University of São Paulo
"Luiz de Queiroz" College of Agriculture

Yield-gap in pasture-based animal production systems in Central-west and Southeast of Brazil (Central Brazil)

Mariely Lopes dos Santos

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

Piracicaba
2021

Mariely Lopes dos Santos
Agricultural Engineer

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versão revisada de acordo com a resolução CoPGr 6018 de 2011

Advisor:
Profa. Dra. **PATRÍCIA MENEZES SANTOS**

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1. *Urochloa brizantha* 2. Produção de longo prazo 3. Produção de forragem 4. Pecuária 5. Gado de corte 6. Taxa de lotação 7. Global yield gap atlas I. Título

To Christ, Lord of salvation, to my parents Maurinho and Maria, to my sisters Maraisa (Tata) and Marilia (Lila) and my brother-in-law Jurandi (Jura). I dedicate this work to you all. I love you!

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“Commit your works to the Lord and your plans will be achieved” - Proverbs 16:3

SUMMARY

RESUMO

Déficit de produtividade em sistemas de produção animal em pastagens na região Centro-Oeste e Sudeste do Brasil (Brasil Central)

A preocupação com a demanda por produção de alimentos de forma sustentável frente ao crescimento população mundial exige estudos sobre segurança alimentar que avaliem e façam projeções do potencial produtivo das principais cadeias alimentares ao redor do globo. As análises de "yield-gap" do projeto Global Yield Gap Atlas (GYGA) tem o propósito de identificar o potencial produtivo das principais culturas agrícolas produzidas no mundo por meio de modelos de simulação de crescimento vegetal, além de quantificar as diferenças entre as produtividades potenciais, atingíveis e reais dos principais países produtores. No entanto, não existem protocolos consolidados para esse tipo de análise voltada para a produção pecuária. O Brasil está entre os maiores produtores de carne do mundo e a maior parte da atividade pecuária de corte brasileira tem as pastagens tropicais como principal fonte de alimento para os animais. A espécie *Urochloa briza*ntha cv. Marandu é a mais amplamente cultivada no país e utilizada em sistemas de produção pecuária, principalmente nas regiões Centro-Oeste e Sudeste. O uso de simulação de produção de forragem em longo prazo é importante para estudos de cenários estratégicos, previsões de déficits de produtividade e análise de risco de perdas de produção. No entanto, os modelos de forragem só foram testados usando dados de curto período. Com este estudo, objetivou-se adaptar os protocolos GYGA para sistemas de pecuária de corte baseados em pastagem, utilizando a adaptação de modelos de forragem para realizar a simulação produção de forragem de longo prazo e por meio de modelos de estimativa de lotação para estimar os níveis de produção de gado de corte em diferentes cenários de manejo no Brasil Central, além de determinar seus déficits de produtividade. É possível estimar os déficits de produtividade de sistemas de produção animal à pasto em diferentes condições edafoclimáticas, incluindo os biomas Amazônia, Cerrado e Mata Atlântica, por meio do desenvolvimento de um protocolo específico de análise de déficit de produtividade para bovinos de corte. Uma das principais contribuições desse estudo foi fornecer uma visão geral do sistema de produção pecuário como um todo, por meio de estimativas de produção de forragem de longo prazo e de lotação animal que levam em consideração a estacionalidade anual de produção, em decorrência de fatores meteorológicos, e a capacidade suporte da pastagem, gerando assim, dados mais consistentes.

Palavras-chave: *Urochloa brizantha*, Produção de longo prazo, Produção de forragem, Pecuária, Gado de corte, Taxa de lotação, Global yield gap atlas

ABSTRACT

Yield-gap in pasture-based animal production systems in Central-west and Southeast of Brazil (Central Brazil)

The demand for sustainable food production in face of world population growth requires efforts in food security analyzes that evaluate and project the productive potential of the main food chains around the globe. The yield-gap analyzes of Global Yield Gap Atlas (GYGA) has the purpose of identifying the productive potential of the main agricultural crops produced in the world through crop simulation models, in addition to quantifying the differences (gaps) between the potential, attainable and real yields of the main producing countries. However, there are no consolidated protocols for this type of analysis aimed at livestock production. Brazil is among the largest meat producers in the world and most of the Brazilian beef cattle activity has tropical pastures as the main source of food for animals. *Urochloa brizantha* cv. Marandu palisadegrass is the most widely cultivated forage species in the country, mainly in the Central-west and Southeast regions. The use of long-term forage production simulation is important for studies of strategic scenarios, yield-gap predictions, and risk analysis of production losses. However, forage models have only been tested using short period data. In this study, we aimed to adapt GYGA protocols for pasture-based beef cattle livestock systems, using the adaptation of forage models to simulate long-term herbage production, and by using a stocking rate model to predict pasture carrying capacity under different scenarios of management in Central Brazil, in addition to estimate the yield-gaps of pasture-based animal production systems in Southeast and Central-west of Brazil. It possible to estimate yield-gap of pasture-based-beef-cattle production systems in different edaphoclimatic conditions in Brazil, including the Amazon, Cerrado and Atlantic Forest Biomes, through the development of a specific protocol for yield-gap analysis for beef cattle livestock. One of the main contributions of this study was to provide an overview of the livestock production system as a whole, by simulations of long-term forage production and animal stocking rates that consider the annual seasonality of production, due to meteorological factors, and its effect on pastures carrying capacity.

Keywords: *Urochloa brizantha*, Long-term production, Forage production, Livestock, Beef cattle, Stocking rate, Global yield gap atlas

1. INTRODUCTION

In face of the growing demand for food, the climate changes, and the relevance of food security and sustainability, Brazil presents global importance as a grain and animal protein producer. The approximate area of the Brazilian territory is 851.5 million ha, of which 63.99 million ha are used as arable land, placing Brazil as fifth country with the largest extensions of cultivated land, following India (179.8 million ha), United States (167.8 million ha), China (165.2 million ha) and Russia (155.8 million ha) (Massey et al. 2018; Xiong et al. 2017a; Teluguntla et al. 2018; Xiong et al. 2017b; Teluguntla et al. 2017; Oliphant et al. 2017; Gumma et al. 2017; Phalke et al. 2017; Massey et al. 2017; Zhong et al. 2017). Besides that, 2018 data from mapbiomas indicate that there are 66% of natural forests and native vegetation, 31% of areas destined for agriculture, 1% of non-vegetated areas and 2% of water (Souza et al. 2020), indicating that Brazil is and will be increasingly recognized as both an agricultural and environmental potency.

Brazilian beef production supplies domestic market with 8.01 million CWE per year (Carcass Weight Equivalent: 242.3 kg), equivalent to 76.3% of its production, while 23.6% is exported to 124 countries such as China, Hong Kong, USA, European Union, and Egypt (ABIEC, 2020). The country has the largest commercial cattle herd in the world, with 213.7 million bovine heads (ABIEC, 2020). The Brazilian livestock production activity is mainly based on tropical grasses pastures that are used as summer season forage in subtropical areas and as perennial forage in tropical regions (Tsuruta et al. 2015). Marandu palisadegrass {*Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webster [syn. Brachiaria brizantha (Hochst. ex A. Rich.) Stapf]}, released by EMBRAPA (Empresa Brasileira de Pesquisa Agropecuária) in 1984, is the most widely cultivated forage grass across the country, with excellent adaptation and high yields promoted by its C4 metabolism, and adapted to rotational grazing, hay and silage production.

In the last two decades, the Brazilian pasture area reduced 12.4% while the herd cattle have increased 49.3%, resulting in an increase on the average stocking rate from 0.71 AU ha^{-1} to 1.06 AU ha^{-1} (ABIEC, 2020). Part of the Brazillian pastures areas is considered in some level of degradation, mainly due to poor grazing management and the use of stocking rates that exceed the pasture recovery capacity. In addition to overgrazing, the lack of periodic fertilization, failures in pastures establishment, the use of fire and problems such as pests attack are pointed out as the main causes of pasture degradation in Brazil (Dias-Filho, 2011).

Long-term estimates of forage production can contribute to studies about yield-gap, aptitude and climate risk zoning, projection trends in response to climate change, sustainable management, as well as become the basis for development of public policies for the agricultural sector. Despite that, there are still several difficulties for the development of forage production

models for long-term simulations, like: few long-term field experiments with good record of pasture management and herbage growth; few experiments monitoring the soil-plant-animal interactions; difficulty in carrying out multiple sequential destructive samples in a perennial crop; few experiments measuring total plant production and partition of photoassimilates under grazing conditions; lack of accurate measurements of residual leaf area and its effects on pasture regrowth.

The yield-gap analysis of pasture-based animal production systems faces several challenges regarding the application of concepts and methods already established for agricultural crops. The concepts of yield levels (yield potential, water-limited yield potential, water-and nutrient-limited yield or attainable yield and actual yield) must be redefined for livestock systems, as the animal component and animal-plant interactions must also be taken into account, in addition to the plant component. Pasture-based animal production depends on primary productivity by forage plants growth and production, harvesting efficiency (herbage consumed as a proportion of herbage accumulated) and feed efficiency (conversion of consumed herbage into animal products as beef or milk) (Pearson and Ison, 1987). Besides that, most studies estimate pastures carrying capacity by dividing annual dry matter production by animal intake (Strassburg et al. 2014; Arantes et al., 2018; Araújo, 2018), not considering the relationship between supply and demand of seasonal forage production throughout the year, which is primarily regulated by climatic factors. Thus, the same annual pasture productivity may be associated with different potential stocking rates and attainable systems productivity.

The Global Yield Gap Atlas (GYGA) protocols may be adapted for animal production systems. Therefore, this study aimed to develop a protocol for yield-gap analysis of pasture-based livestock production systems in different edaphoclimatic conditions through process-based models.

1.1. Objectives

1.1.1. General

Develop a protocol for yield-gap analysis in pasture-based animal production systems, under different edaphoclimatic conditions, using simulation models.

1.1.2. Specific

a) Adapt Global Yield Gap Atlas Extrapolation Domain to perennial tropical pastures.
b) Estimate long-term forage production of Marandu palisadegrass at different edaphoclimatic conditions and levels of intensification in Central Brazil.

c) Estimate the stocking rates based on estimates of forage mass and adequate pasture carrying capacity.
d) Estimate yield-gap of pasture-based beef cattle production systems in Southeast and Central-west regions of Brazil.

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2. LITERATURE REVIEW

2.1. Brazilian livestock overview

Brazil is an important player in global food production and is expected to help the world to achieve the growing demand for food in the coming decades. For that, changes on actual land use and on agriculture production levels will be necessary, arising concerns about the sustainability of Brazilian beef and milk production (Banco Mundial, 2010; MAPA, 2014; FAO, 2018).

Brazil was the second beef producer in the world (10.5 million CWE) and the main beef exporter 2.48 million CWE in 2019. In addition, the country has the largest herd cattle (213.7 million head) (ABIEC, 2020), fed mainly with tropical grasses pastures that are used as summer season forage in subtropical areas and as perennial forage in tropical regions (Tsuruta et al. 2015). From 2018 to 2019, the used pasture area remained practically stable, at 162.5 million hectares, with a current average stocking rate of 1.06 AU ha^{-1} (ABIEC, 2020).

Usually, livestock areas are marginal and located in soil with properties not suitable for big crop production, what can explain problems in livestock productivity and sustainability (Macedo, 2009). On the other hand, although the negative environmental impacts described for pasture-based beef cattle production (IPCC, 2007), a land saving effect was observed on intensified systems when technology was adopted (Martha Junior et al., 2012). Animal production systems intensification may also contribute to greenhouse gases emissions mitigation due to the earlier termination and slaughter that implies on a smaller number of animals and shorter animal life time (Banco Mundial, 2010; Thornton and Herrero, 2010). Furthermore, in addition to serving as a source of food for herbivores, productive tropical pastures also contribute to environmental services and a reduction in disservices, such as the large capacity of soil cover and, due to the highly efficient photosynthetic process in assimilation of atmospheric CO2 by forage plants (mostly C4 metabolism), greater root production and greater carbon stocks in the soil, in addition to better soil use and conservation.

However, it is estimated that the Brazilian area with degraded pastures or in some degree of degradation is about 53 million hectares (IMAFLORA, 2018), negatively affecting the entire production chain. Overgrazing is the greatest cause of grassland degradation, an overriding human-influenced factor in determining soil carbon levels of grasslands (FAO, 2008). Moreover, livestock systems are projected to be adversely affected by impacts of climate change, such as the rising temperatures, depending on the extent of changes in pasture and feed quality, spread of diseases, and water resource availability (Mbow et al. 2019)

Despite the concern over livestock projections, in many systems, improved grazing management, such as optimized stock numbers and rotational grazing, improved pasture management and integrated agroforestry systems are effective alternatives in conserving the environment and mitigating climate change, while providing more diversified and secure livelihoods for inhabitants (FAO, 2008)

In Brazil, there is a great potential for increasing productive efficiency with the recovery of unproductive areas. This can be observed in productive potential studies, as the Strassburg et al. (2014) work, based on modeling and simulation of future scenarios, in which the results concluded that the increase of only 20% in the current pasture productivity would save areas and, consequently, these areas would be enough to produce and meet demands of meat, grains, wood products and biofuels for the next 30 years with no need of opening new areas.

2.2. Yield-gap analysis of Global Yield Gap Atlas: Concepts and importance

Food security analysis can help on the national forecasting of food production capacity, potential for food self-sufficiency and variability of food production capacity due to variation in weather; the determination of the potential of land use and assessment of the amount of additional land compensation or food imports to meet future food demand; the interpretation of historical yield trends and projections of future yield trends at regional, national and global scales (Mbow et al. 2019). In this context, Global Yield Gap Atlas (GYGA) was created for developing a global coverage of yield-gaps for all major food crops (www.yieldgap.org).

The GYGA is an international project that has the collaboration of people with knowledge of production systems, soils, and climate governing crop performance in their countries. A standard protocol for assessing yield potential (Yp), water-limited yield potential (Yw), yield gaps (Yg) and water productivity (WP) is applied for all crops and countries based on best available data, robust crop simulation models, and a bottom-up approach to upscale results from location to region and country (Lobel et al. 2009; Van Ittersum et al. 2013).

In yield-gap analysis protocols described by GYGA for agricultural crops, yield-gap (Yg) is defined as the difference between potential yield (Yp - defined as the yield of an adapted crop cultivar when grown without water and nutrient limitations and kept free of diseases, weeds and insect pests) and the observed average real or actual production (Ya) which is obtained by farmers of the region, involving the most varied management practices such as date of sowing, varieties, population density, nutritional management and crop protection against pests and diseases (yield affected by limiting factors, water and nutrients; and reducing factors such as weeds, pests,

diseases and pollutants) (Van Ittersum e Rabbinge, 1997). The concept of attainable productivity (Yw) is based on productivity obtained by a genotype adapted under real growing conditions and under unfavorable influence of one or more limiting factors. In rainfed crops, where the only limitation is the water factor, Yp is considered as the potential productivity limited by water (Yw). The concept of attainable productivity is based on productivity obtained by a genotype adapted under real growing conditions and under unfavorable influence of one or more limiting factors (Figure 1). Furthermore, there is the exploitable yield-gap, which is the difference between the Ya (actual productivity) and Yp or Yw, commonly, about 80% of Yp or Yw (Van Wart et al., 2013). There is a hypothesis that average national yields begin to plateau when average farm yields reach 70-90% of Yp or Yw (Cassman, 1999; Cassman et al., 2003; Lobell et al., 2009, Grassini et al., 2009; Van Wart et al., 2013). Estimates of yield gap for rice in China, wheat in Germany, and irrigated maize in the USA are consistent with that hypothesis. The plateaus occur because it is impossible for average yield in a region or nation to reach Yp or Yw because 100% of farmers cannot achieve the perfection of crop and soil management required to reach Yp or Yw (Van Wart et al., 2013), and the cost of marginal increments in yield, given existing technologies and policies, could exceed the incremental gain. The cost is high not only in terms of increased use of inputs such as fertilizer, fuel, and water, but also in terms of increased management and supervision time for achieving more efficient input use (Lobell et al., 2009).

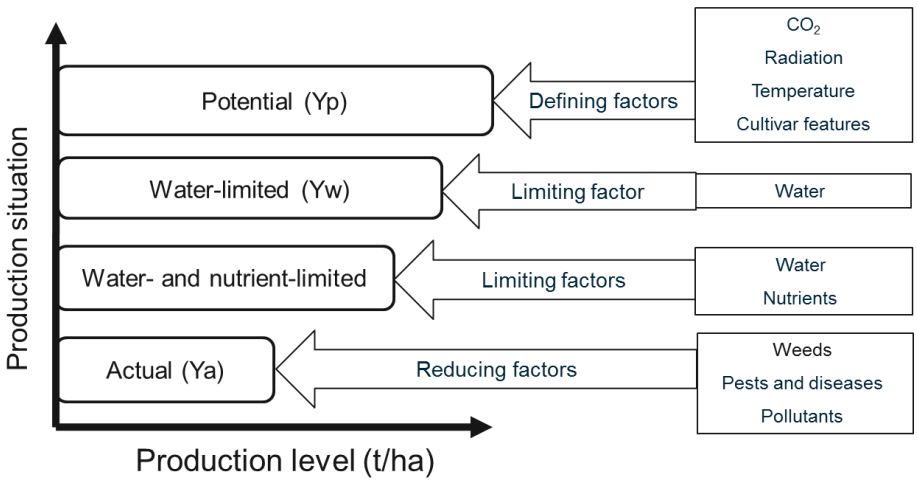

Figure 1. Different production levels as determined by growth defining, limiting, and reducing factors (Van Ittersum and Rabbinge, 1997; van Ittersum et al. (2013). For irrigated systems and rainfed systems, respectively, potential yield (Yp) and water-limited yield (Yw) are the relevant benchmarks for yield gap analysis.

