccuracy in the water availability is under or overestimation of hydraulic conductivity at saturation (Ksat), root water uptake, and errors in root simulation, mainly in deeper horizons.

The temperature parameters were optimized using biomass accumulation data for base temperature (Tb) and first optimum temperature (TO1), which are phenology- driven parameters. We increased Tb from 10.0 to 11.1 ºC and decreased first optimum temperature from 32.0 to 30.2 ºC based on GLUE optimization (Table 6).

Photosynthesis and respiration parameters were adjusted based on the field measurements and GLUE optimizations using biomass and photosynthesis data. There are two options to simulate plant respiration: mass- or protein-based, set via the MRSWITCH parameter. We used mass-based because there is more information on the biomass dataset than on protein-based information. The maintenance respiration as a function of total crop dry weight (RES30C) was maintained unchanged. Maximum leaf photosynthesis (LFMAX) was decreased and set at 1.80 mg CO_2 m^{-2} s^{-1}, to match observed field data (data not shown). The leaf N concentration effect on photosynthesis (FNPGN) was kept the same, with 4% of nitrogen for maximum photosynthesis. The specific leaf weight at which LFMAX is defined (SLWREF) was set based on GLUE optimization for biomass data (Table 6).

3.3.3 Partitioning to storage, regrowth, and winter dormancy

After defoliation, the regrowth is highly dependent on stubble leaf area, tiller density and organic reserves of the forage plant. For most of non-rhizomatous tropical forage grasses, such as palisadegrass, storage organs can be located in tiller bases and roots. Photosynthate partitioning to storage organs is driven by assimilate supply, leaf area index, and storage "rules" that include effects of decreased daylength and temperature. In addition, decrease of forage accumulation during the "winter" months (April-September) is adjusted by "dormancy" parameters, triggered by low temperature and short photoperiod, and adjusted by temperature effects on photosynthesis. The GLUE optimization was used to adjust the sensitivity of single-leaf light-saturated photosynthesis rate to minimum night temperature (FNPGL) and the function describing relative rate of photosynthetic electron transport in response to current temperature (XLMAXT).

Optimizations were made for daylength effect (FNPTD and FNPMD) and for relative dormancy sensitivity effect of daylength (RDRMM and RDRMT) on mobilization and partitioning to increase seasonal cycling variations along the regrowth, making the model slightly more sensitive to daylength effect (Table 7).

To ensure good simulation of the regrowth cycles, carbon and nitrogen mining parameters were optimized. The minimum daily rate of CH_2O and N mobilization from storage (CMOBSRN and NMOBSRN) was kept the same and maximum values (CMOBSRX and NMOBSRX) were increased to better adjust speed of early regrowth and N simulations for Marandu palisadegrass dataset (Table 6). The concentration of carbohydrate in newly produced storage tissue (ALPHSR) was kept the same. However, the maximum fraction of photosynthate which can be allocated to refill storage tissue (CADPV) was decreased. It was done to adjust rapid regrowth and partitioning to leaf and stem. LAI effect on mobilization (LRMOB-4) and on refilling of storage tissue carbohydrate pool (LRREF) was increased because high mobilization ability is necessary for re-growth and the refill occurs mostly under high LAI, mainly to stem in 42-d treatment. Carbohydrate status and canopy photosynthesis effect on refilling of storage tissue (CRREF and PRREF) was optimized to enhance refill of storage tissue under lower storage reserve levels and at times of greater canopy photosynthesis. Maximum mobilization of CH_2O and protein from vegetative tissues (CMOBMX and NMOBMX) were kept close to previous calibration (PEDREIRA et al., 2011). Fraction of carbohydrate reserves that are allocated to storage (CADSRF) was decreased to improve leaf and stem growth.

3.3.4 N concentration in the forage mass

Plant growth is greatly affected by the supply of N. Critical concentration of N required for optimum growth changes with physiological age and is defined as the lowest concentration at which maximum growth occurs. The tissue N concentration below this critical concentration affects growth process. Above this critical concentration there is no further increase in growth rate and luxury consumption of N occurs (Godwin and Singh 1998). We changed leaf and stem N concentration based on GLUE optimization with crude protein data. The fairly poor N predictions (Table 8 and 9) require more improvements (ALDERMAN, 2008).

3.3.5 Partitioning to leaf, stem, and root

Initial simulations with the *B. brizantha* version of CROPGRO perennial forage model adapted by Pedreira et al., (2011) showed the need to modify partitioning parameters (YLEAF, YSTEM and YSTOR values) to increase allocation to stem growth, mainly for the 42-d harvest frequency treatment (Table 4). It is common for tropical forage grasses to increase stem elongation associated with longer harvest frequency. Partitioning to storage was increased considerable compared to Pedreira et al. (2011) values to reduce dependence of regrowth on low stubble LAI which occurred for the 42-d low harvest frequency treatment.

3.3.6 Prediction of specific leaf area, leaf area index, and light interception

The plant growth rate is a function of LAI and photosynthetic efficiency of leaves. The light interception increases due to LAI increment, affecting C fixation of the sward canopy through photosynthesis. The specific leaf area showed seasonal variation relative to light and temperature. The SLAVR was increased to 190 cm^2 g^{-1} as a standard reference cultivar at peak early vegetative phase, under standard growing conditions (optimum temperature, water and high light). The SLA simulations show reduction during cool temperature or water deficit and increased under low light. We used GLUE method to optimize the thinnest SLAMAX and thickest (SLAMIN) leaves in response to temperature effect (XSLATM and YSLATM) of newly-formed leaves using observed SLA data. The leaf appearance rate on main stem (TRIFL) was kept at 0.15 leaves per thermal day, according to values reported in the literature for palisadegrass (PEDREIRA et al., 2011).

In the model, LAI is a cumulative result of daily assimilate partitioning from photosynthesis to leaves at a given SLA under those conditions. Simulated LAI was compared to LAI of destructive samples, hand-separated and scanned in a model LI-3100 leaf area meter (Li-Cor, Lincoln, NE) for accumulated total or stubble LAI. Simulated light interception was compared to LI data collected with the LAI-2000 canopy analyzer).

Table 6 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values for plant composition, phenology, and productivity (photosynthesis and respiration) of Marandu palisadegrass dataset

Name	Definition	Initial values	Optimized values
PRO_ _G	"normal growth" protein conc. Fraction of tissue (leaf = LF, root = RT, stem = ST, storage organ = SR	LF=0.110;RT=0.040 ST=0.070;SR=0.064	LF=0.160;RT=0.040 ST=0.080;SR=0.064
PRO_ _I	"Maximum" protein concentration of tissue	LF=0.220;RT=0.101 ST=0.110;SR=0.092	LF=0.240;RT=0.101 ST=0.120;SR=0.092
PRO_ _F	"Final" protein concentration of tissue (at senescence)	LF=0.050;RT=0.022 ST=0.033;SR=0.056	LF=0.035;RT=0.022 ST=0.025;SR=0.056
Tb	Base temperature for vegetative development, ºC	10.0	11.1
TO1	First optimum temperature for vegetative development, ºC	32.0	30.2
TO2	Second optimum temperature for vegetative development, ºC	40.0	40.0
TM	Maximum temperature for vegetative development, ºC	45.0	45.0
MRSWITCH	Respiration: M = mass based (original CROPGRO code) or P = protein based	M	M
RES30C	Constant describing maintenance respiration as a function of total crop dry weight (minus oil, protein, and starch in the seed), g CH_2O (dry weight)$^{-1}$ h^{-1}	3.0×10^{-4}	3.0×10^{-4}
R30C2	Constant describing maintenance respiration as a function of canopy photosynthesis, g CH_2O g^{-1} photosynthate CH_2O h^{-1}	0.0024	0.0024
LFMAX	Maximum leaf photosynthetic rate at 30ºC, 350 ppm CO_2, and high light, mg CO_2 m^{-2} s^{-1}	1.89	1.80
FNPGN (1-2)	Leaf N concentration effect on photosynthesis or FNPGN(2), which is a two-sided quadratic curve describing leaf photosynthesis response to leaf N concentration: increases from zero at the min. leaf N conc. to max. leaf N concentration	0.80, 4.00	0.80, 4.00
SLWREF	Specific leaf weight at which LFMAX is defined (g m^{-2})	0.0078	0.0071

Table 7 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Marandu palisadegrass dataset) for temperature, solar radiation, and photoperiod effects on vegetative partitioning, specific leaf area, and photosynthesis

Name	Definition	Initial values	Optimized values
XLEAF	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	Describes dry matter partitioning to leaf among vegetative tissue only, as a function of vegetative stage (fraction)	0.8, 0.8, 0.8, 0.75, 0.5, 0.4, 0.4, 0.4	0.8, 0.8, 0.72, 0.63, 0.52, 0.51, 0.5, 0.5
YSTEM	Describes dry matter partitioning to stem among vegetative tissue only, as a function of vegetative stage (fraction)	0.1, 0.1, 0.17, 0.17, 0.15, 0.16, 0.16, 0.16	0.1, 0.1, 0.14, 0.17, 0.32, 0.36, 0.35, 0.35
YSTOR	Describes dry matter partitioning to storage among vegetative tissue only, as a function of vegetative stage (fraction)	0.01, 0.01, 0.01, 0.02, 0.02, 0.03, 0.03, 0.03	0.01, 0.01, 0.03, 0.04, 0.04, 0.04, 0.04, 0.04
SLAVR	Specific leaf area of cultivar under standard growth conditions (cm^2 g^{-1})	170	190
SLAMAX	SLAMAX is the (thinnest) leaves under low light (cm^2 g^{-1})	358	340
SLAMIN	SLAMIN is the (thickest) leaves under high light (cm^2 g^{-1})	130	139
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) (ºC)	7.6, 20.9	5.1, 22.2
XLMAXT(2-3)	Relative rate of photosynthetic electron-transport in response to temperature, linear from base (0.0) to maximum (1.0) (ºC)	10.4, 38.0	6.2, 40.2
XSLATM(3-4)	Relative temperature effect on specific leaf area of newly formed leaves, ºC (x vs. y pair)	11.0, 26.0	10.3, 24.2
YSLATM(3-4)	Relative temperature effect on specific leaf area of newly formed leaves, fraction reduction (x vs. y pair)	0.29, 1.00	0.39, 1.00
FNPTD (2-3)	Daylength effect on partitioning (h)	10.3, 15.2	12.0, 16.0
FNPMD(1-3)	Daylength effect on mobilization (h)	10.1, 14.5, 0.46	7.8, 12.0, 0.62
RDRMT	Relative dormancy sensitivity, day-length effect on partitioning	0.405	0.475
RDRMM	Relative dormancy sensitivity, day-length effect on mobilization	0.532	1.000

Table 8 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Marandu palisadegrass dataset) for carbon and nitrogen mining parameters

Name	Definition	Initial values	Optimized values
CMOBSRN	Minimum daily rate of CH_2O mobilization from storage (fraction)	0.020	0.020
CMOBSRX	Maximum daily rate of CH_2O mobilization from storage (fraction)	0.050	0.072
NMOBSRN	Minimum daily rate on N mobilization from storage (fraction)	0.010	0.010
NMOBSRX	Maximum daily rate of N mobilization from storage (fraction)	0.060	0.068
ALPHSR	Fraction of new storage tissue growth that is available CH_2O (fraction)	0.20	0.20
CADPV	Maximum fraction of photoassimilate available that can be allocated to CH_2O refill during non-stress conditions	0.437	0.356
LRMOB (3,4)	LAI effect on mobilization (most rapid to least rapid)	0.44, 1.03	0.41, 2.75
CRREF (2,3,4)	Carbohydrate status effect on refilling of storage tissue CH_2O pool	0.30, 0.77, 0.29	0.33, 0.81, 0.29
LRREF (1,2)	LAI effect on refilling of storage tissue CH_2O pool (least to most rapid)	0.65, 2.41	0.68, 2.58
PRREF (1,2)	Canopy photosynthesis effect on refilling of storage tissue CH_2O	0.30, 0.45	0.12, 0.38
CMOBMX	Maximum mobilization of CH_2O from vegetative tissues, fraction of available CH_2O pool per day	0.050	0.050
NMOBMX	Maximum mobilization of protein from vegetative tissues, fraction of available protein pool per day	0.088	0.080
CADSRF	Fraction of carbohydrate reserves that are allocated to storage	0.50	0.439

Table 9 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Marandu palisadegrass dataset) for senescence parameters

Name	Definition	Initial values	Optimized values
LFSEN	Natural leaf senescence rate/photothermal day (0.02 means 50-d of life span)	0.02	0.01
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	1.17	1.17
TCMP	Time constant (days) for senescence of lower leaves because of excessive self-shading by the crop canopy	13.1	13.1
PORPT	Stem senescence as a function of the senesced leaf mass (fraction)	0.27	0.27
SENSR	Senescence rate of storage organ tissue (proportion of cumulative storage mass lost per physiological day)	0.011	0.011

3.3.7 Biomass accumulation

The biomass accumulation for irrigated condition was well simulated by the recent model adaptation by PEDREIRA et al. (2011). However, with the optimizations we improved statistics mainly due to small adjustments in the species file related to differences between the two cultivars (Table 8). Figures 1 and 2 show good predictions of biomass for both 28-d and 42-d harvest frequencies under irrigated conditions.

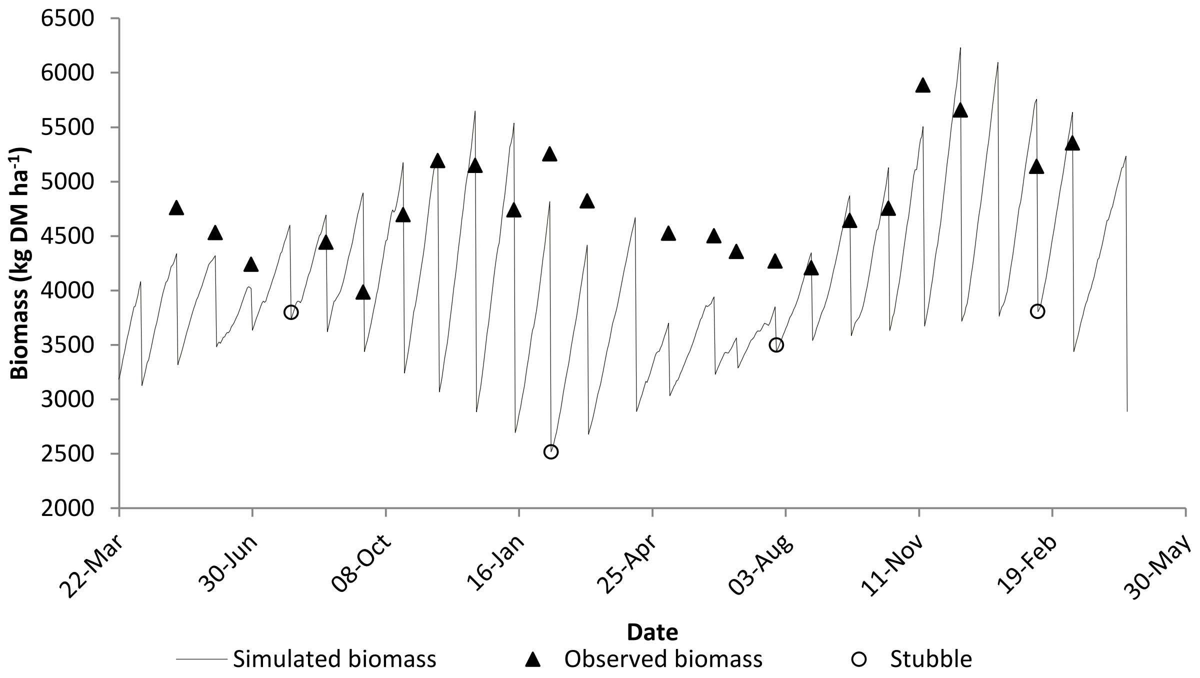

Figure 1 - Marandu palisadegrass biomass simulation irrigated and harvested each 28 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

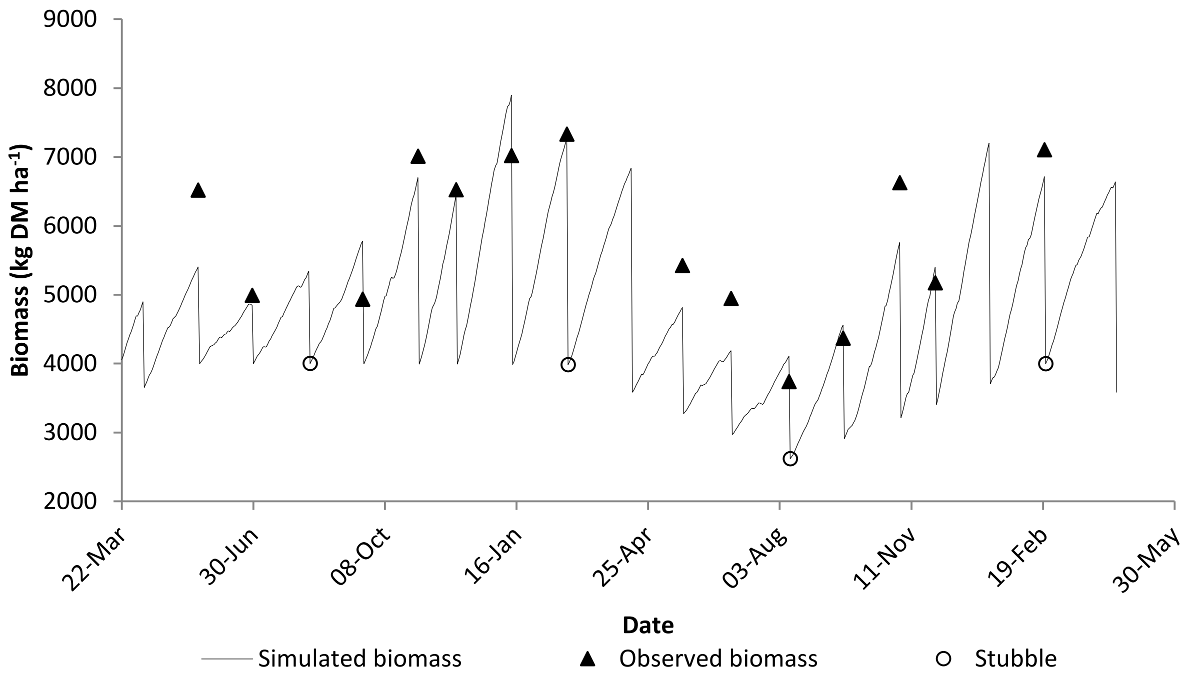

Figure 2 - Marandu palisadegrass biomass simulation irrigated and harvested each 42 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

For the rainfed condition we improved the simulation of biomass accumulation and solved the overestimation of water and N stress by using the evapotranspiration method of Penman-Montieth - FAO 56, instead of Priestley and Taylor method, and adjusting evapotranspiration ratio and soil runoff factor as well (Table 9). Figures 3 and 4 show good predictions of biomass for both 28-d and 42-d harvest frequencies under rainfed conditions.

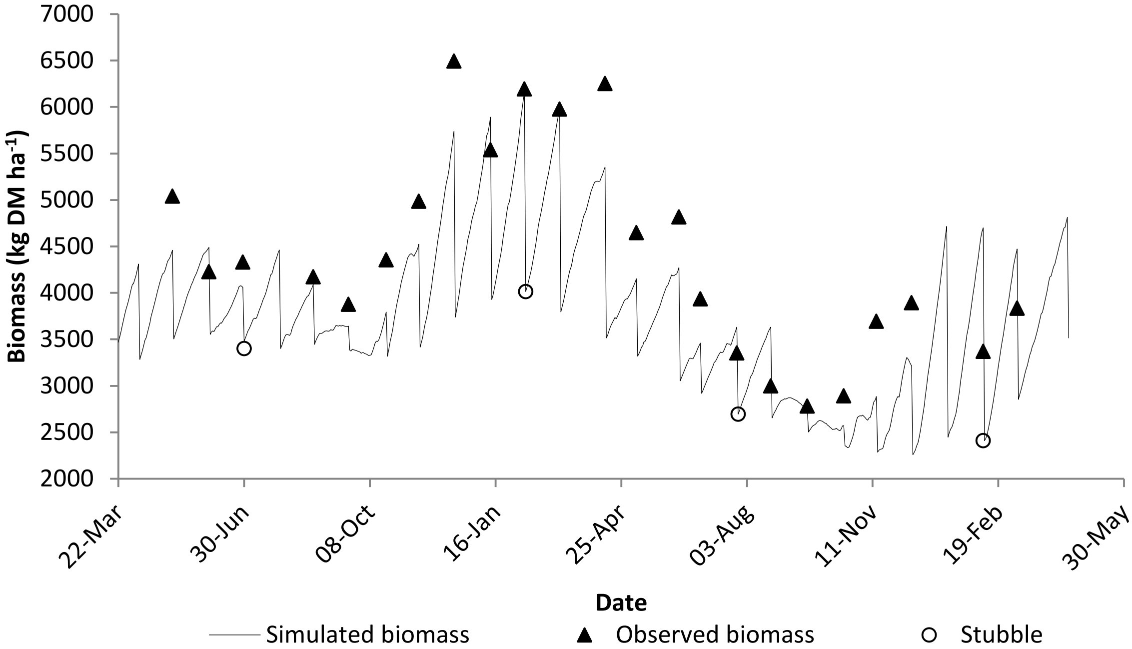

Figure 3 - Marandu palisadegrass biomass simulation rainfed and harvested each 28 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

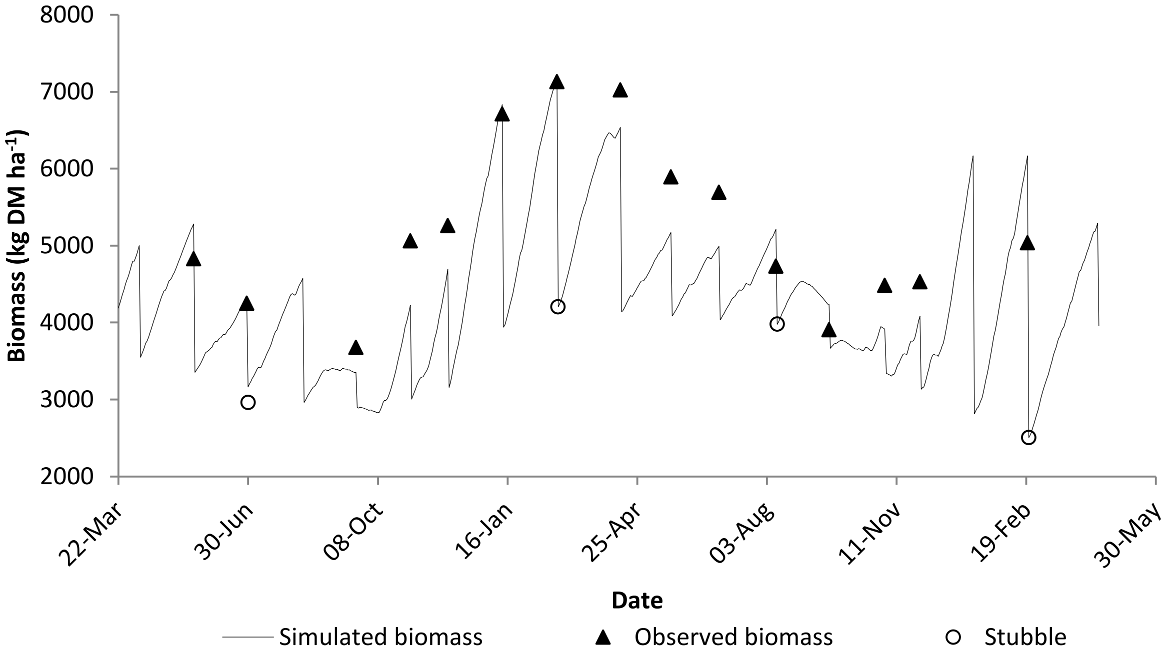

Figure 4 - Marandu palisadegrass biomass simulation rainfed and harvested each 42 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

Table 8. Means and statistics for simulations of irrigated Marandu palisadegrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, after optimizations.

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4566	4582	464	1.001	0.907
Leaf weight (kg DM ha^{-1})	1632	1596	291	0.991	0.961
Stem weight (kg DM ha^{-1})	2606	2655	207	1.024	0.956
LAI (m^2 m^{-2})	2.13	2.61	0.644	1.315	0.935
LI (% of incident light)	90.7	88.88	4.406	0.981	0.772
SLA (cm^2 g^{-1})	161.8	171.1	17.67	1.065	0.326
N (% on DM basis)	1.38	1.41	0.242	1.038	0.345
			42-days		
Biomass (kg DM ha^{-1})	5350	5249	523	0.987	0.962
Leaf weight (kg DM ha^{-1})	2119	1989	378	0.984	0.967
Stem weight (kg DM ha^{-1})	2776	2914	222	1.065	0.976
LAI (m^2 m^{-2})	3.63	3.48	0.722	1.033	0.964
LI (% of incident light)	93.93	93.76	3.192	0.999	0.628
SLA (cm^2 g^{-1})	183.6	174.5	16.34	0.954	0.504
N (% on DM basis)	1.40	1.38	0.223	1.010	0.329

Table 9. Means and statistics for simulations of rainfed Marandu palisadegrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, after optimizations.