There is still no standard protocol described by GYGA for analyzing pasture-based livestock yields and there are controversies regarding the indexes and estimates of the productive potential for the Brazilian livestock activity.

2.3. Yield-gap analysis for pasture-based livestock systems

The same pasture annual primary productivity may be associated to different potential stocking rates and so attainable systems productivity. Seasonality of forage production between the dry and rainy periods must be considered in the estimates and analysis of the productive potential and yield-gap of livestock system. Pasture annual primary productivity is a very crude measure of the pasture-based animal production systems productivity, and the concepts related to yield-gap analysis described for crops by GYGA are not suitable. In pasture-based livestock systems, the defining factors (CO2, solar radiation, temperature and genetic features), limiting factors (water or/and nutrient) and reducing factors (weeds, pests, diseases and pollutants) affects plants, animals, and plant-animal interactions in different ways. The animal productivity (kg of live weight ha^{-1} y^{-1}; kg of carcass weight equivalent ha^{-1} y^{-1}) does not necessarily increases in direct proportion to the increase on total annual forage productivity (kg DM ha^{-1} y^{-1}). In addition, if the system is not well managed, the animal component can be a limiting or reducing factor for the plants and the opposite condition is also true for the animal's performance.

Pasture carrying capacity is the maximum stocking rate that will achieve a target level of animal performance without deterioration of the grazing land (Allen et al. 2011). Carrying capacity is a useful concept when based on adequate historical data and experience, but it is site-specific and varies from season to season and year to year.

Yield-gap analysis and estimates of potential for pasture intensification in Brazil generally does not consider the effect of seasonal forage production and climate risk, tending to overestimate pastures carrying capacity. Araújo (2018) performed a yield-gap analysis for Marandu palisadegrass pastures in the São Paulo state, Brazil, using the CROPGRO perennial forage model to estimate pastures annual dry matter production based on protocols proposed by GYGA, and Strassburg et al. 2014 equation to estimated pastures carrying capacity. The author suggested a possible increase of 0.96 AU ha^{-1}, when compared to stocking rate of 1.33 AU ha^{-1} from IBGE census. In another study about livestock intensification potential, a yearly-based forage production was estimated by dividing dry matter yield in the growing period by 0.8 and a daily dry matter yield estimated by dividing annual yield (kg DM) by 365 (day), so that the stocking rate was calculated by dividing daily dry matter yield by daily animal intake from one animal unit (i.e., 11.25 kg DM), considering a harvest efficiency of 50%, obtaining a daily demand of 22.5 kg DM AU^{-1} (Arantes et al., 2018).

Arantes et al. (2018) estimated a potential carrying capacity from 4.7 to 11.2 UA ha^{-1} for the South of Brazil. Studies in southern Brazil, where predominates natural pastures, suggests that carrying capacity of pastures throughout the year should not exceed 0.8 AU ha^{-1}, thus maintaining productive systems with positive animal performance (live weight gain) and avoiding pasture degradation by overgrazing (Tanure et al. 2011; Mezzalira et al 2012)

This work was divided in two parts, according to the following action plan (Figure 2):

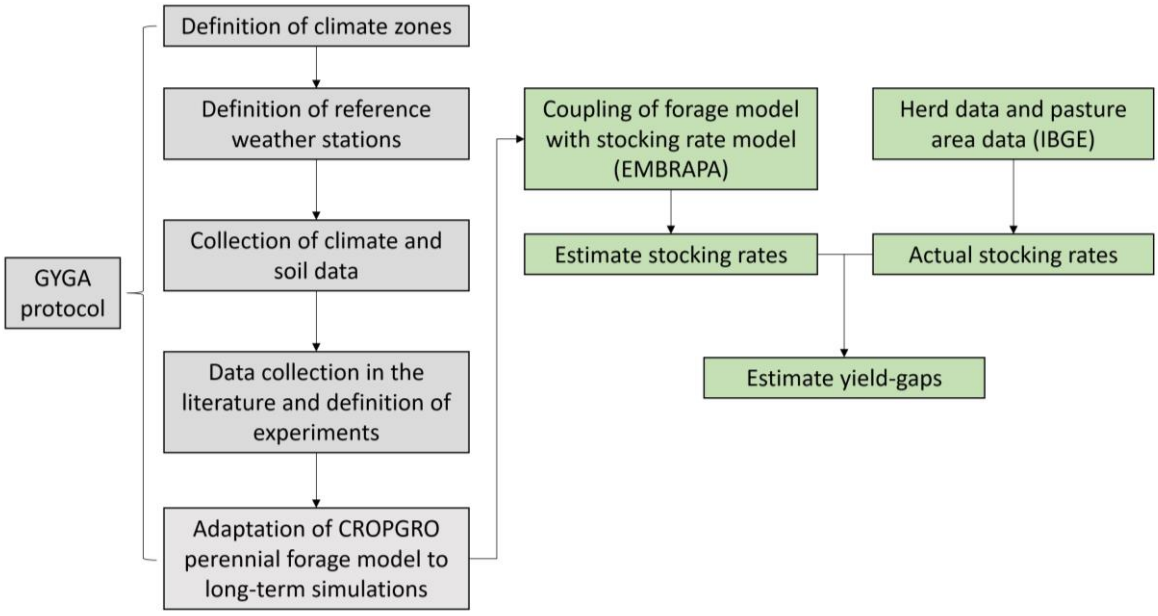

Figure 2. Flowchart of activities performed in chapter 3 (gray text boxes) and chapter 4 (green text boxes) of this work.

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3. ADAPTATION OF CROPGRO PERENNIAL FORAGE MODEL FOR LONG-TERM ESTIMATES OF MARANDU PALISADEGRASS PRODUCTION IN LIVESTOCK SYSTEMS IN THE BRAZIL CENTRAL REGION

ABSTRACT

The use of long-term forage production simulation is important to studies of strategic scenarios, yield-gap predictions and risk analysis of production losses. However, forage models have only been tested using short period data. Therefore, this study aimed to evaluate the capability and application of CROPGRO-PFM to simulate long-term forage production of Marandu palisadegrass {*Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webster [syn. *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf]} in different locations of Central Brazil, under different fertilization levels. We chose nine locations distributed in Amazon, Cerrado and Atlantic Forest Biomes to simulate Marandu palisadegrass production over 36 years (1980-2016). The simulations were carried out using prior calibrations for DSSAT's CROPGRO perennial forage model and, as a reference point of growth and herbage simulation, the Integrated Agrometeorological Model (IAM). The simulated scenarios represented the three beef cattle livestock production systems: 1) potential productivity, water-not-limiting highly fertilized production, 2) rainfed intensive production system, water-limiting with a high level of fertilization and 3) rainfed extensive production system, water-limiting with low maintenance fertilization. In general, the long-term simulations of annual forage production and seasonality were satisfactory and similar for the CROPGRO-PFM and IAM models. As expected for the Central Brazil region, historical averages of monthly herbage accumulation rate of potential yield (Yp) scenarios were relatively constant throughout the year, declining in the winter period for most locations due to mild temperature reduction. In general, all simulated rainfed scenarios showed a reduction in growth rates in the drier months. During the winter season, simulated growth rates were low and similar regardless of N fertilization. Code improvements of CROPGRO-PFM are necessary to include the nutrients cycling, as part of the plant N consumed by animal is excreted by grazing animals and returns to the system. In places with more severe droughts such as Diamantino-MT, the CROPGRO-PFM model was not able to simulate well the dormancy and survival of the plant during these periods. This may require code changes relative to mobilization of reserves, survival, and maintenance respiration during severe droughts. The CROPGRO-PFM model proved to simulate well for applications in different soil and climate conditions from which the model was calibrated. However, it is recommended that new locations be tested before generalizing the application of the model to other regions.

Key-words: *Urochloa brizantha,* crop modelling, herbage production, growth, beef cattle

3.1. Introduction

According to Andrade et al. (2015), crop models can be valuable tools to evaluate long-term effects of environmental variations and management on plant responses. Research on long time series of agricultural systems productivity can help to identify medium and long-term impacts on production systems and strategic scenarios, thus potentially improving the crop management, in addition to summarizing a great amount of information. For example, models are valuable for studies on aptitude and climate risk zoning of livestock, yield-gap analysis, and climate change projection. They can become critical tools for the development of private sector strategies and public policies design. Crop models are important also to estimate the crop systems response to weather and climate variability over years, and allow estimates of average yield and its inter-annual variability (Grassini et al., 2015; Van Ittersum et al., 2013; Van Wart et al., 2013).

Brazil is nationally and globally recognized as one of the important agricultural and environmental regions affecting the scope of world food security and sustainability. Its livestock activity is based on the largest commercial cattle herd in the world (213.7 million head) (ABIEC, 2020), mostly concentrated in states of Central West and Southeast region of Brazil (Central Brazil) (IBGE, 2018), which are in the Amazon Forest, Cerrado, Pantanal and Atlantic Forest Biomes (IBGE, 2019). Pasture growth and productivity models can be important tools for planning and improving livestock efficiency in Brazil, where there is great potential for recovering degraded areas and gaining efficiency in production. Therefore, the improvement and application of pasture growth and productivity models, such as ALMANAC (Agricultural Land Management Alternative with Numerical Assessment Criteria), Century, Orchidee Grassland Management, APSIM (Agricultural production systems simulator), STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) and DSSAT (Decision-Support System for Agro-technology Transfer), are extremely relevant.

The DSSAT is a model platform supporting more than 40 crop models which simulate growth, development and yield of crops as a function of the soil-plant-atmosphere-management dynamics (Hoogenboom et al., 2019; Jones et al., 2003). The CROPGRO perennial forage model (CROPGRO-PFM) is one of the DSSAT's models. It has been adapted for tropical pastures, mainly for Marandu palisadegrass, using data from Brazilian experiments (Pedreira et al., 2011; Pequeno et al., 2014, 2018).

In the latest released version (Hoogenboom et al., 2019), CROPGRO-PFM was calibrated for Marandu palisadegrass, using three years of experimental data of mechanically-harvested plots subject to rainfed and irrigated treatments (Pequeno et al., 2018). Despite reaching acceptable adjustments for both conditions, the authors report partitioning and dormancy limitations during the winter season and flowering period, which reduce the potential regrowth and forage

production in early spring. Moreover, CROPGRO-PFM has not yet been tested for long-term (decadal time scale) impacts on pasture management, and it has also not been tested for low fertility or poor management conditions.

Estimating medium and long-term pasture productivity levels is still an open problem with several challenges, particularly due to the lack of experimental data as listed here: few long-term field experiments with good record of pasture management and herbage growth; few experiments monitoring the soil-plant-animal interactions; difficulty in carrying out multiple sequential destructive samples in a perennial crop; few experiments measuring total plant production and partition of photoassimilates under grazing conditions; lack of accurate measurements of residual leaf area and its effect on regrowth.

CROPGRO-PFM currently does not explicitly model the grazing animals' interface with the pasture. So, the effects of nutrient cycling via animal urine and feces, selective grazing, trampling and other grazing losses related to stocking rates have to be provided indirectly by appropriately modifying the model inputs, assuming no endogenous feedback (Bosi et al., 2020).

Therefore, the aim of this study was the adaptation and application of CROPGRO-PFM for simulating growth and characterizing the long-term forage production of Marandu palisadegrass in different locations of Central Brazil, under different fertilization levels.

3.2. Materials and methods

3.2.1. Sites and database for simulations

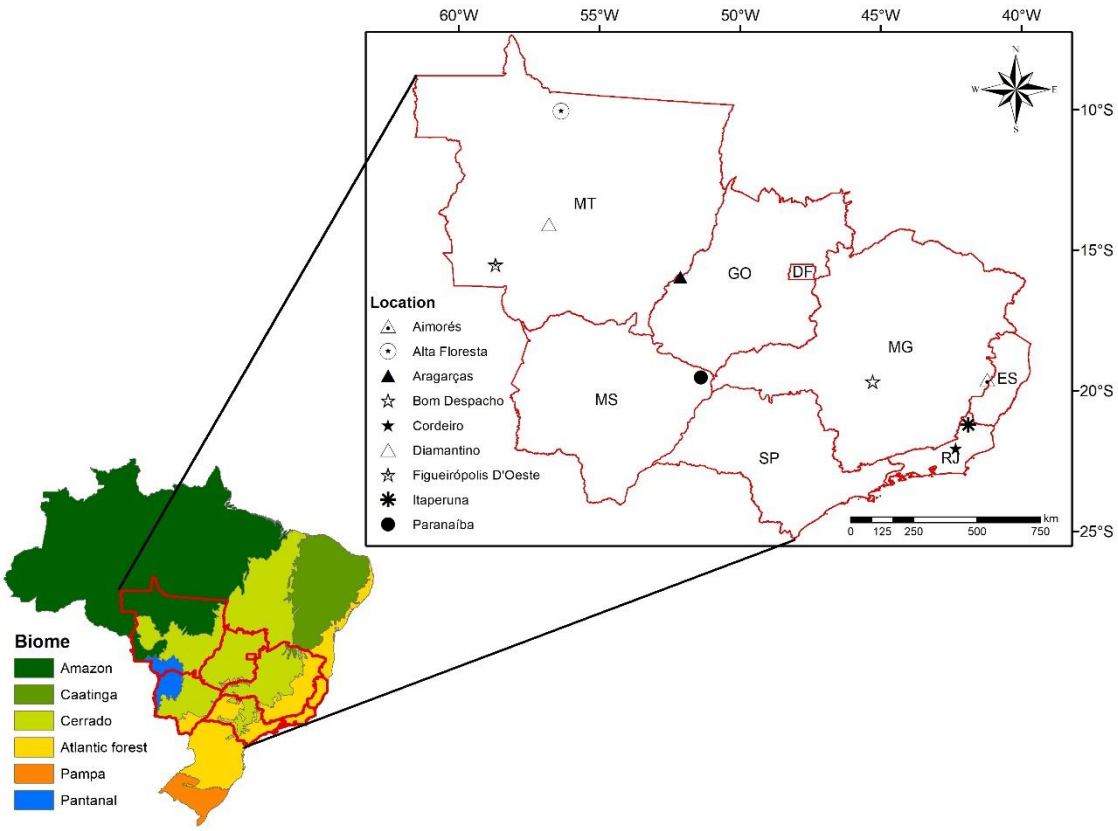

Figure 1. Overview of Brazilian Biomes and the location of the regions of this study (Central Brazil).

We selected nine locations within the Brazil Central region (Central West and Southeast), with distinct climatic and soil features, for testing the CROPGRO-PFM long-term simulations under different environmental conditions: Aimorés - MG, Alta Floresta - MT, Aragarças - GO, Bom Despacho - MG, Cordeiro - RJ, Diamantino - MT, Figueirópolis D'Oeste - MT, Itaperuna - MT and Paranaíba - MS (Figure 1). We used daily gridded weather data for maximum and minimum temperature, solar radiation and rainfall for the period from 1 January 1980 to 31 December 2016, provided by Xavier et al. (2016). The climate base was not updated for rainfall between 2015 and 2016, and for this period we used the rainfall data from the Tropical Rainfall Measuring Mission (TRMM, Huffman et al., 2007). Figure 2 shows the climate variables for the nine sites selected. In general, the Brazil Central West and Southeast regions have two seasons, with the rainy season centered in the summer and the dry season centered in the winter. However, the precipitation amount varies significantly among regions.