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4299	4158	526	0.977	0.934
Leaf weight (kg DM ha^{-1})	1539	1597	383	1.057	0.915
Stem weight (kg DM ha^{-1})	2259	2285	192	1.022	0.967
LAI (m^2 m^{-2})	2.37	2.68	0.568	1.156	0.935
LI (% of incident light)	86.36	86.93	8.045	1.013	0.728
SLA (cm^2 g^{-1})	190.6	166.0	36.59	0.887	0.501
N (% on DM basis)	2.11	1.31	0.946	0.657	0.353
			42-days		
Biomass (kg DM ha^{-1})	4835	4735	501	0.984	0.957
Leaf weight (kg DM ha^{-1})	1819	1806	267	0.987	0.976
Stem weight (kg DM ha^{-1})	2610	2674	329	1.030	0.932
LAI (m^2 m^{-2})	2.38	3.05	1.076	1.431	0.877
LI (% of incident light)	90.47	89.30	8.361	0.993	0.681
SLA (cm^2 g^{-1})	146.3	165.3	31.45	1.157	0.479
N (% on DM basis)	2.05	1.23	0.901	0.614	0.330

3.4 Summary and Conclusions

The *Brachiaria brizantha* version of CROPGRO perennial forage model adapted for the Xaraés cultivar by Pedreira et al., (2011) can accurately simulate the growth and forage yield of Marandu palisadegrass under irrigated condition. Under rainfed conditions, the simulations using the Penman-Monteith-FAO 56 method gave more realistic water stress responses than using the Priestley and Taylor method. The partitioning parameters from *B. brizantha* model were modified to provide more stem and storage for longer regrowth periods. N concentration was simulated and optimized with field data but changes in the code are necessary to improve predictions accuracy. Parameters relative to temperature, photoperiod and solar radiation on photosynthesis processes, partitioning, and mobilization were necessary to increase partitioning and mobilization cycling during regrowth. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Marandu palisadegrass under irrigated and rainfed conditions. Additional validation should be performed to test these results, which can be added into the CROPGRO perennial forage model and the DSSAT software package to be used as a decision support tool in a real system of livestock production.

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4 CALIBRATION OF THE CROPGRO – PERENNIAL FORAGE MODEL TO SIMULATE GROWTH OF CONVERT HD 364 BRACHIARIAGRASS UNDER IRRIGATED AND RAINFED CONDITIONS

Abstract

Crop models are tools widely used to study crop growth and physiological aspects of plants and to identify gaps of knowledge for genetic improvement and management strategies. Convert HD 364 brachiariagrass, a new *Brachiaria* hybrid, was released as an option for a broad range of environmental conditions, high nutritive quality and forage production. The objective of this research was to use the CROPGRO – Perennial Forage Model to simulate the irrigated and rainfed growth of Convert HD 364 (*Brachiaria* spp.), using the model previously calibrated for the tall-growing Xaraes cultivar of the same genus, under non-limiting water conditions. Our null hypothesis was that the forage model previously calibrated for a given cultivar of a species, can accurately simulate the growth and forage yield of a hybrid of the same genus under irrigated and rainfed conditions. Data used to calibrate the model included forage production, plant-part composition, leaf photosynthesis, leaf area index, specific leaf area, light interception and nitrogen concentration from a field experiment conducted in 2011, 2012 and 2013 in Piracicaba, SP, Brazil. Agronomic and morpho-physiological differences between the two grasses, such as maximum leaf photosynthesis, nitrogen concentration and temperature effect on growth rate, were considered in the calibration. Irrigated Convert HD 364 was well simulated by the previous adaptation for *Brachiaria* cultivars. Under rainfed conditions, the simulations using Penman-Monteith FAO 56 method gave more realistic water stress response than using the Priestley and Taylor method. After model adjustments, the mean simulated herbage yield was 4939, and 5189, for 28-d and 42-d irrigated, and 4431 and 5383 kg ha^{-1}, for 28-d and 42-d rainfed, respectively. The RMSE ranged from 532 to 738 kg ha^{-1} and D-Stat from 0.880 to 0.963. The simulated/observed ratio were from 0.950 to 1.027. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Convert HD 364 brachiariagrass under irrigated and rainfed conditions.

Keywords: *Brachiaria* hybrid; DSSAT; Mulato II; Pasture model; Tropical grass

4.1 Introduction

Grasses of the genus *Brachiaria* (syn. *Urochloa*) are widely used in planted pastures by the livestock industry in Brazil, totaling 80% of cultivated pasture area (FONSECA et al., 2006). ‘Mulato’ brachiariagrass (*Brachiaria* hybrid CIAT 36061) was the first *Brachiaria* hybrid originated from the cross between ruzigrass [*Brachiaria ruziziensis* (R. Germ. & C. M. Evrard)] Crins (syn. *Urochloa ruziziensis* Germain and Evrard); clone 44-6] and palisadegrass [*Brachiaria brizantha* (A. Rich.) Stapf, CIAT 6297]. (INYANG et al., 2010). ‘Mulato II’ brachiariagrass (Convert HD 364®) was later developed from three generations of hybridization between ruzigrass (clone 44-6) and signalgrass [*Brachiaria decumbens* (Stapf)

R. D. Webster (syn. *Urochloa decumbens* (Stapf) R. D. Webster)] (cv. Basilisk), where the first generation was exposed to open pollination from lines of *B. brizantha*, including cv. Marandu (ARGEL et al., 2007). This genotype was subsequently identified as *Brachiaria* hybrid accession CIAT 36087 and it was released in 2005 as cv. Mulato II by Semillas Papalotla S.A., Mexico. ‘Mulato II’ was developed to have a broad range of adaptation (including acid soils of low fertility and moderate moisture saturation), high nutritive quality and forage production, and good-quality seed (ARGEL et al., 2007) as well as an option to be used in replacement of Marandu palisadegrass in some degraded pasture areas affected with Marandu death syndrome (DIAS-FILHO, 2005). ‘Mulato II has been commercialized as Convert HD 364® by Dow AgroSciences, Brazil, in 2009.

Despite the importance of pasture-based systems for livestock production in Brazil, intensive pasture management has been a challenge, because stocking rates should ideally be adjusted based on the carrying capacity of the pasture so as to achieve high grazing efficiency (SOLLENBERGER et al., 2005). Forage production and sward characteristics are very sensitive to environmental conditions, such as rainfall, air temperature and incoming solar radiation (TAIZ; ZEIGER, 2004). The pasture management aspects, such as the amount of fertilizer applied (WOODARD; SOLLENBERGER, 2011), and the harvest management with the frequency and intensity of defoliation (PEDREIRA et al., 2009) play an important role in the sward morphology, chemical composition, and in the forage production as well. Thus, mechanistic models can be used to integrate plant responses based on site-specific aspects, and have been useful as decision support tools (BOOTE et al., 1998). For this purpose, models should be extensively calibrated and validated to exhibit reasonable accuracy under a wide range of management practices and environmental conditions (HOOGENBOOM et al. 1994).

When physiological processes are well understood, they can be synthesized using crop models, which can become an important tools in research, allowing simulations of scenarios and assisting decisions in genetic improvement programs, in strategies of soil and cultural management, besides being useful in future climate change simulations (BOOTE et al., 1998; ASSENG et al., 2013). The CROPGRO model is a mechanistic model that predicts production and crop tissue composition based on the plant, climate information, and soil management, enabling the simulation of water and nitrogen balance, organic matter and dynamics of residues into the soil, and damage by pests and/or diseases, which results in numerous applications (BOOTE et al., 2002; JONES et al., 2003).

In 1995, the CROPGRO model was initially adapted as an annual version for *Paspalum notatum* Flugge in order to simulate the growth of pasture as a rotation component of the crop cultivation with peanut in Florida, which was used in systems of crop rotation with corn in the previous version (KELLY, 1995). The results of these simulations were inserted in an economic model to predict the sustainability and viability of the crop peanuts. The species, cultivar, and ecotype files were released later as a model of "grazing" in the DSSAT models (the Decision Support System for Agrotechnology Transfer) version 3.5 (ICASA, 1998). In addition to estimating the production of *P. notatum*, the DSSAT later included an “annualized” version adapted for *Brachiaria decumbens* (GIRALDO et al., 2001), using data from the international network of Tropical Pasture evaluation, CIAT, Colombia.

This “annualized” version of the model was used to simulate hay production of *P. notatum*, but revealed a consistent overestimation of dry matter production, particularly in the colder months. Thus, in 2004 this aspect was evaluated by Rymph et al. (2004) by means of model calibration and adjustments to parameters, getting more realistic representations of seasonal growth and *P. Notatum* growth rate.

Nevertheless, Rymph et al. (2004) concluded that a true perennial version was needed that included a state variable for storage of reserves by the plant. For these reasons, Rymph (2005) developed a true perennial version of the model by adding a state variable for storage of C and N reserves, along with rules for use of those reserves for re-growth even after complete defoliation or surface winter-kill (which the annualized version would not tolerate). In addition to new code, Rymph developed parameterization and released the CROPGRO Perennial Forage model (for version 4.0), giving it the ability to estimate the re-growth and nitrogen concentration of the tissues of *P. notatum* in response to daily variations in climate, fertilization and crop management. These improvements have not yet been incorporated into the publically-released DSSAT models, but the model code has been improved and used in adaptations of parameters to allow prediction of several other tropical forages. More recently, using as a basis the CROPGRO Perennial Forage developed for *P. notatum*, efforts were successful in adapting the model to estimate the growth of *Brachiaria brizantha* and *Panicum maximum* for Brazilian locations (PEDREIRA et al., 2011; LARA et al., 2012).

The objective of this research was to evaluate the CROPGRO – Perennial Forage Model for simulating the irrigated and rainfed growth of Convert HD 364 brachiariagrass, using the model previously calibrated for Xaraes palisadegrass under non-limiting water conditions (PEDREIRA et al., 2011). Our null hypothesis was that the forage model previously calibrated by Pedreira et al., (2011) when used for different pasture cultivar hybrid within the same genus, can accurately simulate growth and forage yield under irrigated and rainfed conditions. Failure to accurately predict growth and forage yield could be attributed to requirement for parameterization of cultivar specific traits when using the model for this purpose.

4.2 Materials and Methods

The information relative to field experimental data and treatments, model calibration and statistical evaluation of model performance were presented in Chapter 3 of this dissertation.

4.3 Results and discussion

4.3.1 Simulation of irrigated and rainfed Convert HD 364 using original *B. brizantha* adaptation

For the irrigated dataset, the *Brachiaria brizantha* version of CROPGRO Perennial Forage model adapted by Pedreira et al., (2011) for Xaraes palisadegrass simulated both harvest frequency of 28 and 42 days quite well, using the Convert HD 364 dataset (Table 4). To the extent that Convert HD 364 and Xaraes are genotypes within the same genus, this is not surprising, although they have distinct agronomic and morphological characteristics. The rainfed simulation, on the other hand, showed a reasonable underestimation for biomass, stem weight (mainly in the 42 days of harvest frequency), light interception (LI) and N concentration, which was due to an overestimation of water and N stress (Table 5).

Table 4 - Means and statistics for simulations of irrigated Convert HD 364 brachiariagrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, simulated using the original *Brachiaria brizantha* adaptation by Pedreira et al. (2011)

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	5125	4714	874	0.919	0.819
Leaf weight (kg DM ha^{-1})	1647	1664	549	1.006	0.915
Stem weight (kg DM ha^{-1})	2936	2615	441	0.888	0.770
LAI (m^2 m^{-2})	2.00	2.51	0.963	1.236	0.868
LI (% of incident light)	91.91	84.57	11.25	0.916	0.631
SLA (cm^2 g^{-1})	121.8	150.9	31.66	1.250	0.345
N (% on DM basis)	1.71	1.36	0.452	0.803	0.381
			42-days		
Biomass (kg DM ha^{-1})	5088	4939	627	0.973	0.951
Leaf weight (kg DM ha^{-1})	2328	2218	321	0.950	0.983
Stem weight (kg DM ha^{-1})	2413	2424	113	1.017	0.991
LAI (m^2 m^{-2})	4.04	3.41	0.987	0.861	0.946
LI (% of incident light)	94.38	92.71	4.79	0.983	0.672
SLA (cm^2 g^{-1})	175.2	153.0	30.75	0.892	0.530
N (% on DM basis)	1.54	1.48	0.297	0.993	0.493

Table 5 - Means and statistics for simulations of rainfed Convert HD 364 brachiariagrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, simulated using the original *Brachiaria brizantha* adaptation by Pedreira et al. (2011)

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4595	3831	1065	0.844	0.683
Leaf weight (kg DM ha^{-1})	1864	1779	535	0.965	0.858
Stem weight (kg DM ha^{-1})	2276	1878	498	0.846	0.827
LAI (m^2 m^{-2})	3.07	2.62	1.018	0.893	0.851
LI (% of incident light)	87.41	83.75	11.11	0.962	0.633
SLA (cm^2 g^{-1})	195.0	144.5	66.19	0.776	0.509
N (% on DM basis)	2.02	1.41	0.722	0.722	0.427
			42-days		
Biomass (kg DM ha^{-1})	5719	4197	1877	0.755	0.639
Leaf weight (kg DM ha^{-1})	2034	1874	505	0.920	0.940
Stem weight (kg DM ha^{-1})	3052	2227	1097	0.752	0.451
LAI (m^2 m^{-2})	2.94	2.80	0.626	0.960	0.964
LI (% of incident light)	92.13	86.37	10.84	0.940	0.606
SLA (cm^2 g^{-1})	150.2	145.7	19.19	0.982	0.456
N (% on DM basis)	1.87	1.36	0.613	0.745	0.399

4.3.2 Model calibration for irrigated and rainfed Convert HD 364

The irrigated experiment did not show any water and nitrogen stress. The absence of water and nitrogen deficit in the irrigated experiment allowed for calibration of the model parameters for ideal conditions. In this situation the uncontrollable environment factors (daylength, temperature, solar radiation, etc.) can be calibrated in the model. On the other hand, the rainfed experiment, with some short-term water and nitrogen limitation, allows for potential calibration of some parameters relative to water and nitrogen stress.

We changed the evapotranspiration method to Penman-Monteith-FAO 56, from the Priestley and Taylor method. This gave a more realistic estimation of evapotranspiration, which decreased water and nitrogen stress overestimation. Additionally, we decreased soil runoff from 0.76 to 0.70 due to unrealistic low water infiltration, and we decreased the computation of the potential evapotranspiration at LAI of 6 (EORATIO) from 1.0 to 0.9 based on water stress vs. field simulation growth data graphics. Marin et al. (2011), parameterizing the DSSAT/CANEGRO model for irrigated and rainfed sugarcane (*Saccharum* spp.) also in Southern Brazil stated that some potential reasons for inaccuracy in the water availability is under or overestimation of hydraulic conductivity at saturation (Ksat), root water uptake, and errors in root simulation, mainly in deeper horizons.

The temperature parameters were optimized using biomass accumulation data for base temperature (Tb) and first optimum temperature (TO1), which are phenology- driven parameters. We kept the same Tb (10.0 ºC) and TO1 (32.0 ºC) based on generalized likelihood uncertainty (GLUE) method optimization (Table 6).

Photosynthesis and respiration parameters were adjusted based on the field measurements and GLUE optimizations using biomass and photosynthesis data. There are two options to simulate plant respiration: mass- or protein-based, set via the MRSWITCH parameter. We used mass-based because there is more information on the biomass data set than on protein-based information. The maintenance respiration as a function of total crop dry weight (RES30C) was maintained unchanged. Maximum leaf photosynthesis (LFMAX) was decreased and set at 1.74 mg CO_2 m^{-2} s^{-1}, to match observed field data (data not shown). The leaf N concentration effect on photosynthesis (FNPGN) was kept the same, with 4% of nitrogen for maximum photosynthesis. The specific leaf weight at which LFMAX is defined (SLWREF) was set based on GLUE optimization for biomass data (Table 6).

4.3.3 Partitioning to storage, regrowth, and winter dormancy

After defoliation, the regrowth is highly dependent on stubble leaf area, tiller density and organic reserves of the forage plant. For most of non-rhizomatous tropical forage grasses, such as *Brachiaria* genotypes, storage organs can be located in tiller bases and roots. Photosynthate partitioning to storage organs is driven by assimilate supply, leaf area index, and storage "rules" that include effects of decreased daylength and temperature. In addition, decrease of forage accumulation during the "winter" months (April-September) is adjusted by "dormancy" parameters, triggered by low temperature and short photoperiod, and adjusted by temperature effects on photosynthesis. The GLUE optimization was used to adjust the sensitivity of single-leaf light-saturated photosynthesis rate to minimum night temperature (FNPGL) and the function describing relative rate of photosynthetic electron transport in response to current temperature (XLMAXT). Optimizations were made for daylength effect (FNPTD and FNPMD) and for relative dormancy sensitivity effect of daylength (RDRMM and RDRMT) on mobilization and partitioning to increase seasonal variations during regrowth, making the model slightly more sensitive to daylength effect (Table 7).

To ensure good simulation of the regrowth cycles, carbon and nitrogen mining parameters were optimized. The minimum daily rate of CH_2O and N mobilization from storage (CMOBSRN and NMOBSRN) was kept the same and maximum values (CMOBSRX and NMOBSRX) were increased to better adjust speed of early regrowth and N simulations for Convert HD 364 brachiariagrass dataset (Table 6). The concentration of carbohydrate in newly produced storage tissue (ALPHSR) was kept the same. However, the maximum fraction of photosynthate which can be allocated to refill storage tissue (CADPV) was decreased. It was done to adjust rapid regrowth and partitioning to leaf and stem. LAI effect on mobilization (LRMOB-4) and on refilling of storage tissue carbohydrate pool (LRREF) was modified to allow high mobilization ability for re-growth and the refill occurs mostly under high LAI, mainly to stem in 42-d treatment (Table 8). Carbohydrate status and canopy photosynthesis effect on refilling of storage tissue (CRREF and PRREF) was optimized to enhance refill of storage tissue under lower storage reserve levels and at times of greater canopy photosynthesis. Maximum mobilization of CH_2O and protein from vegetative tissues (CMOBMX and NMOBMX) were kept close to previous calibration for *Brachiaria brizantha* (PEDREIRA et al., 2011). Fraction of carbohydrate reserves that are allocated to storage (CADSRF) was slightly increased to improve storage refill cycling.

4.3.4 N concentration in the forage mass

Plant growth is greatly affected by the supply of N. Critical concentration of N required for optimum growth changes with physiological age and is defined as the lowest concentration at which maximum growth occurs. The tissue N concentration below this critical concentration affects growth process. Above this critical concentration there is no further increase in growth rate and luxury consumption of N occurs (Godwin and Singh 1998). We changed leaf and stem N concentration based on GLUE optimization with crude protein data. The fairly poor N predictions (Table 8 and 9) require more improvements (ALDERMAN, 2008).

4.3.5 Partitioning to leaf, stem, and root

Initial simulations with the *B. brizantha* version of CROPGRO perennial forage model adapted by Pedreira et al., (2011) showed the need to modify partitioning parameters (YLEAF, YSTEM and YSTOR values) to increase allocation to stem growth, mainly for the 42-d harvest frequency treatment (Table 7). It is common for tropical forage grasses to increase stem elongation associated with longer harvest frequency. Partitioning to storage was increased considerable compared to Pedreira et al. (2011) values to reduce dependence of regrowth on low stubble LAI which occurred for the 42-d low harvest frequency treatment.

4.3.6 Prediction of specific leaf area, leaf area index, and light interception

The plant growth rate is a function of LAI and photosynthetic efficiency of leaves. The light interception increases due to LAI increment, affecting C fixation of the sward canopy through photosynthesis. The specific leaf area showed seasonal variation relative to light and temperature. The SLAVR was increased to 190 cm^2 g^{-1} as a standard reference cultivar at peak early vegetative phase, under standard growing conditions (optimum temperature, water and high light). The SLA simulations show reduction during cool temperature or water deficit and increased under low light. We used GLUE method to optimize the thinnest SLAMAX and thickest (SLAMIN) leaves in response to temperature effect (XSLATM and YSLATM) of newly-formed leaves using observed SLA data. The leaf appearance rate on main stem (TRIFL) was kept at 0.15 leaves per thermal day, according to values reported in the literature for *Brachiaria* spp. (PEDREIRA et al., 2011).

In the model, LAI is a cumulative result of daily assimilate partitioning from photosynthesis to leaves at a given SLA under those conditions. Model simulations of LAI and light interception were compared to observed. Leaf area index was calculated from destructive samples, hand-separated and scanned in a model LI-3100 leaf area meter (Li-Cor, Lincoln, NE) for accumulated total or stubble LAI. The light interception was measured using data collected with the LAI-2000 canopy analyzer).

Table 6 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Convert HD 364 brachiariagrass dataset) for plant composition, phenology, and productivity (photosynthesis and respiration)

Name	Definition	Initial values	Optimized values
PRO_ _G	"normal growth" protein conc. Fraction of tissue (leaf = LF, root = RT, stem = ST, storage organ = SR	LF=0.110;RT=0.040 ST=0.070;SR=0.064	LF=0.180;RT=0.040 ST=0.090;SR=0.064
PRO_ _I	"Maximum" protein concentration of tissue	LF=0.220;RT=0.101 ST=0.110;SR=0.092	LF=0.270;RT=0.101 ST=0.135;SR=0.092
PRO_ _F	"Final" protein concentration of tissue	LF=0.050;RT=0.022 ST=0.033;SR=0.056	LF=0.040;RT=0.022 ST=0.030;SR=0.056
Tb	Base temperature, ºC	10.0	10.0
TO1	First optimum temperature, ºC	32.0	32.0
TO2	Second optimum temperature, ºC	40.0	40.0
TM	Maximum temperature for vegetative development, ºC	45.0	45.0
MRSWITCH	Respiration: M = mass based (original CROPGRO code) or P = protein based	M	M
RES30C	Constant describing maintenance respiration as a function of total crop dry weight (minus oil, protein, and starch in the seed), g CH_2O (dry weight)$^{-1}$ h^{-1}	3.0 x 10^{-4}	3.0 x 10^{-4}
R30C2	Constant describing maintenance respiration as a function of canopy photosynthesis, g CH_2O g^{-1} photosynthate CH_2O h^{-1}	0.0024	0.0024
LFMAX	Maximum leaf photosynthetic rate at 30ºC, 350 ppm CO_2, and high light, , mg CO_2 m^{-2} s^{-1}	1.89	1.74
FNPGN (1-2)	Leaf N conc. effect on photosynthesis or FNPGN(2), which is a two-sided quadratic curve describing leaf photosynthesis response to leaf N conc.: increases from zero at the min. leaf N conc. to max. leaf N conc.	0.80, 4.00	0.80, 4.00
SLWREF	Specific leaf weight at which LFMAX is defined (g m^{-2})	0.0078	0.0067

Table 7 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Convert HD 364 brachiariagrass dataset) for temperature, solar radiation, and photoperiod effects on vegetative partitioning, specific leaf area, and photosynthesis

Name	Definition	Initial values	Optimized values
XLEAF	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	Describes dry matter partitioning to leaf among vegetative tissue only, as a function of vegetative stage (fraction)	0.8, 0.8, 0.8, 0.75, 0.5, 0.4, 0.4, 0.4	0.78, 0.78, 0.72, 0.65, 0.57, 0.53, 0.5, 0.5
YSTEM	Describes dry matter partitioning to stem among vegetative tissue only, as a function of vegetative stage (fraction)	0.1, 0.1, 0.17, 0.17, 0.15, 0.16, 0.16, 0.16	0.1, 0.1, 0.15, 0.19, 0.27, 0.33, 0.35, 0.35
YSTOR	Describes dry matter partitioning to storage among vegetative tissue only, as a function of vegetative stage (fraction)	0.01, 0.01, 0.01, 0.02, 0.02, 0.03, 0.03, 0.03	0.03, 0.03, 0.03, 0.03, 0.03, 0.03, 0.03, 0.03
SLAVR	Specific leaf area of cultivar under standard growth conditions ($cm^2 g^{-1}$)	170	190
SLAMAX	SLAMAX is the (thinnest) leaves under low light (cm^2 g^{-1})	358	340
SLAMIN	SLAMIN is the (thickest) leaves under high light (cm^2 g^{-1})	130	139
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) (ºC)	7.6, 20.9	6.0, 19.2
XLMAXT(2-3)	Relative rate of photosynthetic electron-transport in response to temperature, linear from base (0.0) to maximum (1.0) (ºC)	10.4, 38.0	6.3, 38.0
XSLATM(3-4)	Relative temperature effect on specific leaf area of newly formed leaves, ºC (x vs. y pair)	11.0, 26.0	10.0, 24.0
YSLATM(3-4)	Relative temperature effect on specific leaf area of newly formed leaves, fraction reduction (x vs. y pair)	0.29, 1.00	0.45, 1.00
FNPTD (2-3)	Daylength effect on partitioning (h)	10.3, 15.2	12.0, 16.0
FNPMD(1-3)	Daylength effect on mobilization (h)	10.1, 14.5, 0.46	8.0, 12.3, 0.62
RDRMT	Relative dormancy sensitivity, day-length effect on partitioning	0.405	0.476
RDRMM	Relative dormancy sensitivity, day-length effect on mobilization	0.532	0.861

Table 8 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Convert HD 364 brachiariagrass dataset) for carbon and nitrogen mining parameters

Name	Definition	Initial values	Optimized values
CMOBSRN	Minimum daily rate of CH_2O mobilization from storage (fraction)	0.020	0.020
CMOBSRX	Maximum daily rate of CH_2O mobilization from storage (fraction)	0.050	0.072
NMOBSRN	Minimum daily rate on N mobilization from storage (fraction)	0.010	0.010
NMOBSRX	Maximum daily rate of N mobilization from storage (fraction)	0.060	0.068
ALPHSR	Fraction of new storage tissue growth that is available CH_2O (fraction)	0.20	0.20
CADPV	Maximum fraction of photoassimilate available that can be allocated to CH_2O refill during non-stress conditions	0.437	0.310
LRMOB (3,4)	LAI effect on mobilization (most rapid to least rapid)	0.44, 1.03	0.40, 2.71
CRREF (2,3,4)	Carbohydrate status effect on refilling of storage tissue CH_2O pool	0.30, 0.77, 0.29	0.30, 0.76, 0.25
LRREF (1,2)	LAI effect on refilling of storage tissue CH_2O pool (least to most rapid)	0.65, 2.41	0.61, 2.62
PRREF (1,2)	Canopy photosynthesis effect on refilling of storage tissue CH_2O	0.30, 0.45	0.12, 0.37
CMOBMX	Maximum mobilization of CH_2O from vegetative tissues, fraction of available CH_2O pool per day	0.050	0.050
NMOBMX	Maximum mobilization of protein from vegetative tissues, fraction of available protein pool per day	0.088	0.080
CADSRF	Fraction of carbohydrate reserves that are allocated to storage	0.50	0.506

Table 9 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Convert HD 364 brachiariagrass dataset) for senescence parameters

Name	Definition	Initial values	Optimized values
LFSEN	Natural leaf senescence rate/photothermal day (0.02 means 50-d of life span)	0.02	0.01
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	1.17	1.17
TCMP	Time constant (days) for senescence of lower leaves because of excessive self-shading by the crop canopy	13.1	13.1
PORPT	Stem senescence as a function of the senesced leaf mass (fraction)	0.27	0.27
SENSR	Senescence rate of storage organ tissue (proportion of cumulative storage mass lost per physiological day)	0.011	0.011

4.3.7 Biomass accumulation

The biomass accumulation for irrigated condition was well simulated by the recent model adaptation by PEDREIRA et al. (2011). However, with the optimizations we improved statistics mainly due to small adjustments in the species file related to differences between the two cultivars (Table 8). Figures 1 and 2 show good predictions of biomass for both 28-d and 42-d harvest frequencies under irrigated conditions.