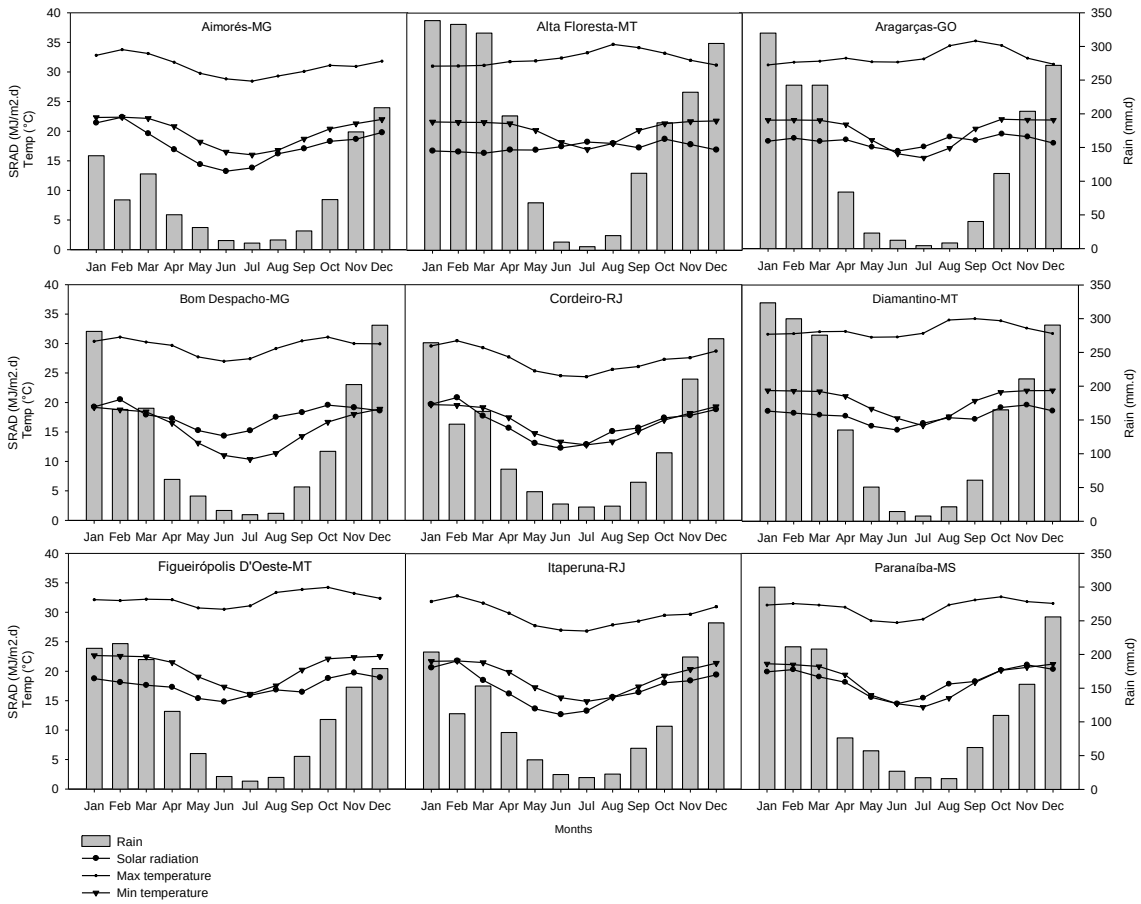

Figure 2. Monthly average of solar radiation (SRAD - MJ m² day^{-1}), maximum and minimum temperature (Temp - °C) and monthly accumulated rainfall (Rain - mm) in Aimorés - MG, Alta Floresta - MT, Aragarças - GO, Bom Despacho - MG, Cordeiro - RJ, Diamantino - MT, Figueirópolis D'Oeste - MT, Itaperuna - MT and Paranaíba - MS, between 1980 and 2016.

Soil profiles were recovered from a soil database provided by EMBRAPA (BDSolos) (https://www.bdsolos.cnptia.embrapa.br/consulta_publica.html), which groups the soil profiles by Biome, first level soil class and texture (Santos et al., 2018). The texture of each soil class observed in the simulation points was determined considering the soil genesis through the geological map of Brazil (CPRM, 2001; Miguel Cooper, University of Sao Paulo, Personal communication) (Table 1).

Table 1. Soil classes used for simulation of Marandu-palisadegrass production in Aimorés - MG, Alta Floresta - MT, Aragarças - GO, Bom Despacho - MG, Cordeiro - RJ, Diamantino - MT, Figueirópolis D'Oeste - MT, Itaperuna - MT and Paranaíba - MS

Location	Lat. (°)	Long. (°)	Soil class*	Soil class**
Itaperuna	-21.21	-41.89	Latossolo Vermelho Amarelo	Oxisol
Bom Despacho	-19.74	-45.25	Cambissolo háplico	Inceptisols
Cordeiro	-22.02	-42.37	Latossolo Vermelho Amarelo	Oxisol
Aimorés	-19.49	-41.07	Latossolo Vermelho Amarelo	Oxisol
Paranaíba	-19.67	-51.20	Latossolo Vermelho	Oxisol
Aragarças	-15.90	-52.23	Neossolo Quartzarênico	Entisols (Quartzipsamments)
Figueirópolis D'Oeste	-15.43	-58.73	Argissolo Vermelho	Ultisols
Diamantino	-14.40	-56.43	Latossolo Vermelho	Oxisol
Alta Floresta	-9.90	-55.90	Argissolo Vermelho Amarelo	Ultisols

*SiBCS: Sistema Brasileiro de Classificação de Solos **Soil Taxonomy.

The soil profile of each simulation point was built using DSSAT's SBuild pedotransfer functions applied to the soil profiles, considering the soil texture and the depths of the soil horizon to estimate the saturated upper limit (SSAT), drained upper limit (SDUL) and lower limit of plant extractable soil water (SLLL). Thereafter, SLLL, SDUL and SSAT resulted in values of water holding capacity close to Brazilian tropical soils reality (Teixeira et al. 2021).

The saturated hydraulic conductivity (SSKS) was estimated using the functions proposed by Tomasella and Hodnett (1997). Volumetric density and percentage of organic C in the soil were also recovered from the soil database. All soil profiles were described through 10 layers, each keeping a constant proportion to the informed soil depth. All values were interpolated vertically to set each layer's attributes.

After the average profiles for the simulation points were determined, the data for each profile was compared to information from literature on the attributes of soil classes in areas used as pastures (Donagemma et al., 2016; Ferreira et al., 2015; Grego et al., 2012; Isernhagen et al., 2017; Lisbôa et al., 2016; Lourente et al., 2007; Macedo, 2005; Muller et al., 2001; Passos et al., 2015; Pequeno et al., 2014, 2018; Salimon et al., 2007; Santos, 2016; Spera et al., 2004; Viana et al., 2015).

3.2.2. Forage Models

To carry out long-term forage production simulations we used the CROPGRO-PFM available in the DSSAT platform v. 4.7.5.011. DSSAT is a software application program that includes process-based models, combining crop, soil, and weather data bases with crop models, such as CROPGRO-PFM, integrating the effects of soil, crop genetics, weather, and management options (Hoogenboom et al., 2019).

Another forage model was used as a reference point using the same weather data that was used in CROPGRO-PFM simulations. The integrated agrometeorological model (IAM), developed by Pezzopane et al. (2018), was used to simulate results for scenarios non sensitive to the effect of N, since that model has been adjusted for Brazil under both irrigated and rainfed conditions. The IAM model uses simplified process representations and empirical relations to estimate the seasonal and inter-annual variability of *Urochloa brizantha* cv. Marandu palisadegrass dry matter production for both irrigated and rainfed conditions. The main drivers of pasture growth in IAM are accumulated degree-days; radiation use efficiency; a thermal factor based on cardinal temperatures; and a water deficit sensitivity index based on the relative soil water content.

3.2.3. Pasture Management Scenarios

The theoretical scenarios of pasture production systems used on our simulations were built to reflect the modal systems in the region of study. The resulting scenarios are: 1. Rainfed extensive cattle production system, featured by some level of pasture degradation and low maintenance fertilization; 2. Rainfed intensive cattle production system with a high level of fertilization, which represented the water-limited potential yield (Yw); and 3. Irrigated intensive cattle production system with high level of fertilization and irrigation, which represented the potential yield.

The following experiments were set up to simulate growth and forage production of *Urochloa brizantha* cv. Marandu in different scenarios: Yp, with no water and N stresses; Yw, under water influence with no nitrogen stress; Ya, attainable yield under water and N influence. Within attainable yield category, we tested two levels of inorganic N fertilization: a) N400, following Primavesi et al. (2001), Oliveira et al. (2004) and Pequeno et al. (2014) recommendations, the dose used was 400 kg N ha^{-1} y^{-1} as urea split-dose applied on the day after each harvest. b) N50, according to Oliveira et al. (2004), 50 kg N ha^{-1} y^{-1} as urea applied in March and December of each year. Furthermore, in both scenarios we added 50 kg N ha^{-1} y^{-1} to represent atmospheric N deposition, in aqua ammonia form, split-applied in the beginning and end of the rainy season (Resende, 2001) (Table 2).

The growth estimates for scenarios Yp and Yw were also performed using the IAM. The planting dates were the same for all experiments. For simulations using CROPGRO-PFM, grazing frequency was established as 42 days during the winter months and 28 days for the other seasons (Domiciano et al. 2020), and for the IAM, grazing events were based on a constant target leaf area index of 2.5 (Pezzopane et al., 2018).

The percentage leaf of the stubble (RSPLF), hypothetical number of leaves left on a primary tiller axis after harvest (MVS) and stubble height after harvest (RSHT) values in the MOW file of the CROPGRO-PFM were based on Pequeno et al. (2014). The stubble mass (MOW) values were fixed to 3000 DM kg ha^{-1} in accordance with Pequeno et al. (2014) and Bosi et al. (2020) studies.

In preliminary tests, we observed that CROPGRO-PFM underestimated the biomass production in long time series due to the increase of N stress along the years. CROPGRO-PFM does not account for the incorporation of atmospheric N deposition, asymbiotic biological N fixation, or the return rates of organic N via animal feces and urine.

Therefore, we set up more two scenarios to include N return inputs: c) N400+ret (N400 scenario with N return) and d) N50+ret (N50 scenario with N return). These scenarios were fertilized with urea (400 kg N ha^{-1} y^{-1} for N400+ret and 50 kg N ha^{-1} y^{-1} for N50+ret), along with 50 kg N ha^{-1} y^{-1} as aqua ammonia plus 75% of total extracted N in harvested herbage (Dubeux et al., 2006; Saraiva, 2010; Souza et al., 2018) based on the forage outputs of N400 and N50 scenarios.

To accomplish this, we did a first simulation of N400 and N50 scenarios to calculate 75% of N amount in plant harvested (inorganic form). This was assumed to return in organic form, and those amounts were then entered into the second run for N400+ret and N50+ret scenarios. The organic N was applied after each grazing date as liquid manure form, with assumed 5% N concentration. To do this, we converted plant mineral N equivalent to organic N by multiplying plant N extracted as feces in each cycle by a conversion factor of 20.

Table 2. Conceptual definition of Yp, Yw, N400, N50, N400+ret and N50+ret scenarios and influence of water and nitrogen in each of them

Scenarios	Conceptual definition	Water effect	N effect	Inorganic fertilizer	Organic fertilizer	Source
Yp	Potential intensive	No	No	-	-	Van Ittersum and Rabbinge, 1997
Yw	Rainfed intensive	Yes	No	-	-	Van Ittersum and Rabbinge, 1997
N400	Rainfed intensive	Yes	Yes	Yes	No	Resende, 2001; Primavesi et al. 2001; Oliveira et al. 2004; Pequeno et al. 2014; Pequeno et al.2018
N50	Extensive	Yes	Yes	Yes	No	Resende, 2001; Oliveira et al. 2004
N400+ret	Rainfed intensive	Yes	Yes	Yes	Yes	Resende, 2001; Primavesi et al. 2001; Oliveira et al. 2004; Dubeux et al. 2006; Saraiva 2010; Pequeno et al. 2014; Pequeno et al.2017; Souza et al. 2018
N50+ret	Extensive	Yes	Yes	Yes	Yes	Resende, 2001; Oliveira et al. 2004; Dubeux et al. 2006; Saraiva 2010; Souza et al. 2018

Additionally, we observed that CROPGRO-PFM sometimes failed to sustain regrowth during severe weather conditions such as years with extended droughts. To partially address this, the RTSEN species parameter (Fraction of existing root length which can be senesced per physiological day) was decreased from 0.008 to 0.005 to slow down the root senescence rate, avoiding plant death. In addition, the soil evaporation method was changed from Suleiman-Ritchie to Ritchie-Ceres, because comparison to unpublished daily ET data shows that the Suleiman-Ritchie method causes too much soil evaporation (Kenneth Boote, DSSAT, personal communication).

The Soil Root Growth Factor (SRGF) values, which range from 0 to 1, were estimated for each layer for all soil profiles according to its depth and root distribution for tropical grasses in soils without impeding soil layers (da Cunha et al., 2010; Prudente Junior, 2019; Stumpf et al., 2016). We altered the proportion of stable C in soil organic matter (SASC - Stable organic carbon, %) from 0.57 (Pequeno et al., 2018, 2014) to 0.80 (Worou et al. 2019; Porter et al., 2009) to better represent common stable pool of soil organic matter in tropical soils. Tropical soils are known for their natural low fertility and they can present high proportion of stable organic C (until 90%) and high decomposition of organic matter rates, alghouth the low organic matter content (Worou et al. 2019; Porter et al., 2009). Due to lack of information about inorganic N in initial condition (ammonium and nitrate), we assumed the same values from Pequeno et al. (2018) experiments. Thus, to achieve a system in equilibrium for each scenario, with more stable values of N and organic carbon in soil, we did an initial twenty-five-years spin-up simulation for all scenarios prior to 01/01/1980 by repeating the first 25 years of weather data and dating the weather and mow files from 1955 to 2016. The spin-up effectively replaces the initial condition assumptions for inorganic N.

3.3. Results

3.3.1. Simulations from both CROPGRO Perennial Forage model and Integrated Agrometeorological model

Annual herbage above-ground dry biomass production simulated by CROPGRO-PFM and by IAM models was similar during the 36 years of simulation for both Potential Intensive (Yp) and Rainfed Intensive (Yw) conditions. In addition, the interannual biomass variability, mean standard deviation (SD) of annual production above-ground dry biomass production, were similar for both models, estimated as 3.1 Mg ha^{-1} y^{-1} for the Yw scenario and as 1.2 Mg ha^{-1} y^{-1} for the Yp scenario (Table 3). The highest standard deviation for the Yw conditions was estimated for Aimorés with both models.

Monthly herbage accumulation rate (HAR) was similar for both model simulations, especially for Yp scenario, in which SD and coefficient of variation (CV) values were lower for CROPGRO-PFM predictions. In general, both models showed the same seasonal tendency of SD and CV throughout the year (Figure 3 and 4).

In locations with more regular rainfall distribution in spring and summer, SD and CV of monthly HAR for Yw scenario simulated by CROPGRO-PFM were smaller in rainy season (summer) until the beginning of dry season (winter) than SD and CV values observed in IAM estimates for the same period (Figure 3.D and 4.D). However, in locations with poor rainfall distribution, such as Aimorés, the SD values were high for both models, mainly in summer/autumn (Figure 3.C). The CV values in Aimorés showed the same tendency and were higher for CROPGRO-PFM, largely in dry season (winter) and in transition to rainy season (Figure 4.C).

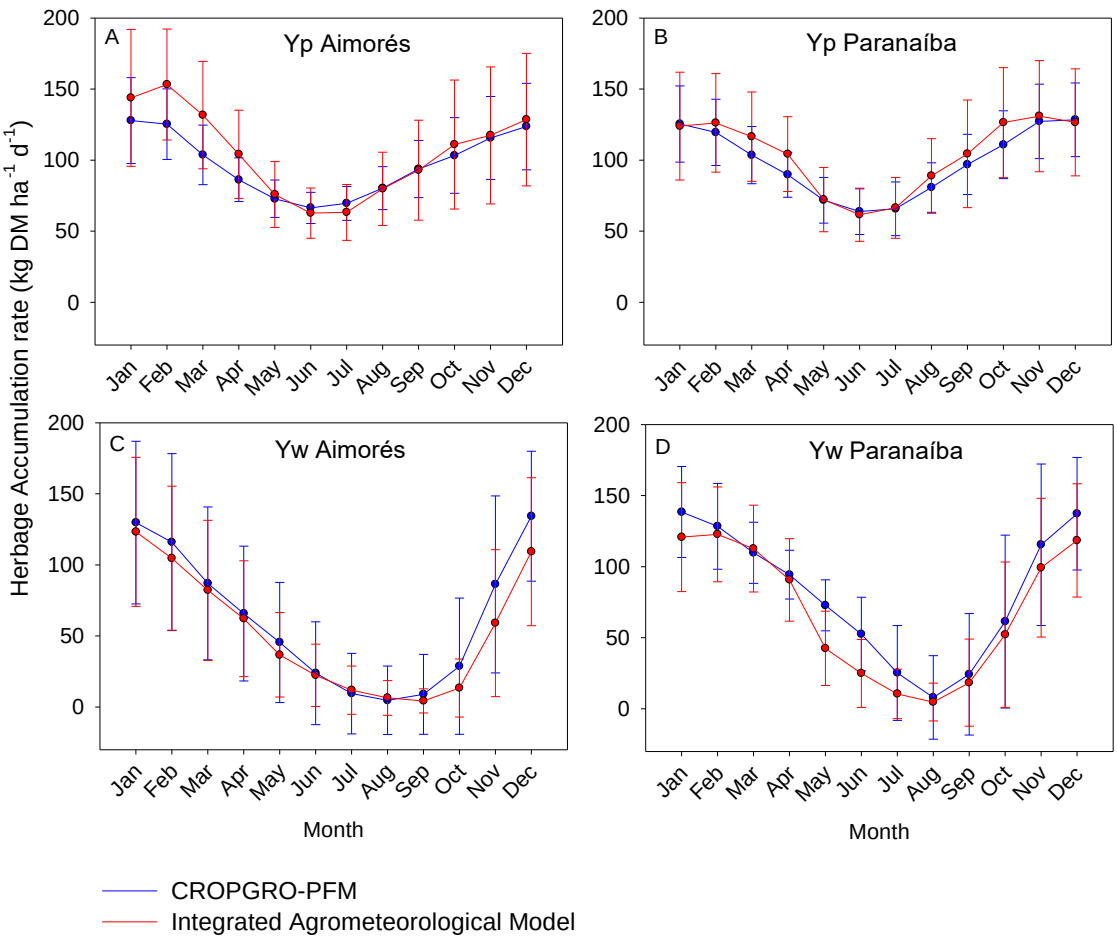

Figure 3. Mean and standard deviation of monthly herbage accumulation rate simulated by CROPGRO-PFM and Integrated Agrometeorological Model between 1980-2016 for Yp and Yw scenarios in Aimorés (A and C) and in Paranaíba (B and D).