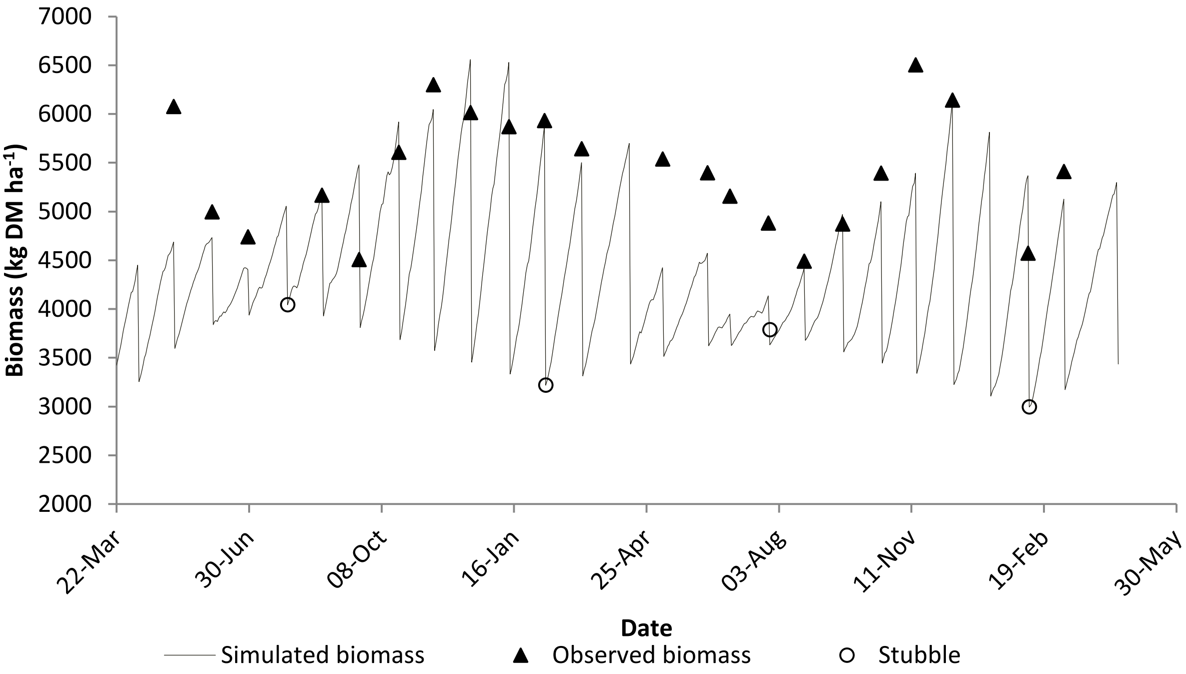

Figure 1 - Irrigated Convert HD 364 biomass simulation harvested each 28 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

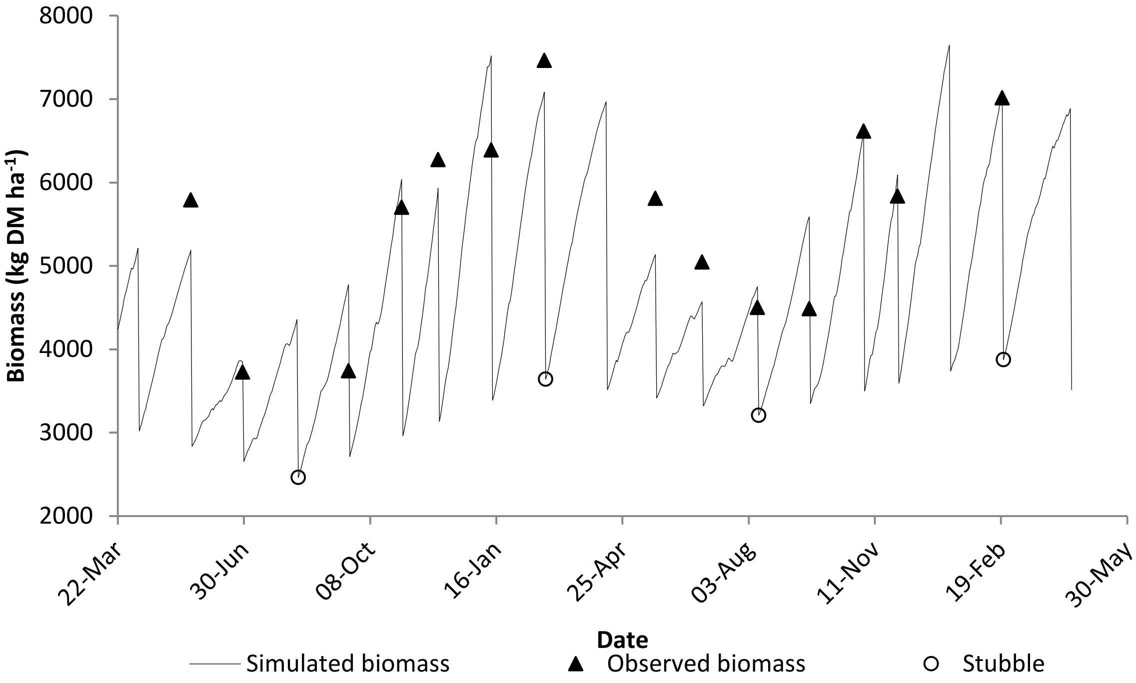

Figure 2 - Irrigated Convert HD 364 biomass simulation harvested each 42 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

For the rainfed condition we improved the simulation of biomass accumulation and solved the overestimation of water and N stress by using the evapotranspiration method of Penman-Montieth - FAO 56, instead of Priestley and Taylor method, and adjusting evapotranspiration ratio and soil runoff factor as well (Table 9). Figures 3 and 4 show good predictions of biomass for both 28-d and 42-d harvest frequencies under rainfed conditions.

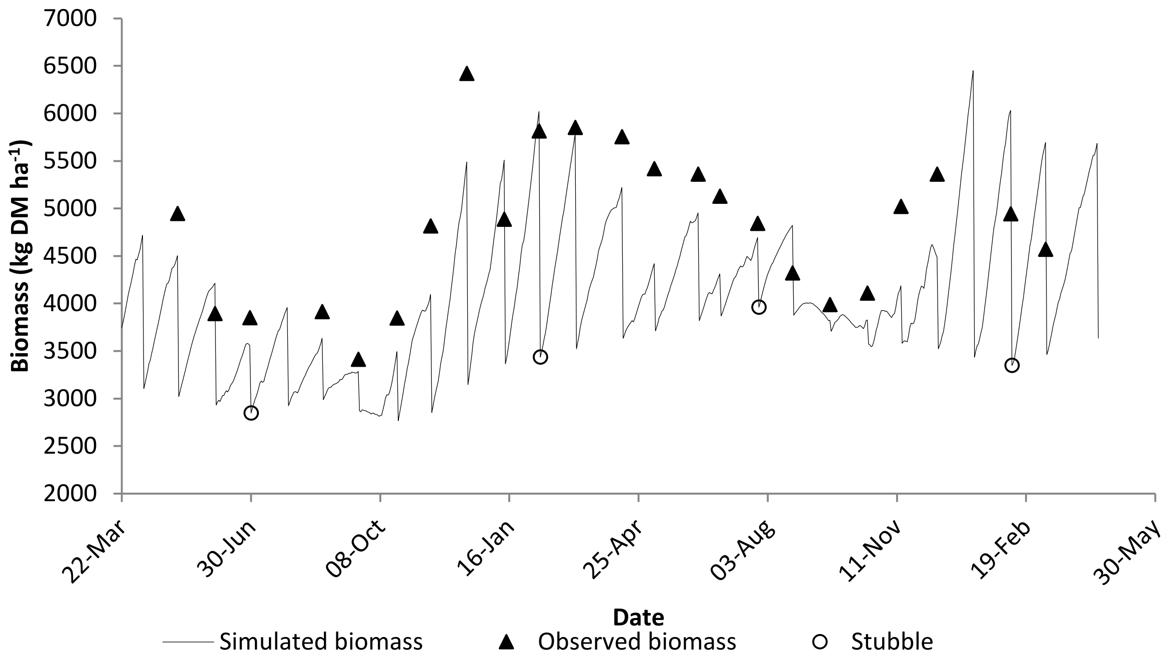

Figure 3 - Rainfed Convert HD 364 biomass simulation rainfed and harvested each 28 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

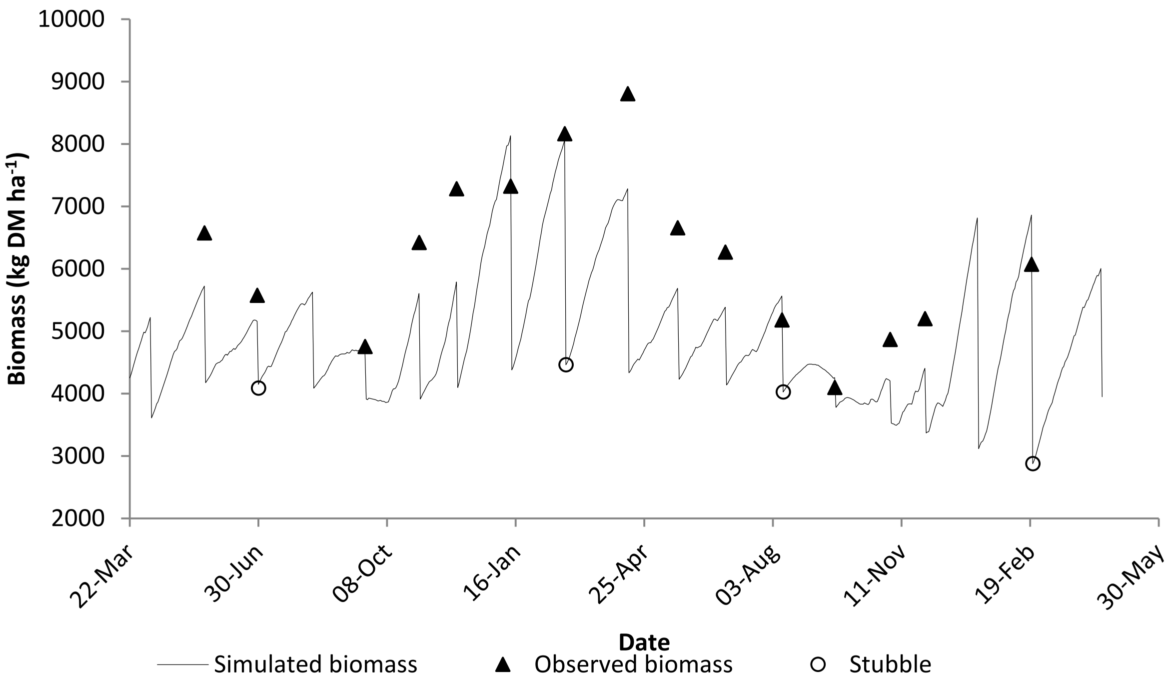

Figure 4 - Rainfed Convert HD 364 biomass simulation rainfed and harvested each 42 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

Table 8 - Means and statistics for simulations of irrigated Convert HD 364 brachiariagrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, after optimizations

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	5125	4939	619	0.968	0.880
Leaf weight (kg DM ha^{-1})	1647	1603	465	0.991	0.928
Stem weight (kg DM ha^{-1})	2936	2885	165	0.987	0.941
LAI (m^2 m^{-2})	2.00	2.81	1.17	1.424	0.815
LI (% of incident light)	91.91	88.62	5.338	0.963	0.818
SLA (cm^2 g^{-1})	121.8	175.3	54.86	1.452	0.253
N (% on DM basis)	1.71	1.54	0.332	0.915	0.280
			42-days		
Biomass (kg DM ha^{-1})	5088	5189	532	1.027	0.963
Leaf weight (kg DM ha^{-1})	2328	2291	164	0.993	0.995
Stem weight (kg DM ha^{-1})	2413	2588	232	1.088	0.966
LAI (m^2 m^{-2})	4.04	4.09	0.583	1.041	0.982
LI (% of incident light)	94.38	95.11	3.689	1.009	0.528
SLA (cm^2 g^{-1})	175.2	177.8	21.71	1.037	0.491
N (% on DM basis)	1.54	1.73	0.296	1.158	0.638

Table 9 - Means and statistics for simulations of rainfed Convert HD 364 brachiariagrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, after optimizations

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4595	4431	571	0.969	0.890
Leaf weight (kg DM ha^{-1})	1864	1862	387	0.999	0.926
Stem weight (kg DM ha^{-1})	2276	2295	185	1.01	0.979
LAI (m^2 m^{-2})	3.07	3.19	0.874	1.086	0.892
LI (% of incident light)	87.41	89.42	8.209	1.03	0.675
SLA (cm^2 g^{-1})	195.0	168.6	52.09	0.908	0.484
N (% on DM basis)	2.02	1.55	0.657	0.798	0.355
			42-days		
Biomass (kg DM ha^{-1})	5719	5383	738	0.950	0.932
Leaf weight (kg DM ha^{-1})	2034	1986	323	0.969	0.975
Stem weight (kg DM ha^{-1})	3052	3109	335	1.029	0.921
LAI (m^2 m^{-2})	2.94	3.44	0.780	1.183	0.952
LI (% of incident light)	92.13	90.92	7.244	0.991	0.683
SLA (cm^2 g^{-1})	150.2	169.5	27.48	1.144	0.509
N (% on DM basis)	1.87	1.38	0.636	0.756	0.324

4.4 Summary and Conclusions

The *Brachiaria brizantha* version of CROPGRO perennial forage model adapted for the Xaraés cultivar by Pedreira et al., (2011) can accurately simulate the growth and forage yield of Convert HD 364 brachiariagrass under irrigated condition. Under rainfed conditions, the simulations using the Penman-Monteith-FAO 56 method gave more realistic water stress responses than using the Priestley and Taylor method. The partitioning parameters from *B. brizantha* model were modified to provide more stem and storage for longer regrowth periods using the plant-part composition of the 42-d treatment. SLA and N were improved with field data but changes in the code are necessary to improve simulations. Parameters relative to temperature, photoperiod and solar radiation on photosynthesis processes, partitioning, and mobilization were necessary to increase partitioning and mobilization cycling during regrowth. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of *Brachiaria* hybrid cv. Convert HD 364 under irrigated and rainfed conditions. Additional validation should be performed to test these results, which can be added into the CROPGRO perennial forage model and the DSSAT software package to be used as a decision support tool in a real system of livestock production.

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5 ADAPTING THE CROPGRO – PERENNIAL FORAGE MODEL TO PREDICT GROWTH OF TIFTON 85 BERMUDAGRASS UNDER IRRIGATED AND RAINFED CONDITIONS

Abstract

Tifton 85 bermudagrass (*Cynodon* ssp.) has been one of the most successful pasture cultivars in tropical and subtropical areas. Among other *Cynodon* cultivars, it is one of the most productive and has a remarkably high nutritive value. The objective of this research was to adapt the CROPGRO – Perennial Forage Model to simulate accurately the growth of irrigated and rainfed Tifton 85 bermudagrass, and to describe model adaptation for this species. Data used to calibrate the model included forage production, plant-part composition, leaf photosynthesis, leaf area index, specific leaf area, light interception and plant nitrogen concentration from a field experiment conducted in 2011, 2012 and 2013 in Piracicaba, SP, Brazil. Agronomic and morpho-physiological aspects, such as maximum leaf photosynthesis, nitrogen concentration and temperature effect on growth rate, were considered in the calibration. Under rainfed conditions, the simulations using Penman-Monteith FAO 56 method gave more realistic water stress response than using the Priestley and Taylor method. After model adjustments, the mean simulated herbage yield was 4642, and 5402, for 28-d and 42-d irrigated, and 4244 and 4856 kg ha^{-1}, for 28-d and 42-d rainfed, respectively. The RMSE ranged from 313 to 630 kg ha^{-1} and D-Stat from 0.810 to 0.979. The simulated/observed ratio were from 0.949 to 1.023. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Tifton 85 bermudagrass under irrigated and rainfed conditions.

Keywords: *Cynodon* spp.; DSSAT; Pasture model; Tropical grass

5.1 Introduction

Among the other *Cynodon* spp. cultivars, Tifton 85 is one of the most productive and with a remarkably high nutritive value (HILL et al., 1993). Tifton 85 is a hybrid strain of bermudagrass released by the University of Georgia and the USDA-ARS in 1992 which has been one of the most successful pasture cultivars in tropical and subtropical areas, and is widely grown throughout the world in Africa, Asia, Australia, and the Americas (MANDEBVU et al., 1999; SOLLENBERGER, 2008). Bermudagrass probably has its center of origin in the geographic area between Africa and Southeast Asia (SOLLENBERGER, 2008). It is a F1 hybrid between a bermudagrass - PI 290884 from South Africa (*Cynodon dactylon* [L.] Pers) and Tifton 68 stargrass (*Cynodon nlemfuensis* Vanderyst). It is taller, has larger stems, broader leaves and a darker green color than other bermudagrass hybrids, and in addition it has large rhizomes, crowns, and large rapidly-spreading stolon (BURTON et al., 1993).

Sward characteristics and growth rate of Tifton 85 bermudagrass are very sensitive to environmental conditions, such as rainfall, air temperature and incoming solar radiation (TONATO et al., 2010). Management aspects, such as the amount of fertilizer applied (WOODARD; SOLLENBERGER, 2011), and the harvest management with the frequency and intensity of defoliation (PEDREIRA et al., 1999) play an important role in the sward morphology, chemical composition, and in the forage production as well. Thus, mechanistic models can be used to integrate plant responses based on site-specific aspects, and have been useful as decision support tools (BOOTE et al., 1998). For this purpose, models should be extensively calibrated and validated to exhibit reasonable accuracy under a wide range of management practices and environmental conditions (HOOGENBOOM et al. 1994).

The CROPGRO model is a process-based mechanistic model that predicts production and crop tissue composition based on the plant, climate information, and soil management, enabling the simulation of water and nitrogen balance, organic matter and dynamics of residues into the soil, and damage by pests and/or diseases, which results in numerous applications (BOOTE et al., 2002; JONES et al., 2003).

In 1995, the CROPGRO model was initially adapted as an annual version for *Paspalum notatum* Flugge in order to simulate the growth of pasture as a rotation component of the crop cultivation with peanut in Florida, which was used in systems of crop rotation with corn in the previous version (KELLY, 1995). The results of these simulations were inserted in an economic model to predict the sustainability and viability of the crop peanut. The species, cultivar, and ecotype files were released later as a model of "grazing" in the DSSAT models (the Decision Support System for Agrotechnology Transfer) version 3.5 (ICASA, 1998). In addition to estimating the production of *P. notatum*, the DSSAT later included an “annualized” version adapted for *Brachiaria decumbens* (GIRALDO et al., 2001), using data from the international network of Tropical Pasture evaluation, CIAT, Colombia.

This “annualized” version of the model was used to simulate hay production of *P. notatum*, but revealed a consistent overestimation of dry matter production, particularly in the colder months. Thus, in 2004 this aspect was evaluated by Rymph et al. (2004) by means of model calibration and adjustments to parameters, getting more realistic representations of seasonal growth and *P. notatum* growth rate.

Nevertheless, Rymph et al. (2004) concluded that a true perennial version was needed that included a state variable for storage of reserves by the plant. For these reasons, Rymph (2005) developed a true perennial version of the model by adding a state variable for storage of C and N reserves, along with rules for use of those reserves for re-growth even after complete defoliation or surface winter-kill (which the annualized version would not tolerate). In addition to new code, Rymph developed parameterization and released the CROPGRO Perennial Forage model (for version 4.0), giving it the ability to estimate the re-growth and nitrogen concentration of the tissues of *P. notatum* in response to daily variations in climate, fertilization and crop management. These improvements have not yet been incorporated into the publically-released DSSAT models, but the model code has been improved and used in adaptations of parameters to allow prediction of several other tropical forages. More recently, using as a basis the CROPGRO Perennial Forage developed for *P. notatum*, efforts were successful in adapting the model to estimate the growth of *Brachiaria brizantha* and *Panicum maximum* for Brazilian locations (PEDREIRA et al., 2011; LARA et al., 2012).

The objective of this research was to adapt the CROPGRO – Perennial Forage Model to simulate accurately the growth of irrigated and rainfed Tifton 85 bermudagrass, and to describe model adaptation for this species.

5.2 Materials and Methods

The information relative to field experimental data and treatments, model calibration and statistical evaluation of model performance were presented in Chapter 3 of this dissertation.

5.3 Results and discussion

5.3.1 Model calibration for irrigated and rainfed Tifton 85 bermudagrass

The irrigated experiment did not show water and nitrogen stress. The absence of water and nitrogen deficit in the irrigated experiment allowed for calibration of the model parameters for ideal conditions. In this situation the uncontrollable environment factors (daylength, temperature, solar radiation, etc.) can be calibrated in the model. On the other hand, the rainfed experiment, with some short-term water and nitrogen limitation, allows for calibration of some parameters relative to water and nitrogen stress.

The evapotranspiration method was changed to Penman-Monteith-FAO 56, from the Priestley and Taylor method. This gave a more realistic estimation of evapotranspiration, which decreased water and nitrogen stress overestimation. Additionally, we decreased soil runoff from 0.76 to 0.70 due to unrealistic low water infiltration. Marin et al. (2011), parameterizing the DSSAT/CANEGRO model for irrigated and rainfed sugarcane

(*Saccharum* spp.) also in Southern Brazil stated that some potential reasons for inaccuracy in the water availability is under or overestimation of hydraulic conductivity at saturation (Ksat), root water uptake, and errors in root simulation, mainly in deeper horizons.

The temperature parameters were optimized using biomass accumulation data for base temperature (Tb) and first optimum temperature (TO1), which are phenology- driven parameters. We decreased Tb from 10.0 to 8.9 ºC and decreased first optimum temperature from 32.0 to 31.5 ºC based on generalized likelihood uncertainty (GLUE) method optimization (Table 6).

Photosynthesis and respiration parameters were adjusted based on the field measurements and GLUE optimizations using biomass and photosynthesis data. There are two options to simulate plant respiration: mass- or protein-based, both in the MRSWITCH parameter. We used mass-based because there is more information on the biomass data set than on protein-based information. The maintenance respiration as a function of total crop dry weight (RES30C) was not changed. Maximum leaf photosynthesis (LFMAX) was decreased and set at 1.84 mg CO_2 m^{-2} s^{-1}, to match observed field data (data not shown). The leaf N concentration effect on photosynthesis (FNPGN) was kept the same, with 4% of nitrogen for maximum photosynthesis. The specific leaf weight at which LFMAX is defined (SLWREF) was set based on GLUE optimization for biomass data (Table 6)

5.3.2 Partitioning to storage, regrowth, and winter dormancy

After defoliation, the regrowth is highly dependent on stubble leaf area, tiller density and organic reserves of the forage plant. For most of rhizomatous forage grasses, such as Tifton 85, storage organs can be located in roots and rhizomes, and tiller bases (PEDREIRA et al., 2000). Photosynthate partitioning to storage organs is driven by assimilate supply, leaf area index, and storage "rules" that include effects of decreased daylength and temperature. In addition, decrease of forage accumulation during the "winter" months (April-September) is adjusted by "dormancy" parameters, triggered by low temperature and short photoperiod, and adjusted by temperature effects on photosynthesis. The GLUE optimization was used to adjust the sensitivity of single-leaf light-saturated photosynthesis rate to minimum night temperature (FNPGL) and the function describing relative rate of photosynthetic electron transport in response to current temperature (XLMAXT).

Optimizations were made for daylength effect (FNPTD and FNPMD) and for relative dormancy sensitivity effect of daylength (RDRMM and RDRMT) on mobilization and partitioning due to low stubble LAI in 42-day treatment (Table 8) and higher dependence on storage reserves, making the model slightly more sensitive to daylength effect (Table 7).

To ensure good simulation of the regrowth cycles, carbon and nitrogen mining parameters were optimized. The minimum daily rate of CH_2O and N mobilization from storage (CMOBSRN and NMOBSRN) was kept the same and maximum values (CMOBSRX and NMOBSRX) were increased to better adjust speed of early regrowth and N simulations for Tifton 85 bermudagrass dataset (Table 6). The concentration of carbohydrate in newly produced storage tissue (ALPHSR) was kept the same. However, the maximum fraction of photosynthate which can be allocated to refill storage tissue (CADPV) was increased. It was done to allow more storage reserves due to higher dependence of regrowth on stored assimilates for Tifton 85, a rhizomatous species, mainly when coupled with low harvest frequency and high defoliation intensity, which was critical for 42-d treatment of the present study (Table 8). LAI effect on mobilization (LRMOB-4) and on refilling of storage tissue carbohydrate pool (LRREF) was increased because high mobilization ability is necessary for re-growth and the refill occurs mostly under high LAI, mainly to stem in 42-d treatment. Carbohydrate status and canopy photosynthesis effect on refilling of storage tissue (CRREF and PRREF) was optimized to enhance refill of storage tissue under lower storage reserve levels and at times of greater canopy photosynthesis. Maximum mobilization of CH_2O and protein from vegetative tissues (CMOBMX and NMOBMX) were kept close to *Brachiaria* calibration (Pedreira et al., 2011). Fraction of carbohydrate reserves that are allocated to storage (CADSRF) was slightly decreased to allow more use of photosynthate for regrowth.