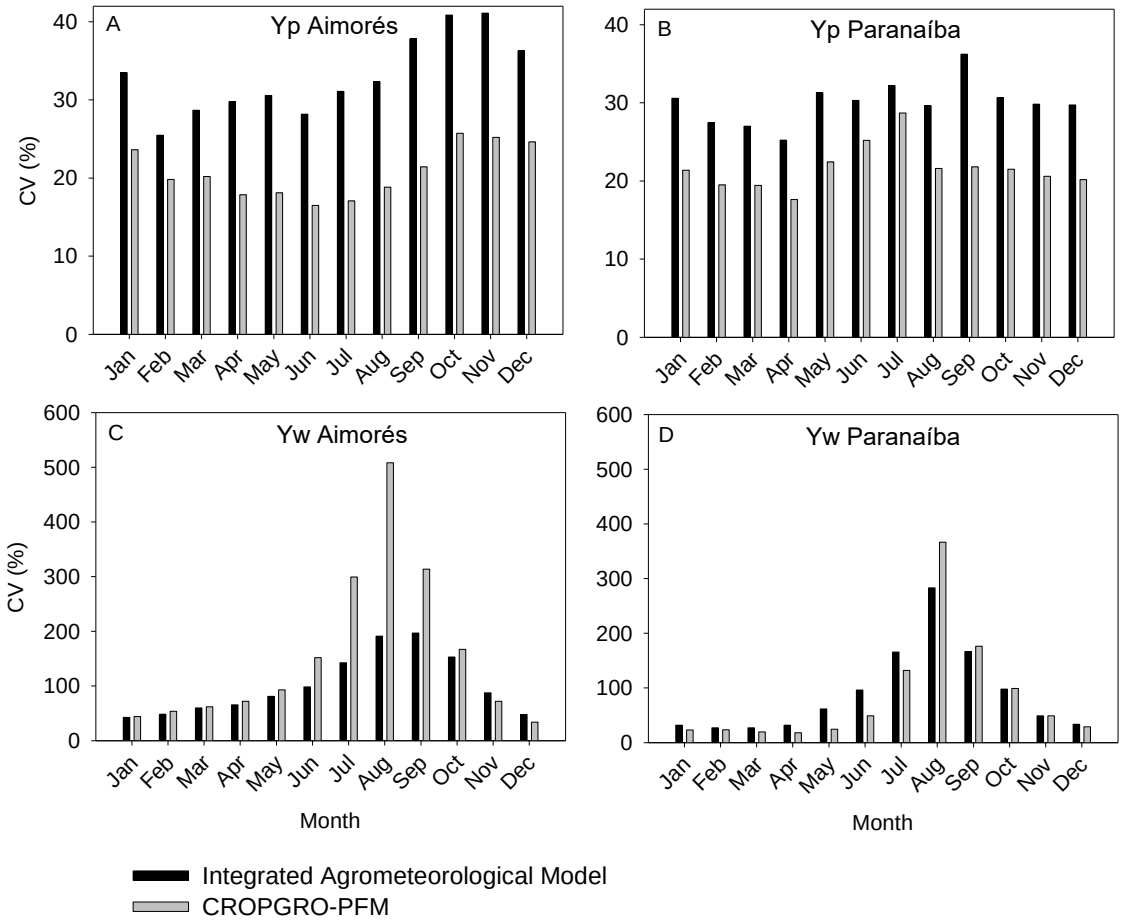

Figure 4. Coefficient of variation (CV) of monthly herbage accumulation rate simulated by CROPGRO-PFM and Integrated Agrometeorological Model between 1980-2016 for Yp and Yw scenarios in Aimorés (A and C) and in Paranaíba (B and D).

3.3.2. Annual production simulated by CROPGRO Perennial Forage model

The average annual herbage above-ground dry biomass accumulated under the Yp scenario was similar in most locations (34.9 Mg ha^{-1} y^{-1}). The lowest values were noted in Cordeiro and Bom Despacho (32.6 Mg ha^{-1} y^{-1}) (Table 3). The Yp scenario produced about 8.5 Mg ha^{-1} y^{-1} more than achieved in Yw.

Over all locations, Yw scenario produced an annual average of accumulated herbage of 28.1 Mg ha^{-1} y^{-1}, except at Bom Despacho, Aimorés and Aragarças, where the average was 22.7 Mg ha^{-1} y^{-1} (Table 3). The same pattern of annual production in Yw was noted for all scenarios under both water and N effect, with the lowest values estimated for Bom Despacho, Aimorés and Aragarças.

As expected, the estimates of herbage production for scenarios fertilized with inorganic plus organic N forms were greater than in scenarios only fertilized with inorganic N, in both Intensive and Extensive conditions. N400+ret scenario produced on average 5.1 Mg ha^{-1} y^{-1} more than N400 in all sites, while N50+ret produced 3.7 Mg ha^{-1} y^{-1} more than N50 scenario (Table 3). Furthermore, the annual production of N400+ret scenario was close (only slightly less) than values estimated for Yw scenario in all locations due to organic N addition in the system.

Table 3. Average annual accumulated herbage between 1980 and 2016 simulated by CROPGRO-PFM and IAM for all scenarios in each location (mean and standard deviation)

Location	Soil class	Integrated Agrometeorological Model		---------- CROPGRO Perennial Forage Model ----------					
		Yp	Yw	Yp	Yw	N400	N400+ret	N50	N50+ret
		Mg ha^{-1} y^{-1}							
Diamantino	Oxisol	40.8 (±2.0)	27.6 (±3.1)	36.8 (±1.0)	29.6 (±2.4)	22.5 (±1.6)	28.4 (±2.5)	14.4 (±1.1)	-
Cordeiro	Oxisol	28.0 (±2.3)	22.1 (±2.7)	32.7 (±1.4)	28.8 (±2.3)	20.0 (±1.4)	25.7 (±1.8)	12.1 (±0.8)	16.5 (±1.2)
Bom Despacho	Cambisol	31.3 (±2.1)	17.1 (±2.2)	32.4 (±2.4)	22.3 (±2.7)	16.1 (±1.4)	20.5 (±2.2)	9.6 (±0.8)	12.6 (±1.3)
Aimorés	Oxisol	38.4 (±3.9)	19.3 (±5.1)	35.5 (±1.2)	22.5 (±5.5)	17.8 (±3.8)	21.9 (±5.4)	10.4 (±1.8)	13.5 (±2.8)
Itaperuna	Oxisol	34.4 (±3.2)	23.9 (±3.9)	34.6 (±1.1)	27.5 (±3.6)	20.3 (±2.5)	25.7 (±3.5)	12.9 (±1.4)	17.0 (±2.4)
Paranaíba	Oxisol	38.0 (±2.4)	24.8 (±2.8)	36.0 (±1.0)	29.4 (±3.4)	20.7 (±2.0)	26.6 (±3.0)	13.0 (±1.2)	17.4 (±1.7)
Figueiropolis D'Oeste	Argisol	39.9 (±2.4)	25.7 (±3.3)	34.8 (±1.1)	26.1 (±2.8)	21.3 (±1.9)	26.1 (±2.8)	12.1 (±1.0)	15.7 (±1.4)
Alta Floresta	Argisol	39.3 (±2.3)	27.1 (±3.0)	35.0 (±1.0)	27.6 (±2.3)	20.8 (±1.6)	26.6 (±2.4)	11.4 (±0.8)	14.7 (±1.2)
Aragarças	Neosol	40.9 (±2.7)	21.9 (±2.3)	35.9 (±1.1)	23.2 (±2.5)	17.4 (±1.5)	21.5 (±2.3)	9.6 (±0.9)	12.3 (±1.0)
Average	-	36.8 (±2.6)	22.5 (±2.8)	34.9 (±1.2)	26.3 (±3.1)	19.7 (±2.0)	24.8 (±2.9)	11.7 (±1.1)	15.4 (±1.7)

3.3.3. The need to return excreted n to pastures

Monthly HAR and SD for N400+ret scenario were closer to the results of Yw scenario than the N400 (Figure 5 and 7). This demonstrates that simulated rainfed scenarios supplied only with mineral fertilizer do not meet the potential plant demand for N and, consequently, there was a drop in biomass production, even at the higher dose of 400 kg N ha^{-1} y^{-1}.

The same pattern was verified when comparing the HAR of scenarios N400 and N50 with those of scenarios N400+ret and N50+ret, respectively (Figure 5 and 6). Therefore, the inclusion of N via organic fertilization, which represents the return of N deposition from animal excreta, increased the monthly HAR in months with greater precipitation accumulation, for all locations.

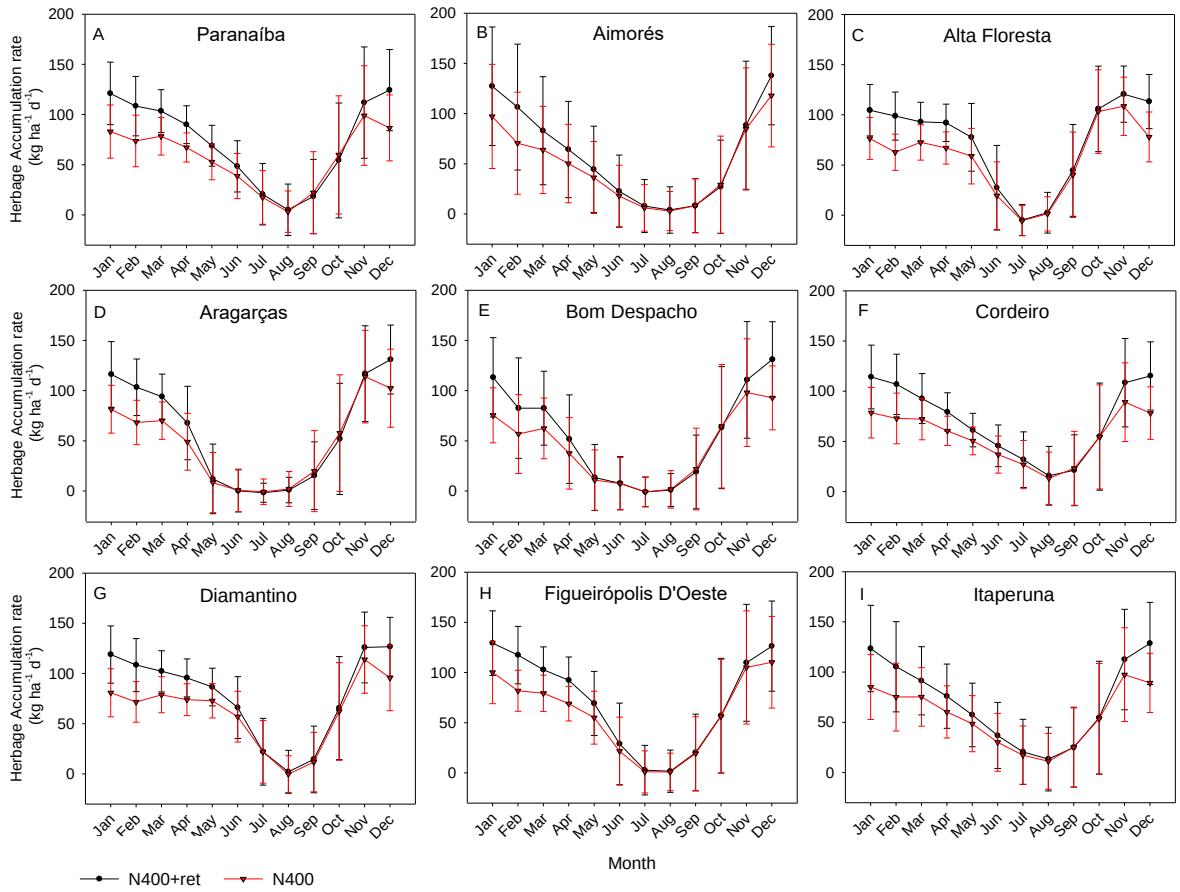

Figure 5. Mean monthly herbage accumulation rate (and standard deviation) for CROPGRO-PFM for Rainfed Intensive scenario with inorganic fertilization (N400) and Rainfed Intensive scenario with both inorganic and organic fertilization (N400+ret).

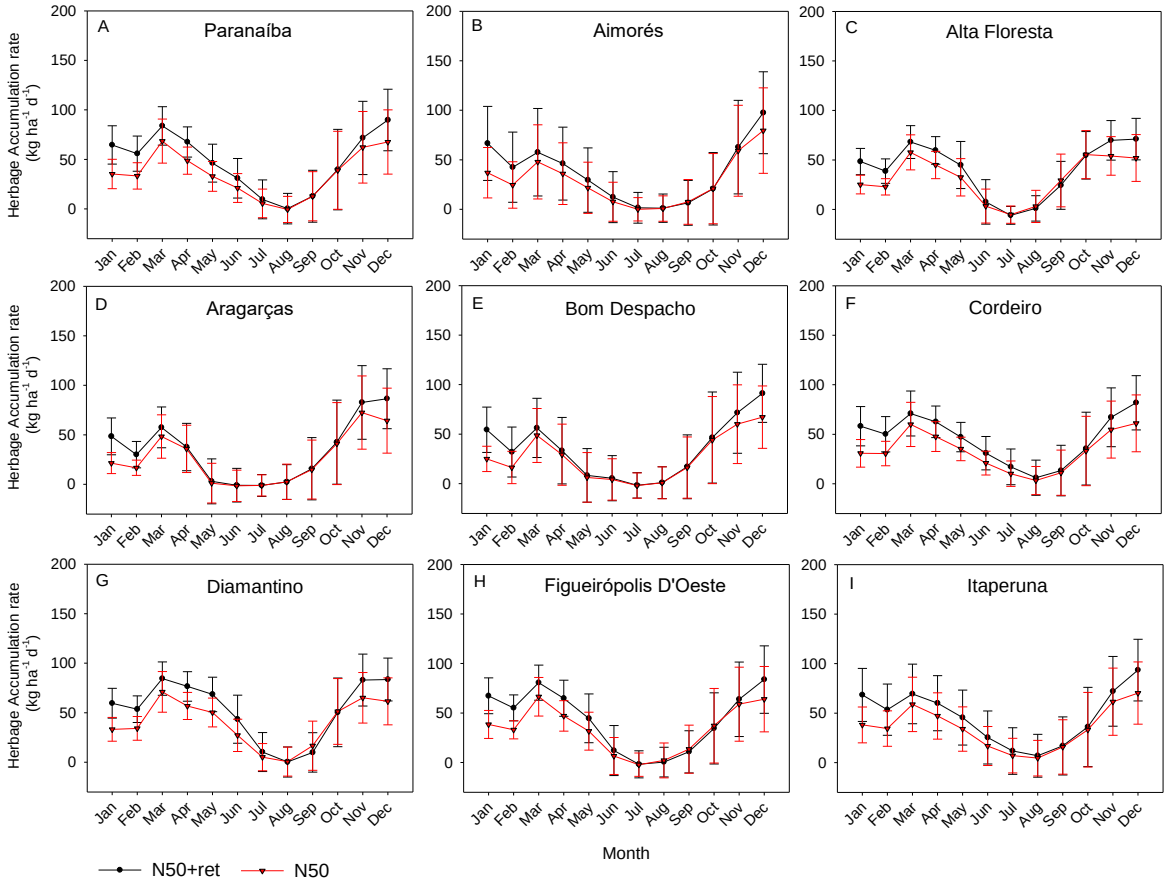

Figure 6. Mean monthly herbage accumulation rate (and standard deviation) for CROPGRO-PFM for the Extensive scenario with inorganic fertilization (N50) and the Extensive scenario with both inorganic and organic fertilization (N50+ret).