5.3.3 N concentration in the forage mass

Plant growth is greatly affected by the supply of N. Critical concentration of N required for optimum growth changes with physiological age and is defined as the lowest concentration at which maximum growth occurs. The tissue N concentration below this critical concentration affects growth process. Above this critical concentration there is no further increase in growth rate and luxury consumption of N occurs (Godwin and Singh 1998). We changed leaf and stem N concentration based on GLUE optimization with crude protein data. The fairly poor N predictions (Table 8 and 9) require more improvements (ALDERMAN, 2008).

5.3.4 Partitioning to leaf, stem, and root

Initial simulations showed the need to modify partitioning parameters (YLEAF, YSTEM and YSTOR values) to increase allocation to stem growth, mainly for the 42-d harvest frequency treatment (Table 7). It is common for tropical forage grasses to increase stem elongation associated with longer harvest frequency. Partitioning to storage was increased considerable compared to Pedreira et al. (2011) values to reduce dependence of regrowth on low stubble LAI which occurred for the 42-d low harvest frequency treatment.

5.3.5 Prediction of specific leaf area, leaf area index, and light interception

The plant growth rate is a function of LAI and photosynthetic efficiency of leaves. The light interception increases due to LAI increment, affecting C fixation of the sward canopy through photosynthesis. The specific leaf area showed seasonal variation relative to light and temperature. The SLAVR was increased to 181 $cm^2 g^{-1}$ as a standard reference cultivar at peak early vegetative phase, under standard growing conditions (optimum temperature, water and high light). The SLA simulations show reduction during cool temperature or water deficit and increased under low light. We used GLUE method to optimize the thinnest SLAMAX and thickest (SLAMIN) leaves in response to temperature effect (XSLATM and YSLATM) of newly-formed leaves using observed SLA data.

In the model, LAI is a cumulative result of daily assimilate partitioning from photosynthesis to leaves at a given SLA under those conditions. Simulated LAI was compared to LAI of destructive samples, hand-separated and scanned in a model LI-3100 leaf area meter (Li-Cor, Lincoln, NE) for accumulated total or stubble LAI. Simulated light interception was compared to LI data collected with the LAI-2000 canopy analyzer).

Table 6 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Tifton 85 bermudagrass dataset) for plant composition, phenology, and productivity (photosynthesis and respiration)

Name	Definition	Initial values	Optimized values
PRO_ _G	“normal growth” protein conc. Fraction of tissue (leaf = LF, root = RT, stem = ST, storage organ = SR	LF=0.110;RT=0.040 ST=0.070;SR=0.064	LF=0.210;RT=0.040 ST=0.075;SR=0.064
PRO_ _I	“Maximum” protein concentration of tissue	LF=0.220;RT=0.101 ST=0.110;SR=0.092	LF=0.300;RT=0.101 ST=0.150;SR=0.092
PRO_ _F	“Final” protein concentration of tissue	LF=0.050;RT=0.022 ST=0.033;SR=0.056	LF=0.100;RT=0.022 ST=0.030;SR=0.056
Tb	Base temperature, ºC	10.0	8.9
TO1	First optimum temperature, ºC	32.0	31.5
TO2	Second optimum temperature, ºC	40.0	40.0
TM	Maximum temperature for vegetative development, ºC	45.0	45.0
MRSWITCH	Respiration: M = mass based (original CROPGRO code) or P = protein based	M	M
RES30C	Constant describing maintenance respiration as a function of total crop dry weight (minus oil, protein, and starch in the seed), g CH_2O (dry weight)$^{-1}$ h^{-1}	3.0×10^{-4}	3.0×10^{-4}
R30C2	Constant describing maintenance respiration as a function of canopy photosynthesis, g CH_2O g^{-1} photosynthate CH_2O h^{-1}	0.0024	0.0024
LFMAX	Maximum leaf photosynthetic rate at 30ºC, 350 ppm CO_2, and high light, mg CO_2 m^{-2} s^{-1}	1.89	1.84
FNPGN (1-2)	Leaf N conc. effect on photosynthesis or FNPGN(2), which is a two-sided quadratic curve describing leaf photosynthesis response to leaf N conc.: increases from zero at the min. leaf N conc. to max. leaf N conc.	0.80, 4.00	0.80, 4.00
SLWREF	Specific leaf weight at which LFMAX is defined (g m^{-2})	0.0078	0.0067

Table 7 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Tifton 85 bermudagrass dataset) for temperature, solar radiation, and photoperiod effects on vegetative partitioning, specific leaf area, and photosynthesis

Name	Definition	Initial values	Optimized values
XLEAF	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	Describes dry matter partitioning to leaf among vegetative tissue only, as a function of vegetative stage (fraction)	0.8, 0.8, 0.8, 0.75, 0.5, 0.4, 0.4, 0.4	0.70, 0.71, 0.74, 0.58, 0.50, 0.50, 0.50, 0.50
YSTEM	Describes dry matter partitioning to stem among vegetative tissue only, as a function of vegetative stage (fraction)	0.1, 0.1, 0.17, 0.17, 0.15, 0.16, 0.16, 0.16	0.13, 0.13, 0.14, 0.25, 0.31, 0.34, 0.34, 0.34
YSTOR	Describes dry matter partitioning to storage among vegetative tissue only, as a function of vegetative stage (fraction)	0.01, 0.01, 0.01, 0.02, 0.02, 0.03, 0.03, 0.03	0.04, 0.04, 0.04, 0.05, 0.06, 0.06, 0.06, 0.06
SLAVR	Specific leaf area of cultivar under standard growth conditions ($cm^2 g^{-1}$)	170	181
SLAMAX	SLAMAX is the (thinnest) leaves under low light (cm^2 g^{-1})	358	326
SLAMIN	SLAMIN is the (thickest) leaves under high light (cm^2 g^{-1})	130	133
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) (ºC)	7.6, 20.9	6.5, 22.2
XLMAXT(2-3)	Relative rate of photosynthetic electron-transport in response to temperature, linear from base (0.0) to maximum (1.0) (ºC)	10.4, 38.0	5.5, 38.0
XSLATM(3-4)	Relative temperature effect on specific leaf area of newly formed leaves, ºC (x vs. y pair)	11.0, 26.0	11.0, 27.0
YSLATM(3-4)	Relative temperature effect on specific leaf area of newly formed leaves, fraction reduction (x vs. y pair)	0.29, 1.00	0.48, 1.00
FNPTD (2-3)	Daylength effect on partitioning (h)	10.3, 15.2	12.0, 16.0
FNPMD(1-3)	Daylength effect on mobilization (h)	10.1, 14.5, 0.46	8.0, 13.0, 0.64
RDRMT	Relative dormancy sensitivity, day-length effect on partitioning	0.405	0.538
RDRMM	Relative dormancy sensitivity, day-length effect on mobilization	0.532	0.867

Table 8 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Tifton 85 bermudagrass dataset) for carbon and nitrogen mining parameters

Name	Definition	Initial values	Optimized values
CMOBSRN	Minimum daily rate of CH_2O mobilization from storage (fraction)	0.020	0.020
CMOBSRX	Maximum daily rate of CH_2O mobilization from storage (fraction)	0.050	0.120
NMOBSRN	Minimum daily rate on N mobilization from storage (fraction)	0.010	0.010
NMOBSRX	Maximum daily rate of N mobilization from storage (fraction)	0.060	0.074
ALPHSR	Fraction of new storage tissue growth that is available CH_2O (fraction)	0.20	0.20
CADPV	Maximum fraction of photoassimilate available that can be allocated to CH_2O refill during non-stress conditions	0.437	0.493
LRMOB (3,4)	LAI effect on mobilization (most rapid to least rapid)	0.44, 1.03	0.51, 3.30
CRREF (2,3,4)	Carbohydrate status effect on refilling of storage tissue CH_2O pool	0.30, 0.77, 0.29	0.38, 0.87, 0.30
LRREF (1,2)	LAI effect on refilling of storage tissue CH_2O pool (least to most rapid)	0.65, 2.41	0.95, 2.76
PRREF (1,2)	Canopy photosynthesis effect on refilling of storage tissue CH_2O	0.30, 0.45	0.11, 0.47
CMOBMX	Maximum mobilization of CH_2O from vegetative tissues, fraction of available CH_2O pool per day	0.050	0.050
NMOBMX	Maximum mobilization of protein from vegetative tissues, fraction of available protein pool per day	0.088	0.080
CADSRF	Fraction of carbohydrate reserves that are allocated to storage	0.50	0.446

Table 9 - Model parameter names, definitions, initial values (PEDREIRA et al., 2011) and optimized values (Tifton 85 bermudagrass dataset) for senescence parameters

Name	Definition	Initial values	Optimized values
LFSEN	Natural leaf senescence rate/photothermal day (0.02 means 50-d of life span)	0.02	0.01
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	1.17	1.17
TCMP	Time constant (days) for senescence of lower leaves because of excessive self-shading by the crop canopy	13.1	13.1
PORPT	Stem senescence as a function of the senesced leaf mass (fraction)	0.27	0.27
SENSR	Senescence rate of storage organ tissue (proportion of cumulative storage mass lost per physiological day)	0.011	0.011

5.3.6 Biomass accumulation

Figures 1 and 2 show good simulations of biomass accumulation after optimizations procedures for both 28-d and 42-d harvest frequencies under irrigated conditions. D-statistic values were above 0.95, with good performance even during cool season.

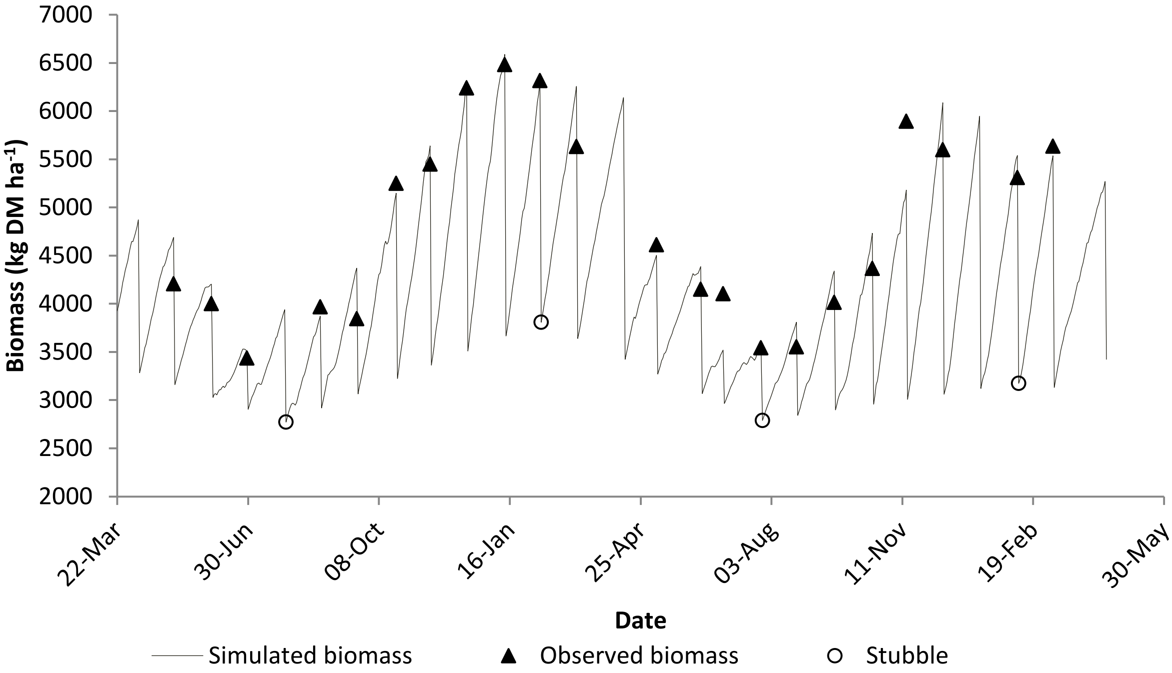

Figure 1 - Irrigated Tifton 85 bermudagrass biomass simulation harvested each 28 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

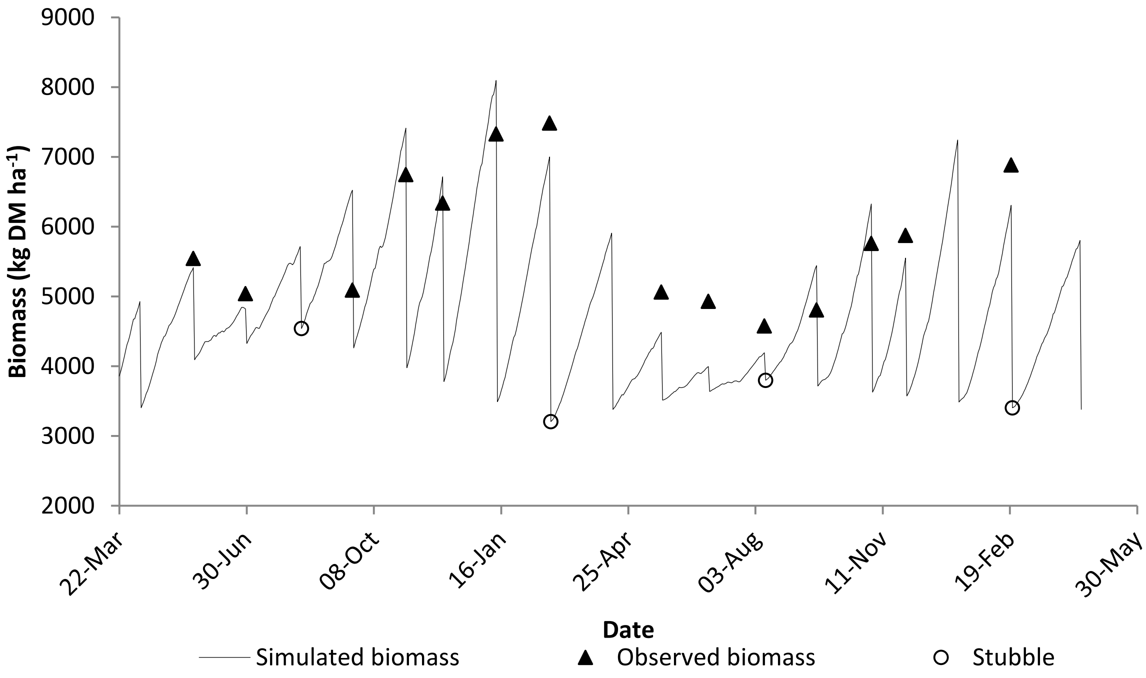

Figure 2 - Irrigated Tifton 85 bermudagrass biomass simulation harvested each 42 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

For the rainfed condition we improved the simulation of biomass accumulation and solved the overestimation of water and N stress by using the evapotranspiration method of Penman-Montieth - FAO 56, instead of Priestley and Taylor method, and adjusting soil runoff factor as well (Table 9). Figures 3 and 4 show good predictions of biomass for both 28-d and 42-d harvest frequencies under rainfed conditions with d-statistic values above 0.80.