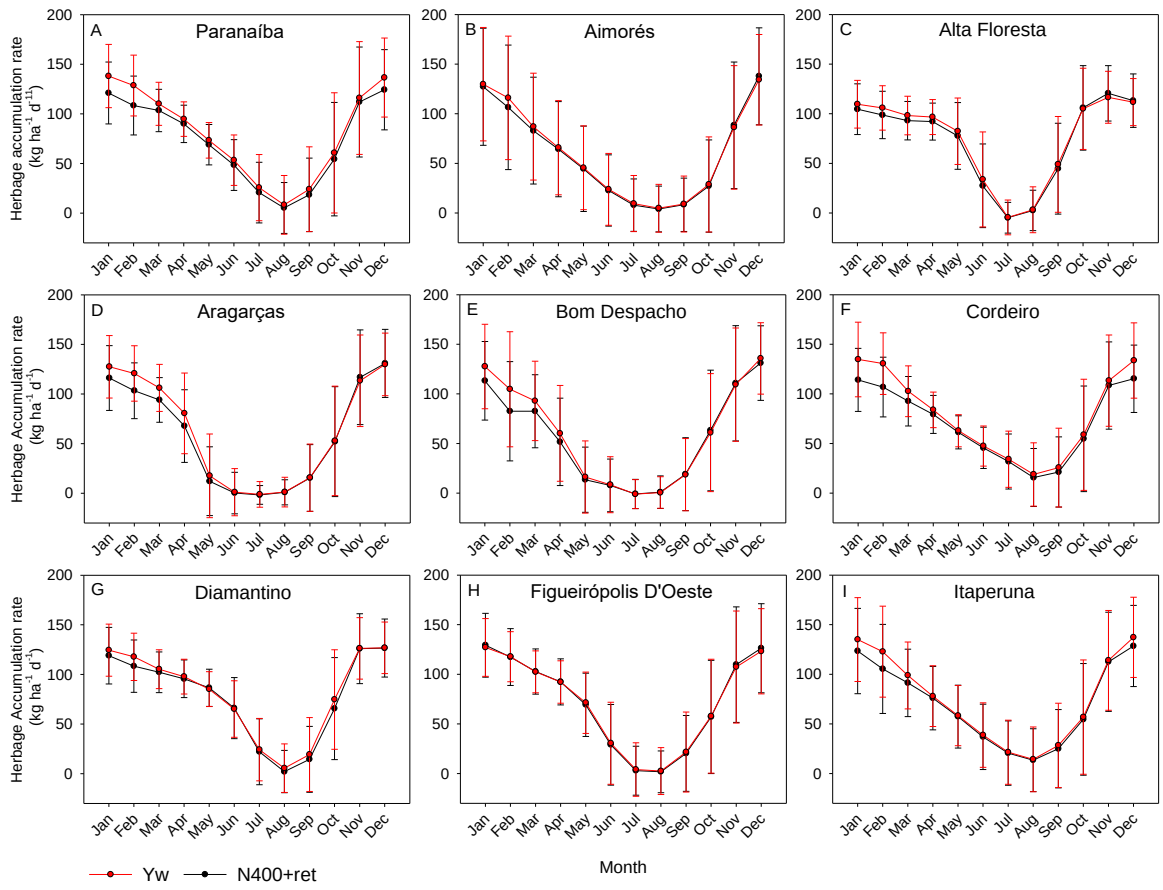

Figure 7. Mean monthly herbage accumulation rate (and standard deviation) simulated with CROPGRO-PFM for Rainfed Intensive scenario with N not limiting (Yw) and Rainfed Intensive scenario fertilized with both inorganic and organic nitrogen (N400+ret).

3.3.4. Productivity sensitivity to drought and low temperatures in winter

In general, all simulated rainfed scenarios showed a reduction in growth rates in the drier months. During the winter season, rates were low and similar across level of fertilization in these scenarios.

As expected for the Central Brazil region, historical averages of monthly HAR of Yp scenarios declined in the winter period for most locations due to the mild temperature reduction effect in that period (Figure 8). In places with less variation in temperature and similar normal climatology, such as Alta Floresta, Aragarças and Diamantino (Figure 1), the historical average of monthly HAR were more constant throughout the year.

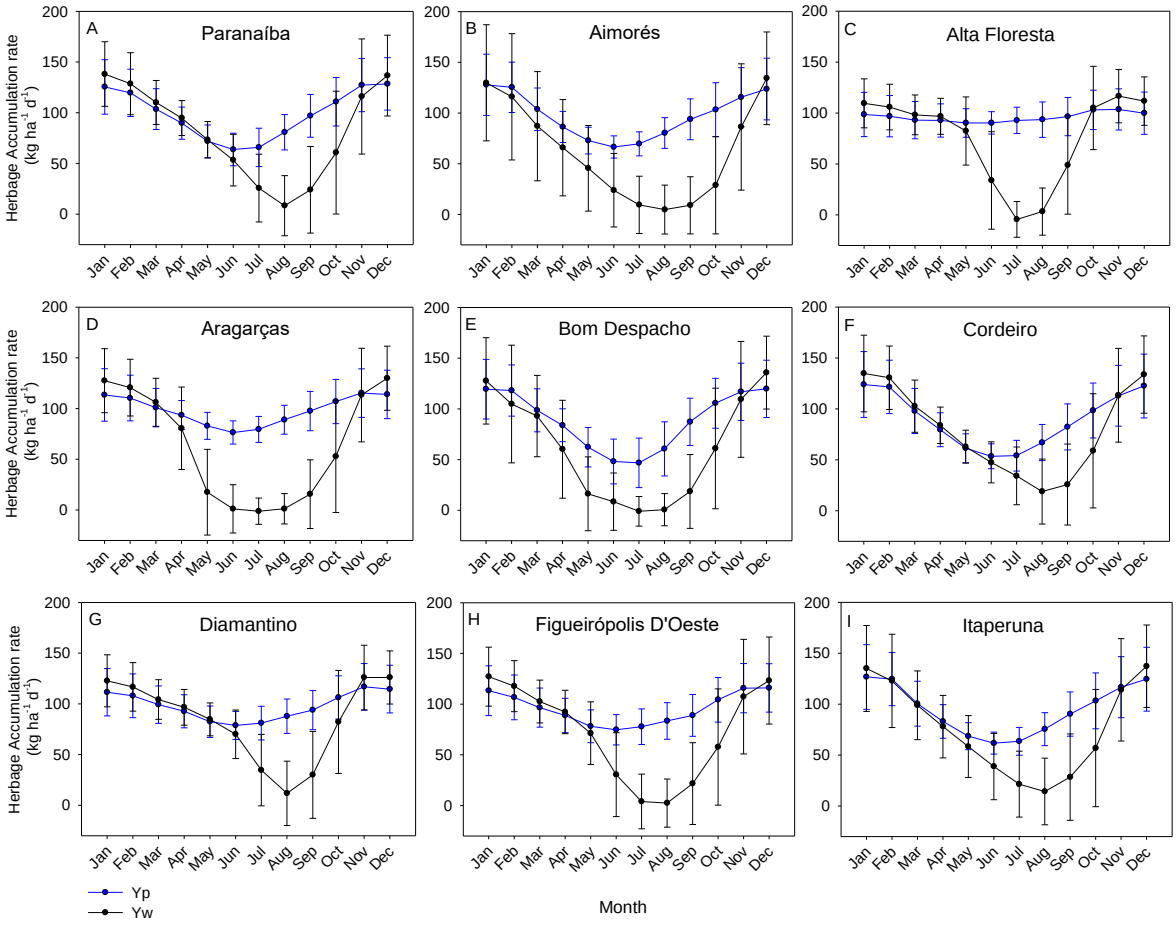

Figure 8. Mean simulated monthly herbage accumulation rate and standard deviation for potential production scenario (Yp) and Rainfed Intensive scenario with N not limiting (Yw) to all locations.

3.3.5. Plant failure to survive during extended drought

Even with the model adjustments stated above, the CROPGRO-PFM simulated plant death when severe drought periods occurred, for example, for N400+ret scenario during winter of 1974 in Aragarças and for N50+ret during winter of 1983 in Diamantino. However, after replacing 1974 climatic year by repeating weather data from 1973, N400+ret simulation in Aragarças ran to the end of the December 2016 cycle without simulating plant death. However, CROPGRO-PFM-simulated palisadegrass kept dying in Diamantino even after replacing some years in weather data for N50+ret scenario. In Diamantino, CROPGRO-PFM simulated the last harvest of the Extensive scenario (N50+ret) to occur in July 1983, the third year after spin-up period, followed by plant death in the middle of spring of the same year. In 1983, the dry season extended for four and a half months between Jun and October, with only 30 mm of accumulated rainfall.

For those cases when CROPGRO-PFM simulated plant death, the root and storage dry biomass declined dramatically (Figure 9.A) as well as the carbohydrate pool concentration in storage, leaf, and stem (Figure 9.B), having spent all available energy of mobilized carbohydrates to drive re-growth (Figure 10). When CH2O in storage reached level of 4% no more mobilization occurred. Thus, below that level, mobilization from storage ended, and in absence of rainfall and positive photoassimilation and refill of storage the death of the plant occurred.

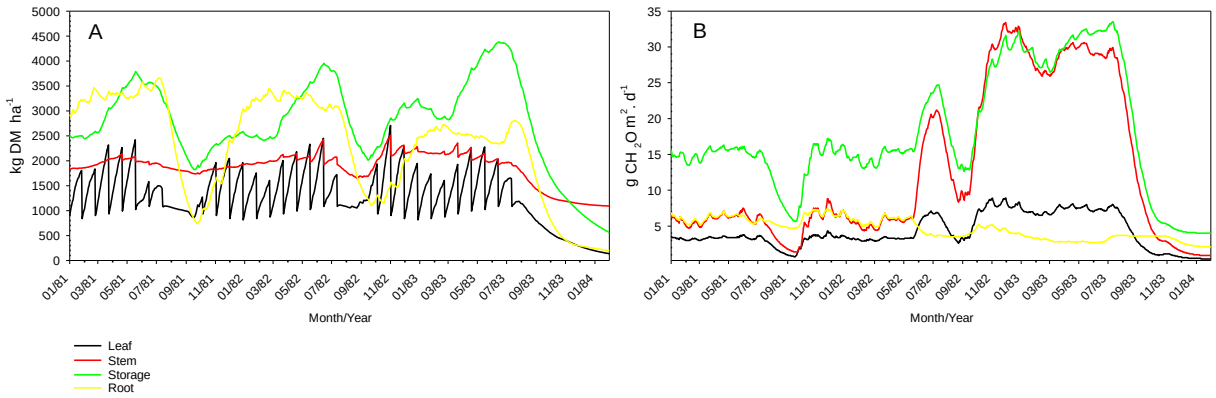

Figure 9. Leaf, stem, storage and root weight (A) and Carbohydrate concentration (B) for N50+ret scenario in Diamantino-MT when CROPGRO-PFM simulated Marandu palisadegrass died in third year after spin-up (1983) simulation.

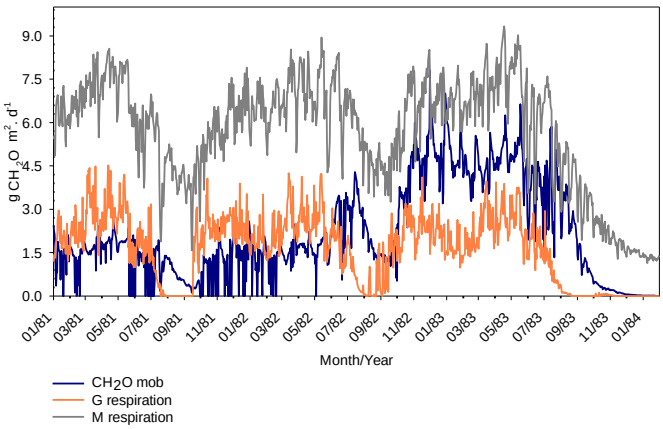

Figure 10. Carbohydrate mobilization (CH2O mob); Growth respiration (G respiration); and Maintenance respiration (M respiration) for N50+ret scenario in Diamantino-MT when Marandu palisadegrass died in third year after spin-up (1983) simulation by CROPGRO-PFM.

3.3.6. Soil organic matter

Today, agriculture is important not only for providing food, but also for its environmental services. Specifically, in relation to climate change, agricultural producers are being asked to reduce

greenhouse gas emissions and contribute to mitigating climate change effects through, for example, more efficient production and carbon sequestration in agro-ecosystems. Regardless of the choice of proportion of stable C in soil organic matter values in the initial simulation conditions (SASC), there were losses of soil organic carbon (SOC) pools over the years of simulation (Table 4).

Table 4. Simulated soil organic carbon (SOC) pools between 1955-2016 of N400+ret scenario in Paranaíba, using two levels of stable soil carbon (SASC) in initial conditions

SOC pools	SASC initial conditions (fraction SOC3)							
	---------- 0.57 ----------				---------- 0.80 ----------			
	initial	final	final-initial	variation	initial	final	final-initial	variation
	---------- kg ha^{-1} ----------			%	---------- kg ha^{-1} ----------			%
Litter C on surface	0	1069	1069	106800	0	963	963	96200
Total soil litter C	4000	516	-3484	-87	4000	624	-3376	-84
SOC1	3558	597	-2961	-83	1623	650	-973	-60
SOC2	67599	15972	-51627	-76	30835	16013	-14822	-48
SOC3	95099	82732	-12367	-13	133798	117968	-15830	-12
Total SOC	170256	99817	-70439	-41	170256	131467	-38789	-23

Note: easily decomposable (SOC1), recalcitrant (SOC2) and almost inert (SOC3).

However, with the change in SASC fraction in initial conditions to 0.80 and the spin-up process, we simulated more gain of litter C on surface (Figure 12), less SOC loss and less fluctuation SOC1 and SOC2 pools, especially in more superficial layers (0-15 cm) and for scenarios fertilized with both urea and liquid manure, although there continued to be depletion of the SOC3 (Figure 11) and total soil organic carbon over 36 years (Figure 13).

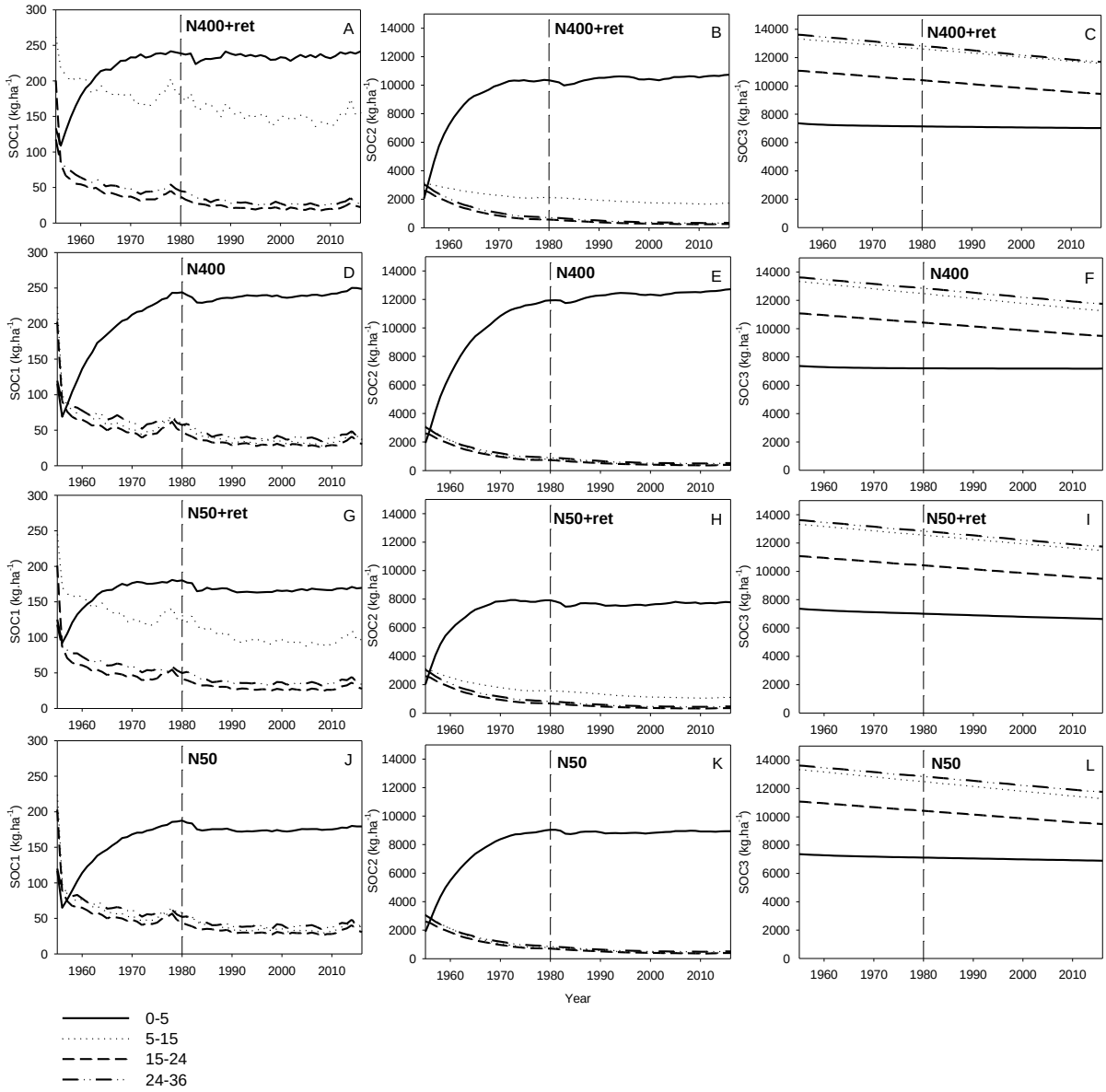

Figure 5. Soil organic matter pools – easily decomposable (SOC1), recalcitrant (SOC2) and almost inert (SOC3) – in each layer (cm) of an Oxisol sandy-clay in Paranaíba, simulated by CROPGRO-PFM linked to CENTURY for the spin-up period (1955 to 1979) until 2016 for rainfed and fertilized scenarios N400+ret (A, B, C), N400 (D, E, F), N50+ret (G, H, I) and N50 (J, K, L).

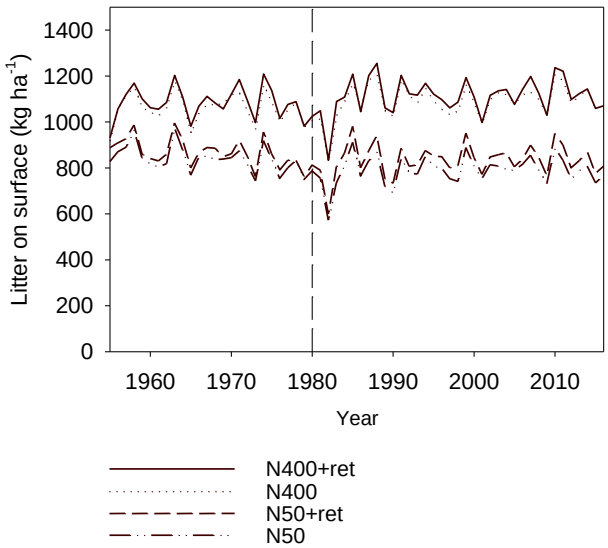

Figure 6. Litter C on surface of an Oxisol sandy-clay in Paranaíba, simulated by CROPGRO-PFM linked to CENTURY for the spin-up period (1955 to 1979) until 2016 for rainfed and fertilized scenarios N400+ret, N400, N50+ret and N50.

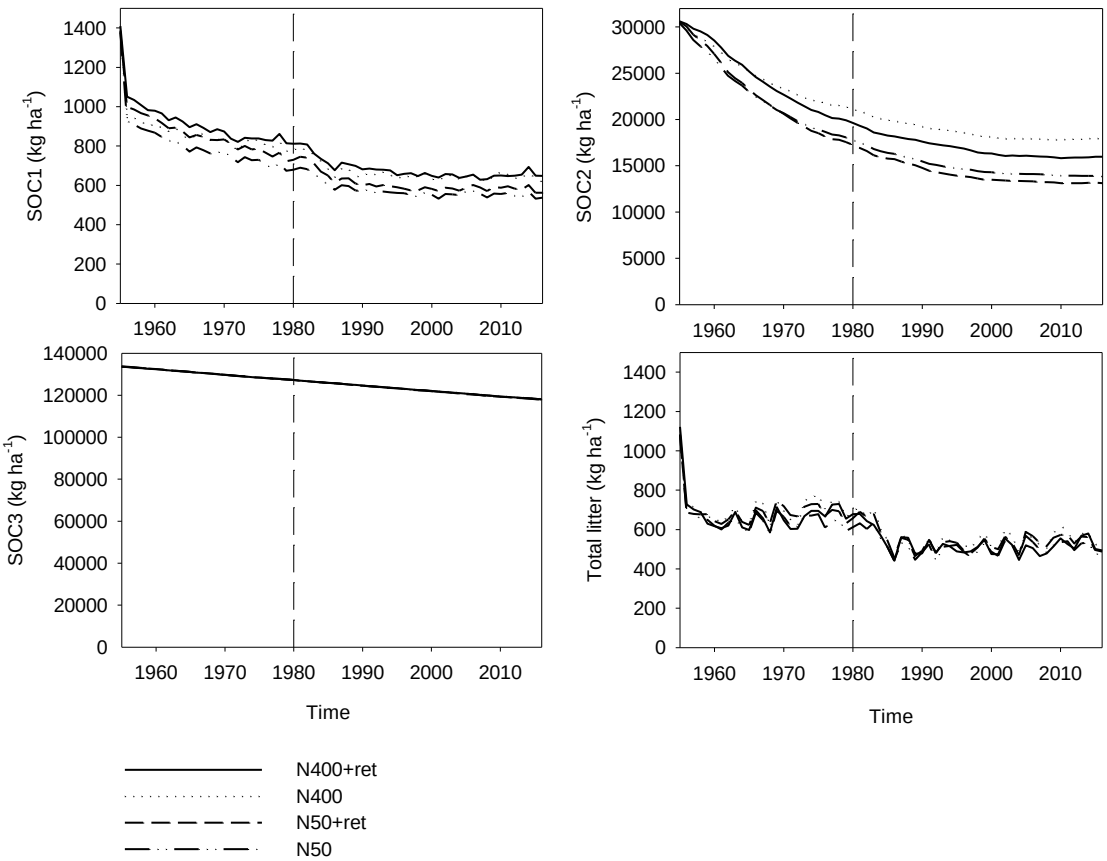

Figure 7. Total soil organic carbon – easily decomposable (SOC1), recalcitrant (SOC2), almost inert (SOC3) and total litter C – of an Oxisol sandy-clay in Paranaíba, simulated by CROPGRO-PFM linked to CENTURY for the spin-up period (1955 to 1979) until 2016 for rainfed and fertilized scenarios N400+ret, N400, N50+ret and N50.

3.4. Discussion

3.4.1. Simulations from both CROPGRO Perennial Forage model and Integrated Agrometeorological model

While classical validation for the models was not performed due to the lack of an adequate database on observed production for all tested locations, the similarity of the CROPGRO-PFM estimates with the IAM estimates showed that the long-term annual and seasonal production simulations resulted in good consistency. According Pezzopane et al. (2018), the IAM effectively estimates the seasonality of Marandu palisadegrass productivity in the Southeastern Brazil and it is sensitive to the impact of air temperature and rainfall variation. Those variations were consistent in the current study for both models as they responded accordingly to climate differences for the evaluated locations as well as responding consistently between potential and rainfed scenarios, even although both models were calibrated using experimental data from different locations (Bosi et al., 2020; Pedreira et al., 2011; Pequeno et al., 2018, 2014). Nonetheless, those model calibrations used experiments that were carried out in good management conditions such as irrigation and high or moderate levels of fertilization to represent Yp and Yw. In future, it is important to calibrate and evaluate the model for less fertilized and more degraded conditions, which are the more typical case for extensive areas in Brazil.

3.4.2. Annual and seasonal forage production simulated by CROPGRO Perennial Forage model

Marandu palisadegrass requires well-drained soils with medium to high fertility and produces between 8 to 20 Mg ha^{-1} y^{-1}, values that agree with those (17.8 Mg ha^{-1} y^{-1}) found by Pequeno et al. (2015) in an experiment conducted in Piracicaba-SP, with regrowth interval of 28 days and high level of fertilization in rainfed conditions (400 kg N ha^{-1} y^{-1} applied as a NH_4NO_3 split-applied after each harvest.). These simulation values are within the range of historical average of annual herbage production results simulated for the N400 scenario in the 9 locations. Similar results were found in an experiment in Sinop-MT, Brazil by Santos (2016), in which the annual herbage production of Marandu palisadegrass was 20.4 Mg ha^{-1} y^{-1}, using the same cutting frequency as the current study (28 and 42 days) and fertilization of 550 kg N ha^{-1} y^{-1}. In that same study, an unfertilized treatment of Marandu palisadegrass produced 13.4 Mg ha^{-1} y^{-1}, close to the simulated historical averages of the N50 scenario for locations belonging to the Cerrado or the transition region between Amazon and Cerrado biomes. However, it is worth remembering that these experiments were carried out in plots and did not have the presence of grazing animals and, therefore, did not account for N return via excreta deposition, as

well as losses by animal trampling. In the study by Da Silva et al. (2020) conducted with grazing ("put and take") and fertilization with 50 kg N ha^{-1} y^{-1} in the ecotone between Amazon and Cerrado (MT, Brazil), the annual herbage production value of Marandu palisadegrass of 12.3 Mg ha^{-1} y^{-1} was like the values found in simulations for scenario N50. Da Silva et al. (2020) experiment included the effect of animal presence on pasture (feces and urine deposition) and it was stocked continuously with beef cattle using a variable stocking rate.

Simulation results were consistent with expected behavior in response to variations of temperature, water supply and soil type. The lower annual herbage production in Cordeiro and Bom Despacho even in conditions of no water deficit were found to be associated with lower average minimum temperature during the winter seasons. In Bom Despacho, lower annual herbage production under rainfed conditions (Yw) was additionally also associated with poor rainfall distribution, although the historical average annual rainfall was 1385 mm. In Aimorés and Aragarças, although the yield in potential conditions was high, the herbage productions in rainfed conditions were among the lowest, which was clearly associated with low annual rainfall and its poor distribution. In addition, in Aragarças, besides the poor rainfall distribution, the plant water stress was greater due to low water holding capacity typical of quartzarenic neossols.

As expected, simulations of rainfed scenarios showed that plant growth and biomass production were drastically reduced in the dry winter period, even with periodic fertilization at high levels. The limitation by water and temperature in this period causes a greater reduction than the limitation by N, as observed in DSSAT outputs, WSPD (Water stress - photosynthesis), WSGD (Water stress - expansion/partitioning/development) and NSTD (Nitrogen stress factor). When simulated photoassimilation is limited because of cool temperature or water deficit, the demand for N is reduced, thus there is less simulated N stress. In addition, when the applied fertilizer N is not incorporated into the soil, the fertilizer does not achieve contact with the roots until rainfall movement of N. The assimilation of N is proposed to depend considerably on the water absorption by the roots, in which the N is loaded via mass flow in the transpiration process (Taiz and Zeiger, 2013), which also decreases in this period due to water stress. The model, however, does not use mass flow for N uptake, but does reduce N uptake per unit root length as a function of decreasing soil water content. In addition, without precipitation or irrigation, some of the N can be lost to the atmosphere by the volatilization process (Naz and Sulaiman, 2016; Siman et al., 2020; Tasca et al., 2011). This indicates that the model adequately estimates by mimicking the no N response when nitrogen fertilization occurs during drought periods.

3.4.3. Return of excreted nitrogen by animals to pastures

The results from scenarios under both water and N effects showed that it is important to include N return by animal feces and urine in simulations to achieve values close to reality. According to Souza et al. (2018) and Barcellos et al. (2008), 75 to 95% of the N ingested by the animal returns to the soil surface as excreta, and of that amount, 50 to 80% is supplied as urine, but with irregular distribution and potential large losses due to volatilization and leaching. The authors reported that the distribution of excreta and the N amount in excreta increases with grazing intensity and with forage quality, that is, these variables are dependent on the nitrogen concentration (composition) of the pasture and the animal diet. In addition, the N amount that returns to the soil via animal excreta varies according to climatic conditions and the seasons, as noted by Teixeira et al. (2012) who found significant interactions between stocking rate and evaluation periods for both fecal K and N concentration. They reported that one grazing cycle (about a month) after a decrease in accumulated rainfall, fecal K and N concentrations decreased at all tested stocking rates (1.9, 3.2 and 4.2 AU ha^{-1}).

The simulations of the current study, with a fixed N return rate of 75%, resulted on average annual N return values of 127 kg ha^{-1} for the scenario N400+ret and 46 kg ha^{-1} for the scenario N50+ret in Aragarças, where the average of annual rainfall was 1578 mm. These values are of the same order as those found in the study of N cycling in tropical grasses developed by Saraiva (2010), in Itambé-PE, Brazil, where the annual rainfall during the trial period was 1480 mm. The author used *Pennisetum purpureum Schum*. fertilized with N dose of 300 kg ha^{-1} y^{-1} with intermittent grazing of crossbred Dutch/Zebu and the results of his study indicate that the total N return through feces was equivalent to 98 kg ha^{-1} y^{-1} (53%) and 87 kg ha^{-1} y^{-1} via urine (47%), totaling 185 kg ha^{-1} y^{-1}, without discounting leaching and volatilization losses.

The solution used to overcome this problem (of no animal N return in the model) was to prescribe the amount of return by the animal by doing a first run with scenarios only fertilized with inorganic N and then entering the N returned in organic form into a second run. The estimated animal N return is based on the herbage N produced (consumed) minus animal off-take. However, the ideal would be coding to link a dynamic animal consumption model with the crop model to account for this, so that it incorporates recycling in a dynamic way. In this study, the Yw scenario can hypothetically be replaced by the N400+ret scenario, as they should have similar results and because N400+ret is highly fertilized (assuming it removes the N limitation) and sensitive to the effect of N, which allows tests with other levels of fertilization from this scenario.

3.4.4. Plant failure to survive during extended drought

The simulations of the death of Marandu palisadegrass in Diamantino in the first years after spin-up period, even with modified soil data or soil profile change, indicate limitation of the model

under extreme drought weather conditions that occur for four months and a half or more, as observed in the Diamantino climate series. Diamantino is located in an ecotone between Amazon and Cerrado biomes in Mato Grosso state, Brazil, characterized by a tropical savanna climate with dry-winter characteristics (Aw) according to Köppen classification, although the great levels of total annual rainfall. It is commom in this region the predominance of megathermic climates, with annual total abundant rainfall ranging from 1200 to 2000 mm, however, 70% of the total rainfall is concentrated between November and March (summer), while water deficiencies extend from 4 to 6 months due to the extremely dry winter (Souza et al. (2013), in accordance with our weather data for Diamantino. During dry winter period, the carrying capacity of pastures decrease and normally, the animals are supplemented with sources other than forage to avoid a decrease in the average daily liveweight gain of cattle (Barioni et al., 2011; Bicalho et al., 2014). However, due to Marandu palisadegrass to be a perennial plant with good regrowth capacity and tolerance to drought, (Nunes et al., 1984), the plant survival during “winter-dry” months (April–September) should be more than that was simulated by CROPGRO-PFM (Figure 14). Marandu palisadegrass is not supposed to die as long as it is well managed and not affected by the sudden pasture death syndrome (Moura et al., 2017), and it should start regrowth at the beginning of the rainy season (spring).

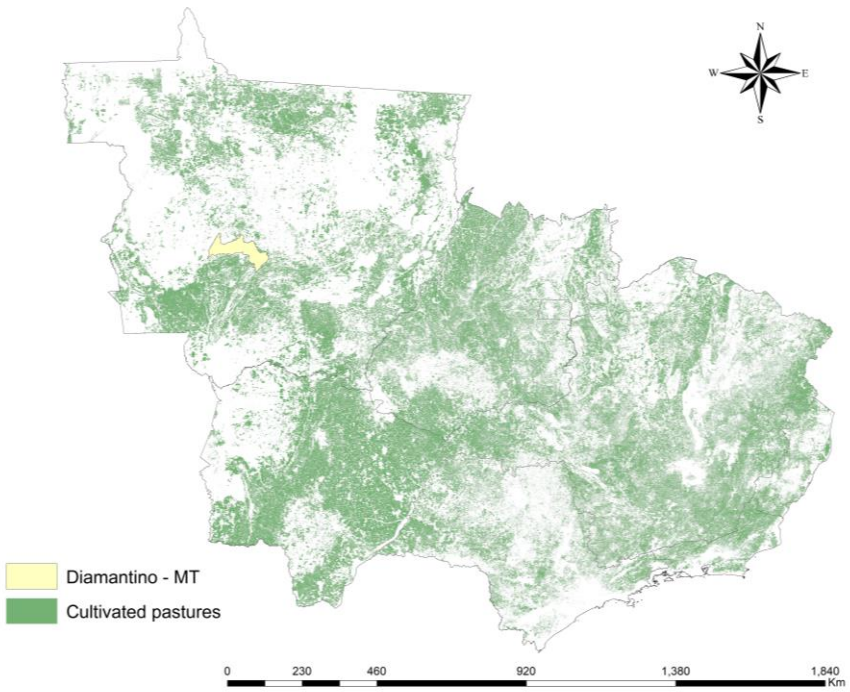

Figure 14. Diamantino location and total cultivate pasture area of Central-west and Southeast regions of Brazil

To continue plant survival and production for our 36-year simulations, we tried to restart the simulation after plant death with a new set of initial conditions (which is not recommended due to the different soil initial condition when simulation ends) but the simulated plant did not survive, even after changing the start date and changing soil profile or soil attributes. Only by replacing 5 non-consecutive climatic years in weather data, did we obtain at least 30 years of herbage harvest and Marandu palisadegrass survival for the Diamantino location until July 2012 (Figure 15).

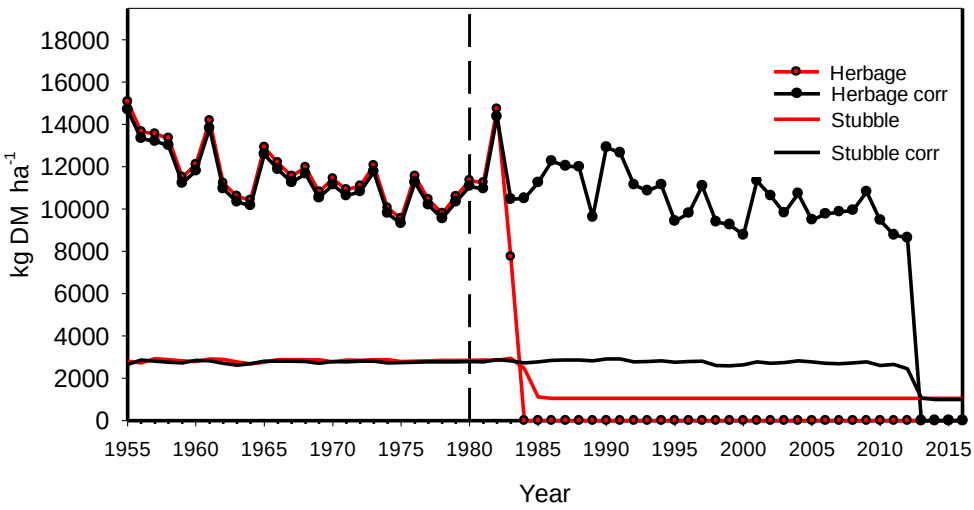

Figure 15. Annual herbage production (red line with red points) and average stubble mass (red line) simulated by CROPGRO-PFM for N50+ret scenario in Diamantino-MT, before correcting (replacing) weather data and annual herbage (black line with black points) and stubble mass (black line) production simulated after replacing weather data, during spin-up period (1955 to 1979) and from 1980 to 2016.