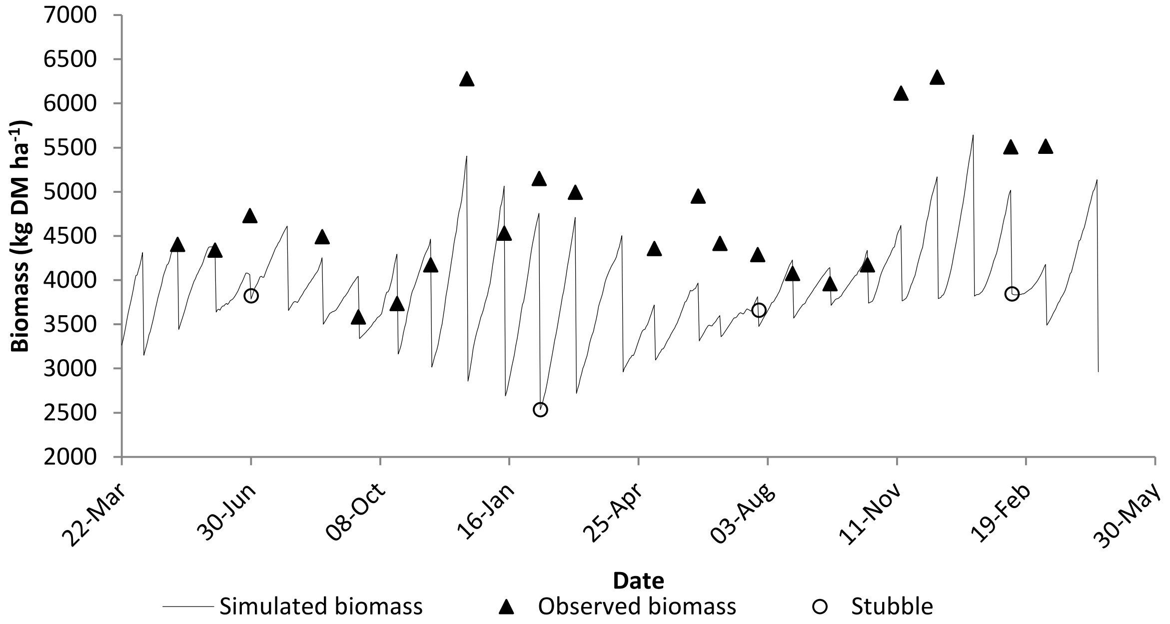

Figure 3 - Rainfed Tifton 85 bermudagrass biomass simulation rainfed and harvested each 28 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

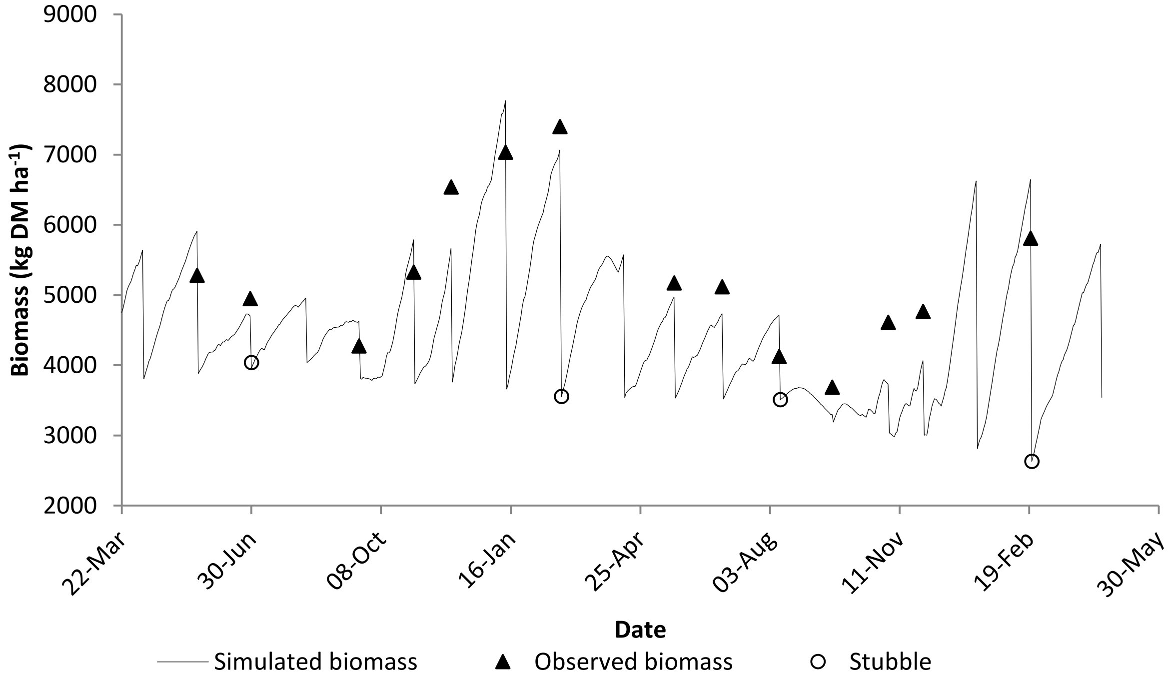

Figure 4 - Rainfed Tifton 85 bermudagrass biomass simulation rainfed and harvested each 42 days during April 2011 to April 2013 in Piracicaba, SP, Brazil

Table 8. Means and statistics for simulations of irrigated Tifton 85 bermudagrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, after optimizations.

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4545	4642	313	1.023	0.979
Leaf weight (kg DM ha^{-1})	1904	1846	265	0.980	0.976
Stem weight (kg DM ha^{-1})	2218	2351	199	1.075	0.971
LAI (m^2 m^{-2})	3.00	3.11	0.552	1.088	0.964
LI (% of incident light)	90.96	91.33	2.758	1.005	0.862
SLA (cm^2 g^{-1})	171.3	168.9	13.17	0.991	0.228
N (% on DM basis)	2.04	1.92	0.323	0.958	0.391
			42-days		
Biomass (kg DM ha^{-1})	5358	5402	579	1.006	0.950
Leaf weight (kg DM ha^{-1})	1328	1426	395	1.027	0.952
Stem weight (kg DM ha^{-1})	3647	3654	296	1.007	0.912
LAI (m^2 m^{-2})	1.38	2.42	1.430	1.657	0.735
LI (% of incident light)	93.38	86.91	9.972	0.930	0.538
SLA (cm^2 g^{-1})	101.2	169.5	68.30	1.728	0.300
N (% on DM basis)	1.27	1.55	0.456	1.264	0.313

Table 9. Means and statistics for simulations of rainfed Tifton 85 bermudagrass dataset (22 and 14 regrowth cycles, for 28- and 42-days of harvest frequency, respectively, from 2011 to 2013) in Piracicaba, SP, Brazil, after optimizations.

Parameter	**Observed**	**Simulated**	**RMSE**	**Ratio (obs/ sim)**	**Willmott's *d***
			28-days		
Biomass (kg DM ha^{-1})	4537	4244	630	0.949	0.810
Leaf weight (kg DM ha^{-1})	1081	1025	186	0.986	0.975
Stem weight (kg DM ha^{-1})	3006	2929	163	0.979	0.978
LAI (m^2 m^{-2})	0.91	1.68	0.88	1.975	0.710
LI (% of incident light)	89.09	77.54	15.77	0.871	0.413
SLA (cm^2 g^{-1})	93.2	164.8	72.50	1.788	0.209
N (% on DM basis)	1.82	1.41	0.524	0.786	0.342
			42-days		
Biomass (kg DM ha^{-1})	4879	4856	519	0.994	0.958
Leaf weight (kg DM ha^{-1})	2325	2256	400	0.983	0.964
Stem weight (kg DM ha^{-1})	2204	2406	402	1.095	0.848
LAI (m^2 m^{-2})	4.14	3.76	0.940	0.958	0.941
LI (% of incident light)	91.80	91.81	4.44	1.001	0.798
SLA (cm^2 g^{-1})	199.7	163.8	47.57	0.838	0.447
N (% on DM basis)	2.07	1.71	0.541	0.854	0.364

5.4 Summary and Conclusions

Under rainfed conditions, the simulations using the Penman-Monteith-FAO 56 method gave more realistic water stress responses than using the Priestley and Taylor method. The partitioning parameters were modified to provide more stem and storage for longer regrowth periods using the plant-part composition of the 42-d treatment. SLA and N were improved with field data but changes in the code are necessary to improve simulations. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Tifton 85 bermudagrass under irrigated and rainfed conditions. Additional validation should be performed to test these results, which can be added into the CROPGRO perennial forage model and the DSSAT software package to be used as a decision support tool in a real system of livestock production.

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6 GENERAL CONCLUSIONS

Irrigation and harvest frequency impacted herbage accumulation and nutritive value of the grasses. Convert HD 364 was released as a good forage option due to high herbage accumulation and nutritive value, compared to grasses already in use by the Brazilian livestock industry, including Marandu and Tifton 85. The management recommendations for this new grass will depend on the economical and practical aspects of the livestock enterprise. When irrigation is viable, Convert HD 364 should be managed under a 28-day harvest frequency. This will result in higher annual herbage accumulation than Marandu and Tifton 85, coupled with higher nutritive value than when harvested every 42 days. Irrigation increased annual herbage accumulation by about 20% compared to rainfed conditions. When irrigation is not viable, or high forage accumulation is not the main interest, rainfed pastures can result in higher forage nutritive value than the irrigated condition. Tifton 85 has higher CP concentration than the other two grasses when harvested at shorter intervals and when irrigated. The NDF concentration in Convert HD 364 was lower than in the other grasses regardless of irrigation treatment, harvest frequency, and season of the year, resulting in high IVOMD (more than 650 g kg^{-1}), similar to that of Marandu. The 42-day harvest frequency resulted in increased annual herbage accumulation only for rainfed Convert HD 364 (13% more than under 28-d schedule) and for irrigated Marandu (19% more than under 28-d). Tifton 85 annual herbage accumulation did not respond to harvest frequency in the levels used in this study. During the rainy season, the 42-d harvest schedule was an interesting option to increase seasonal herbage accumulation in all the three grasses, but it can decrease herbage accumulation during the dry season.

Forage responses to management and weather variation over the year were used in the CROPGRO perennial forage model to calibrate cultivar-specific parameters using the Generalized Likelihood Uncertainty Estimation, or GLUE. In general, model performance was good for the three grasses. Only SLA and N concentration were not accurate. Leaf and stem weight were improved for the *Brachiaria* cultivars relative to previous calibration, due to increase in partitioning to stem for low harvest frequencies. The LAI and LI were well predicted by the model, showing increase for lower harvest frequency, with exception to Tifton 85, which decreased LAI with longer harvest intervals attributed to high stem elongation and decrease in leaf weight. Convert HD 364 and Marandu showed a slight underestimation of biomass production during cooler months, which was not enough to compromise the overall accuracy of the simulations. Tifton 85 had the best fit for herbage accumulation, showing good accuracy even during cooler months. Under rainfed conditions, the simulations using the Penman-Monteith-FAO 56 method resulted in more realistic water stress responses than using the Priestley and Taylor method for the three grasses. Calibration results suggest that the CROPGRO – Perennial Forage Model can be used to adequately simulate growth of Marandu, Convert HD 364, and Tifton 85 under irrigated and rainfed conditions, and to simulate the response to different harvest managements. Additional validation should be performed to test these results, which can be added into the CROPGRO Perennial Forage model and the DSSAT platform to be used as a decision support tool in a real system of livestock production. Further research is needed to implement forage nutritive value simulations in the CROPGRO Perennial Forage model.