To enhance forage plant survival during these extended droughts, we recommend improvements in CROPGRO-PFM dormancy code and rules for mobilization from the storage organs. More specifically, the mobilization from reserves as well as maintenance respiration should be reduced under severe water deficit and low temperature conditions during which the plant is relatively dormant. Root senescence under this type of drought-induced dormancy should also be less severe. In actual practice, plant survival after long periods of drought may come from preserved meristems and seed bank in the soil, which allows for slow recovery and new regrowth after those periods of strong water deficit. The preserved meristem idea could be partially captured by the suggestions above.

3.4.5. Soil organic matter simulations

The CENTURY model is used in DSSAT crop models as a module for simulating soil organic matter and dynamics of a residue layer on top of the soil (Parton et al., 1988), which can handle the long-term SOC dynamics of agricultural systems including decomposition of plant litter deposited during the season and root/rhizome/stolon mass that senesces in the soil during the long multi-year growth of perennial crops. The CENTURY-based module discriminates SOC in three categories: easily decomposable (SOC1); recalcitrant (SOC2), which contains lignin and cell walls; and an almost inert (SOC3). For the scenarios with the animal return of organic N, the SOC values decreased over the years (1980-2016), with significant changes in stable fractions (-10%). This is different from the Urquiaga et al. (2010) study, in which authors observed that after a period of 20 to 30 years, changes in C stocks and mineralization rates tend to reach equilibrium after modification of native vegetation by the agricultural system or one agricultural system with another. In addition to agricultural systems of no-tillage, in which there is less soil disturbance, these systems with well-managed pastures in the Cerrado and in the Atlantic Forest region, have a greater potential for assimilation of CO_2 and increased C stocks in the soil in the form of organic matter.

For this study, the spin-up effectively replaces the initial condition assumptions for inorganic N. The spin-up process was useful in the current study for long-term simulations that aim to represent soils of livestock systems in equilibrium, however, it is recommended to have long-term information about SOC for those sites.

Another observation is that there is a need for improvements in the dynamics of dead plant material simulated by CROPGRO-PFM, in which the senescent shoot biomass falls from the plant to become surface litter for later incorporation into the soil and senescent root biomass goes to the soil (Kenneth Boote, DSSAT, Personal communication). However, in tropical grass pastures, the senescent dead leaves may remain attached to tillers for many days, depending on removal by wind, rainfall, and animal trampling. This dead pool of tissue needs to be simulated as remaining on the plant so as to provide dead tissue available for animal consumption, which is especially critical for animal intake during the dry winter season when the plant may stop growing but continue to be a valuable fodder resource for animals. New coding is needed to add that capability.

3.5. Conclusion

Long-term simulation of Marandu palisadegrass production for grazing situations using the CROPGRO-PFM was successful, but required adaptations to grow during severe drought periods and for return of animal excreta to the plant. Both potential and rainfed systems, as well as for more extensive systems, were then successfully simulated for a broad edaphoclimatic conditions including

the Brazilian Amazon, Cerrado and Atlantic Forest Biomes. However, CROPGRO-PFM was not able to simulate pasture growth under extreme drought conditions for the full 36 years for one region (of 9 evaluated) where pastureland is known to be grown for decades without the need for replanting. Improvements in dormancy code to reduce mobilization (for regrowth) from storage during severe drought and cool conditions are needed to better represent plant survival under severe weather conditions. Possibly maintenance respiration should be less and root senescence should also be less under severe drought and such semi-dormancy conditions. Our results show the importance of including organic N as animal excreta return for simulating plant growth and herbage production in pasture-based animal production systems, and this is not presently endogenously considered in the CROPGRO-PFM model. Without that, the model shows a continuous trend for pasture degradation, i.e. loss of available N and reduction in growth rates, and does not reach a equilibrium as expected.

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Annexes

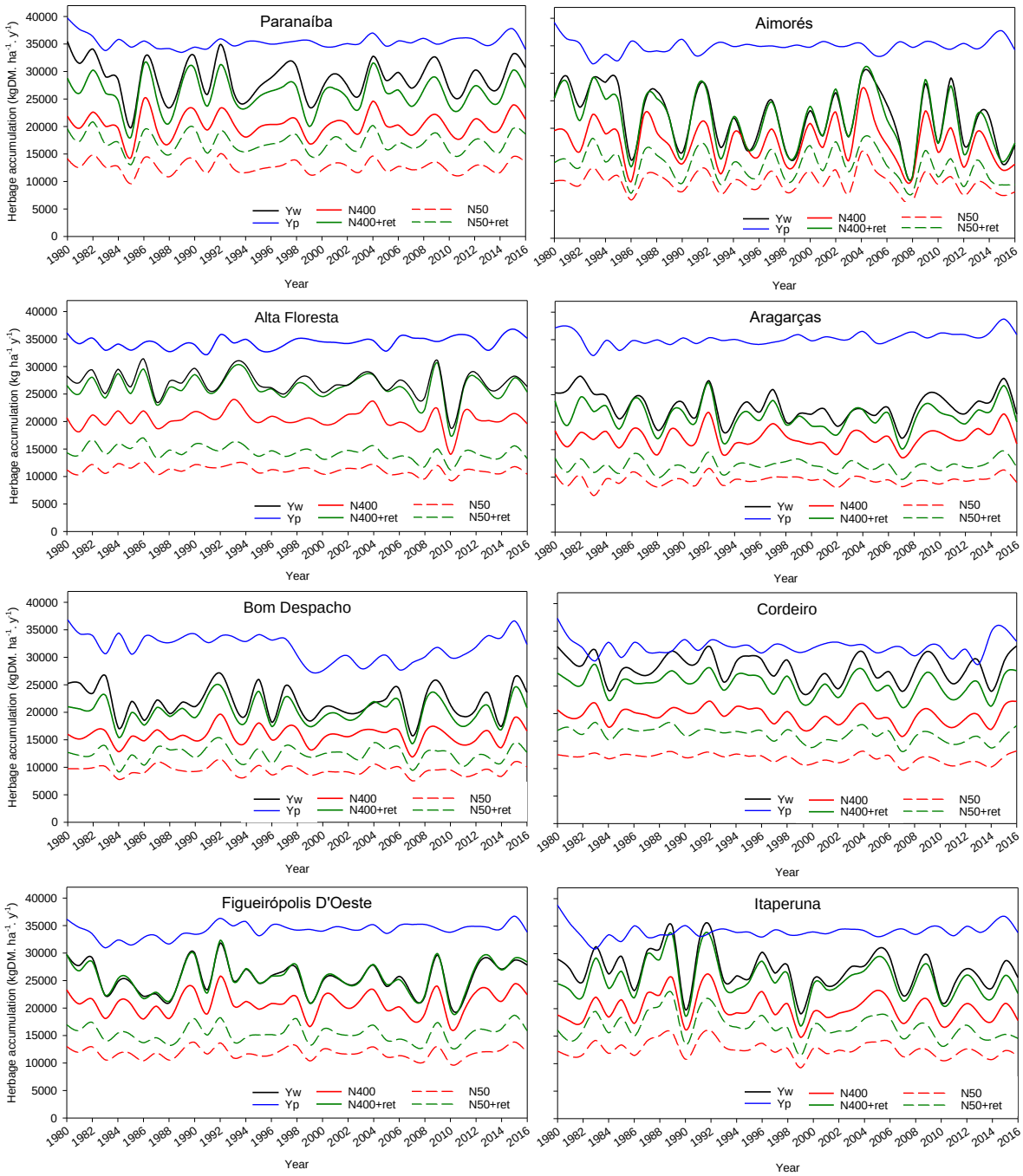

Figure 16. Annual accumulated herbage between 1980 and 2016 estimated by CROPGRO-PFM to all scenarios in each location.

4. YIELD-GAP ANALYSIS OF PASTURE-BASED BEEF CATTLE LIVESTOCK SYSTEMS IN CENTRAL BRAZIL REGION: A NEW APPROACH

ABSTRACT

Yield-gap analysis from Global Yield Gap Atlas (GYGA) protocols allows the characterization of national levels of crops production by a zoning method. With this study, we aimed to adapt GYGA protocols for pasture-based beef cattle livestock systems by using long-term forage production simulations coupled with stocking rate models. This approach considered seasonal and interannual variation of forage production, in addition to inclusion of animal factor in simulations to predict beef cattle production indicator (AU ha^{-1}) levels and to determine their yield-gaps under different scenarios of management in Central Brazil. Pastures carrying capacity increased with levels of intensification on pasture management (dose of fertilization and irrigation), mainly in the zones represented by Alta Floresta, Diamantino and Figueirópolis D'Oeste. However, the critical stocking rates did not respond positively to the increase in fertilization level in the rainfed scenarios N400+ret and N50+ret due to the seasonality of forage production. Moreover, locations with milder minimum temperature records during the winter months, such as Bom Despacho and Cordeiro demonstrated greater limitations in forage production and critical stocking rate, even in potential conditions. The largest simulated yield-gap for upper limit stocking rate is, on average, 5.81 AU ha^{-1} (Figueirópolis D'Oeste) and the smallest one is 5.40 AU ha^{-1} (Bom Despacho, Alta Floresta and Itaperuna). While the largest yield-gap for critical stocking rate is, on average, 5.44 AU ha^{-1} (Figueirópolis D'Oeste) and the smallest is 2.91 AU ha^{-1} (Bom Despacho). The greatest exploitable gaps are, on average, 4.38 AU ha^{-1} for N400+ret and 2.44 AU ha^{-1} for N50+ret (Figueirópolis D'Oeste and Diamantino). The smallest exploitable gaps are 3.04 AU ha^{-1} for N400+ret (Aimorés and Bom Despacho) and 1.60 AU ha^{-1} for N50+ret (Aimorés, Alta Floresta and Bom Despacho). This research indicated there are gaps in both plant production and pasture carrying capacity due to interactions between climate, soil, plant and animal. The protocol developed to determine productive potential and perform yield-gap analyzes of pasture-based beef cattle livestock systems, provides greater reliability than previous studies.

Keywords: Animal stocking rate, Forage production, Global Yield Gap Atlas.

4.1. Introduction

Concern about food security and sustainability has increased at the same pace as population increases. Food security analysis can help on: 1. the national forecasting of food production capacity and of potential for food self-sufficiency and variability of food production capacity due to variations in the weather; 2. the determination of land use potential and assessment of the amount of additional land compensation or food imports to meet future food demand; 3. the interpretation of historical

yield trends and projections of future yield trends at regional, national and global scales (Mbow et al. 2019).

Brazil is an important global player in grain and animal protein production, using only 7.6 to 7.8% of its total territory for agricultural production, (De Miranda, 2018; Zhong et al. 2017). Besides that, according to the monitoring of land use and coverage, the areas dedicated to the protection, preservation, and conservation of native vegetation in Brazil are equivalent to 66% of its territory (Souza et al. 2020), indicating that Brazil is and will be increasingly recognized as both an agricultural and environmental potency.

The difference between potential or attainable (water or nutrient-limited) production and actual production achieved on farms is defined as "yield-gap", which indicates the biophysical amplitude to intensify production on a given area (Lobell et al., 2009; Van Ittersum et al., 2013). Besides climate and biological factors (i.e. variety, soil fertility, management practices etc.), there are many reasons for Yield-gaps existence, such as farms location, farmer objectives, conditions for transfer of technology, socio-economic and policy factors (De Koeijer et al., 1999; RAP, 1999; Van Dijk et al., 2017; Van Der Linden et al. 2018).

The analysis of the Global Yield Gap Atlas (GYGA) project allows the characterization of national levels of crops production by a zoning method which seeks to balance the need to minimize the number of location-specific sites requiring weather, soils, and crop management data with the goal of minimizing climatic heterogeneity within the climate zones (Van Wart et al. 2013). However, the yield-gap analysis for pasture-based animal production systems faces several challenges regarding the application and execution of the methodologies already established for agricultural crops.

Brazil has the largest commercial cattle herd in the world, with 213.7 million bovine heads registered in 2019 (ABIEC, 2020). The Brazilian livestock production is mainly based on tropical-grass pastures that are used as summer season forage in subtropical areas and as perennial forage in tropical regions (Tsuruta et al. 2015). Animal stocking rate (AU ha^{-1}) and number of cattle heads slaughtered per year are usually used to evaluate livestock productivity levels. Animal production depends on primary productivity by forage plants growth and production, harvesting efficiency (herbage consumed as a proportion of herbage accumulated) and feed efficiency (conversion of consumed herbage into animal products as beef or milk) (Pearson and Ison, 1987), factors that should be considered in pasture-based animal production modeling studies. However, most of studies on productive potential and yield-gaps in livestock estimate pastures carrying capacity by the relation of annual dry matter production and the annual animal intake (Strassburg et al. 2014; Arantes et al., 2018; Araújo, 2018), not considering the relationship between supply and demand and seasonal food production throughout the year, which is primarily regulated by climatic factors. This way, the same

annual pasture productivity may be associated with quite different potential stocking rates and attainable systems productivity.

The Brazilian Central West and Southeast regions known as Central Brazil totalize 29.9% (253.7 million ha) of the Brazilian territory and it is covered by Amazon Forest, Cerrado, Pantanal and Atlantic Forest Biomes (IBGE, 2019). This region presents great livestock support and potential expansion for that activity, including 51.9% of total number of bovine heads in the country (ABIEC, 2020). Unlike South and Northeast (comprising Pampa and Caatinga Biomes), where native pastures are commonly grown and used for livestock, Central Brazil region is widely covered by exotic forage species, such as Marandu palisadegrass {*Urochloa brizantha* (Hochst. ex A. Rich.) R.D. Webster [syn. *Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf]}.

Livestock activity in this area may expand based on the restoration of degraded pasture areas and intensification of animal production systems, uncoupling livestock production and deforestation, and contributing to meet the Paris Agreement, which includes the restoration of 15 million hectares of degraded pasture area in Brazil by 2030 (IMAFLORA, 2018).

Therefore, we aimed to adapt GYGA protocols for pasture-based beef cattle livestock systems. We used long-term herbage production simulations and stocking rate models to predict beef cattle production levels under different scenarios of management in Central Brazil and determined their yield-gaps.

4.2. Material and methods

The region of this study comprehended the Central West and Southeast of Brazil, which are mainly covered by Amazon, Cerrado and Atlantic forest Biomes, with large area of cultivate pastures and beef cattle herd (Figure 1).

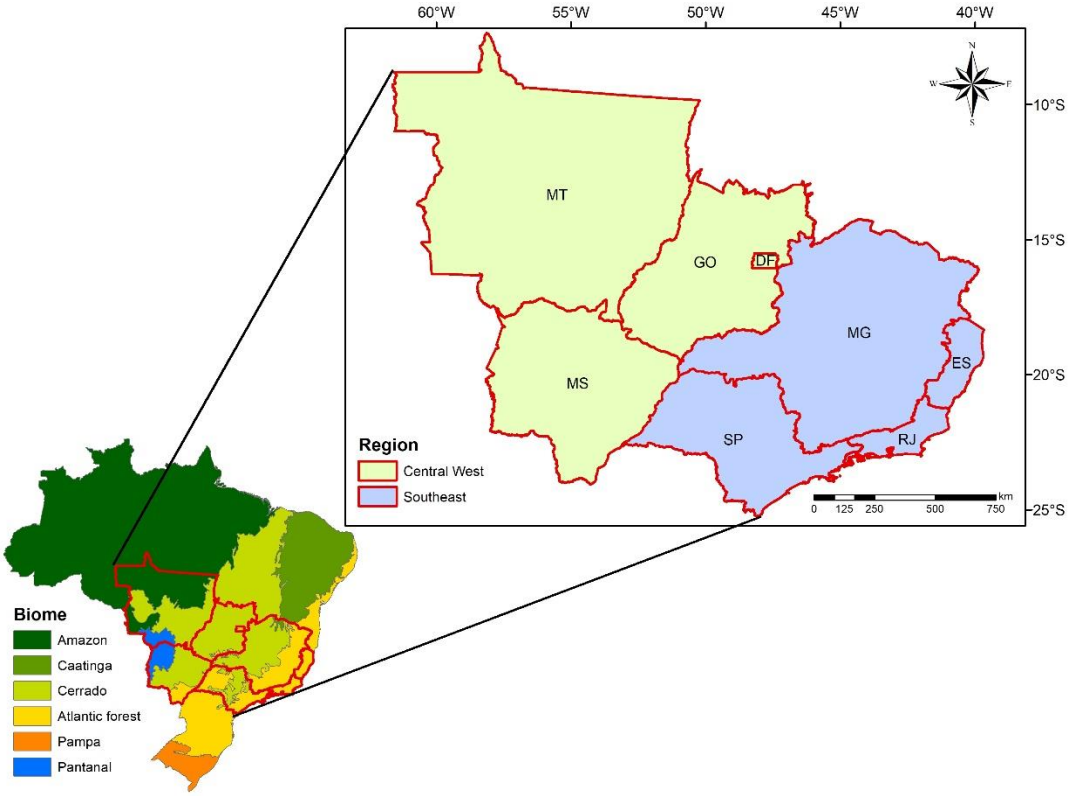

Figure 1. Overview of the Brazil map, Brazilian Biomes and the location of the region of this study (Central Brazil).

4.2.1. Homogeneous climate zones definition

The zoning method and protocol for upscaling described by the Global Yield Gap Atlas – GYGA (www.yieldgap.org) was adapted to identify the most homogeneous climatic zones (HCZ) and reckons the minimum number of points of simulation per zone (Van Wart et al., 2013) in our study.

Following the GYGA climatic zonation method, we reproduced the HCZ map to the Southeast and Central West regions of Brazil in ArcGIS 10.1/ArcMap®software based on a matrix of three climatic variables relevant for crop production: (i) growing degree days (base temperature of 0◦C, divided into 10 classes), (ii) aridity index (ratio of mean annual precipitation to annual potential evapotranspiration, divided into 10 classes) and (iii) temperature seasonality (standard deviation of monthly average temperatures, divided into 3 classes). In this matrix, combinations of climate and soil conditions were expected to be similar (see for more details (Van Wart et al., 2013).

The most representative HCZs for the cultivated pasture area were selected by overlapping the HCZs map and the map of cultivated pastures area in Southeast and Central West regions of Brazil.

Nine HCZs were selected covering 68,001,971.36 ha, equivalent to 81% of the total pasture area in this region (Figure 2.A).

We used the LAPIG (Laboratory of Image Processing and GIS of Universidade Federal de Goiás) pasture map, which considers a total of 175,396,874 ha of mapped areas in Brazil, either through visual interpretation of Landsat-8 images or public maps. According to LAPIG map, 84,353,229 ha of cultivated pastures are located in Central West and Southeast regions, constituting 48.3% of total cultivated pastures area in Brazil (Figure 2.B).

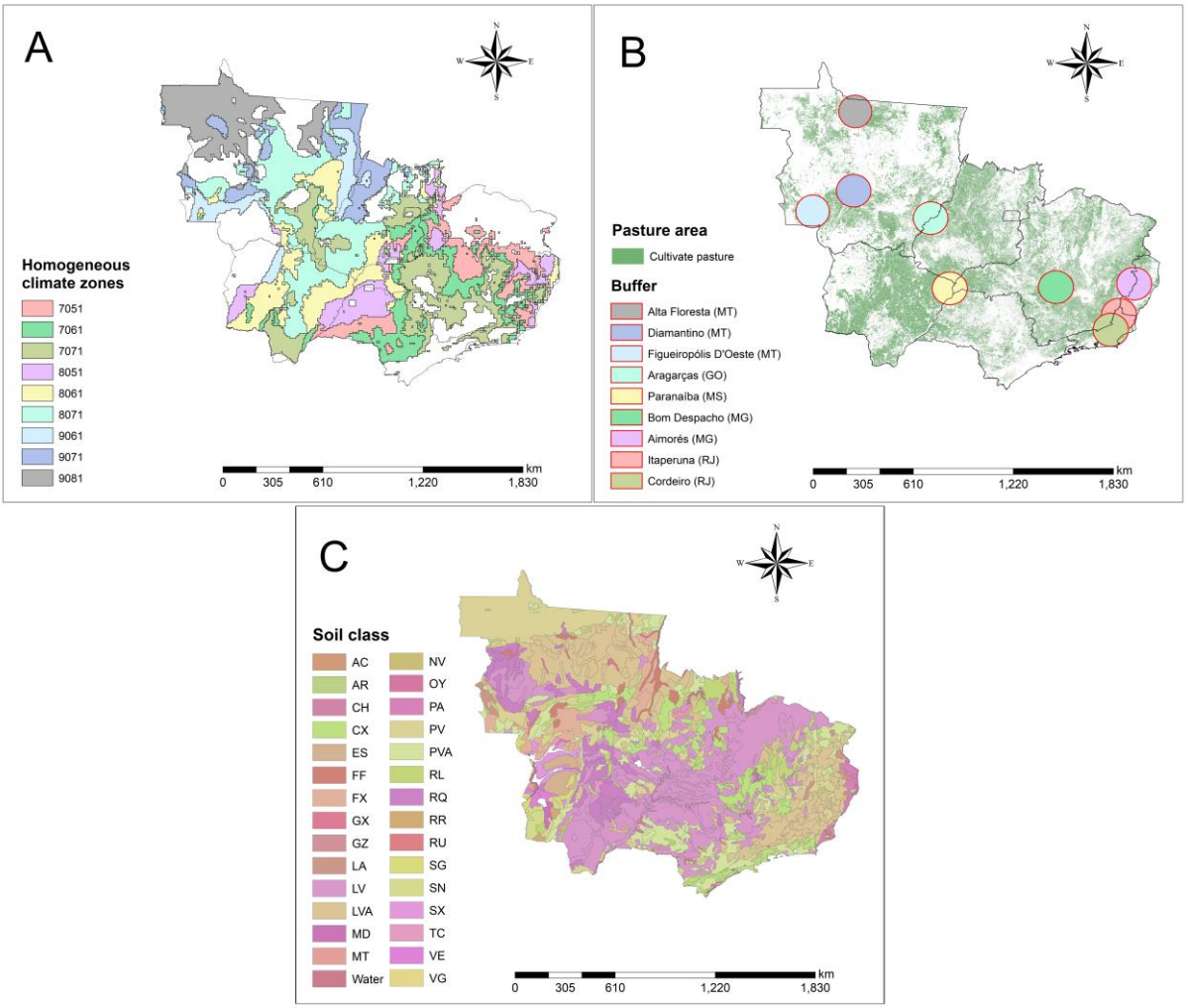

Figure 2. Distribution of the homogeneous climate zones (A) which cover 81% of the total cultivated pasture area of Central-west and Southeast regions; Cultivate pasture area and buffers of reference weather stations in the same color as their respective zones (B); and soil classes (C).

4.2.2. Weather station's location and soil classes definition

To determine the reference weather stations, we intersected the chosen HCZs map with the weather stations points from INMET (Instituto Nacional de Meteorologia) database (https://mapas.inmet.gov.br/). The weather stations located in the nine HCZs were separated into a new shapefile, and, using the buffer tool in ArcGIS 10.1/ArcMap®, we created a buffer with a radius of 100 km around each point. Thereby, the buffers covering the largest pasture area were selected as the reference weather stations location (Table 1). Moreover, due to the lack of weather stations information in the INMET map, two other reference weather stations were chosen for HCZ 9061 and 9081, nearby of counties with large area of cultivated pasture and cattle herd, following IGBE census information (IBGE, 2009).

Similar criteria were used for soil classes definition. We intersected the reference weather stations buffers with the map of soils from Brazil (Santos et al., 2018) (Figure 2.C). Thus, the soil classes in the greatest proportion within each buffer were selected (Table 1).

Table 1. The most representative soil classes in each reference weather station buffer for Aimorés - MG, Alta Floresta - MT, Aragarças - GO, Bom Despacho - MG, Cordeiro - RJ, Diamantino - MT, Figueirópolis D'Oeste - MT, Itaperuna - MT and Paranaíba – MS and their respective Homogeneous Climate Zone (HZC)

HCZ code	Location	State	Lat. (°)	Long. (°)	Soil class*	Soil class**
7051	Itaperuna	RJ	-21.21	-41.89	Latossolo Vermelho Amarelo	Oxisol
7061	Bom Despacho	MG	-19.74	-45.25	Cambissolo háplico	Inceptisols
7071	Cordeiro	RJ	-22.02	-42.37	Latossolo Vermelho Amarelo	Oxisol
8051	Aimorés	MG	-19.49	-41.07	Latossolo Vermelho Amarelo	Oxisol
8061	Paranaíba	MS	-19.67	-51.20	Latossolo Vermelho	Oxisol
8071	Aragarças	GO	-15.90	-52.23	Neossolo Quartzarênico	Entisols (Quartzipsamments)
9061	Figueirópolis D'Oeste	MT	-15.43	-58.73	Argissolo Vermelho	Ultisols
9071	Diamantino	MT	-14.40	-56.43	Latossolo Vermelho	Oxisol
9081	Alta Floresta	MT	-9.90	-55.90	Argissolo Vermelho Amarelo	Ultisols

*SiBCS: Sistema Brasileiro de Classificação de Solos. **Soil Taxonomy.

4.2.3. Climate and soil database for simulations

Our climate data set included the period of 1 January 1980 to 31 December 2016. Daily gridded variables such as maximum and minimum temperature, solar radiation and rainfall were provided by Xavier et al. (2016). The climate base was not updated for rainfall between 2015 and 2016, and for this period we used the rainfall data from the Tropical Rainfall Measuring Mission (TRMM,

Huffman et al. 2007). Figure 3 shows the climate variables for the nine sites selected. In general, the Brazil Central West and Southeast regions have two seasons, with the rainy season centered in the summer and a dry season centered in the winter (Figure 3). However, the precipitation amount varies significantly among regions (Figure 3).

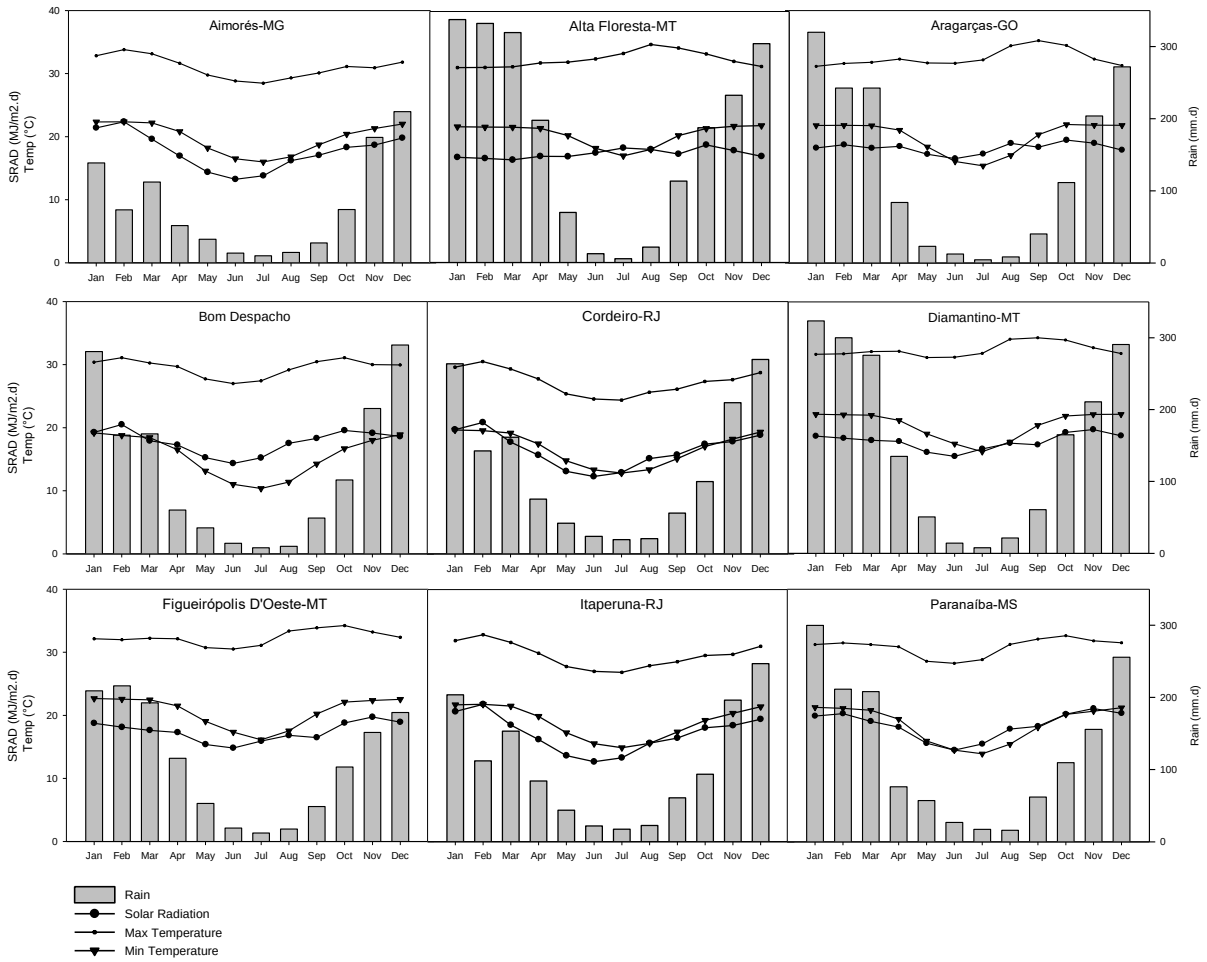

Figure 3. Monthly average of solar radiation (SRAD - MJ m² day^{-1}), maximum and minimum temperature (Temp - °C) and monthly accumulated rainfall (Rain - mm) in Aimorés - MG, Alta Floresta - MT, Aragarças - GO, Bom Despacho - MG, Cordeiro - RJ, Diamantino - MT, Figueirópolis D'Oeste - MT, Itaperuna - MT and Paranaíba - MS, between 1980 and 2016.

Soil profiles were recovered from EMBRAPA soil database (BDSolos) (https://www.bdsolos.cnptia.embrapa.br/consulta_publica.html), which groups the soil profiles by Biome, first level soil class and texture (Santos et al., 2018). The texture of each soil class observed in the simulation points was determined considering the soil genesis through the geological map of Brazil (CPRM, 2001; Miguel Cooper, University of Sao Paulo, Personal communication) (Table 1).

The average soil profile of each simulation point was built using the DSSAT's Sbuild pedotransfer functions, applied to the soil profiles, considering the soil texture and the depths of the soil horizon to estimate the saturated upper limit (SSAT), drained upper limit (SDUL) and lower limit of plant extractable soil water (SLLL). Thereafter, SLLL, SDUL and SSAT resulted in values of water holding capacity close to Brazilian tropical soils condition (Teixeira et al., 2021).

The saturated hydraulic conductivity (SSKS) was estimated using the functions proposed by Tomasella and Hodnett (1997). Volumetric density and percentage of organic C in the soil were also recovered from the BDSolos' soil database. All soil profiles were described through 10 layers, each keeping a constant proportion to the informed soil depth. All values were interpolated vertically to set each layer's attributes.

After the average profiles for the simulation points were determined, the data for each profile was compared to information from literature about attributes of soil classes in areas used as pastures (Donagemma et al., 2016; Ferreira et al., 2015; Grego et al., 2012; Isernhagen et al., 2017; Lisbôa et al., 2016; Lourente et al., 2007; Macedo, 2005; Muller et al., 2001; Passos et al., 2015; Pequeno et al., 2014, 2018; Salimon et al., 2007; Santos, 2016; Spera et al., 2004; Viana et al., 2015).

4.2.4. Forage model

To carry out long-term forage production simulations we used the CROPGRO Perennial Forage Model (CROPGRO-PFM) available in the DSSAT platform v. 4.7.5.011. DSSAT is a software application program that includes process-based models, combining crop, soil, and weather data bases with crop models, such as CROPGRO-PFM, integrating the effects of soil, crop genetics, weather, and management options (Hoogenboom et al., 2019).

4.2.5. Stocking rate model

In grazing systems, seasonal and interannual variation may impair maximum utilization of forage produced because animals' feed requirement needs to be met year-round and most of the forage surplus will senesce and decay before transferred from one season to another. Climate-related variation of pasture productivity was considered to determine attainable stocking rates by applying a novel method developed by Barioni et al. (2021, submitted). The method is based on cumulative forage deficit (CFD), computed through Equation 1.

Equation 1. Forage accumulated deficit calculation

$$CFD_{t+\Delta t} = \max(CFD_t + (D_t - P_t) * \Delta t, 0),$$

where CFD_t is the cumulative forage deficit at a given instant of time (kg ha^{-1}); P_t is the average daily accumulation rate at time t (kg ha^{-1} day^{-1}); D_t is the average daily forage demand by animals at time t (intake plus losses, kg ha^{-1} day^{-1}), and; Δt is the time step (days). Note that Barioni's method applies principles of traditional feed budgeting (REF) but only accumulates unattended feed demand from pasture, by truncating CFD to zero when forage surplus is available.

The method does not require an estimate of initial standing herbage mass but requires the definition of a CFD threshold (CFDT) which corresponds to the limit of transference of pasture standing biomass for later intake. So, a CFD time series is determined from an herbage accumulation model leading to the definition of two types of events:

1. a forage deficit event (FDE) which defines any period where the sum of forage demand exceeds herbage accumulation rates, and;

2. a critical forage deficit event (FDEc), which defines any period where CFD exceeds CFDT (Figure 5). For the current study, CFDT was set as 2500 kg DM ha^{-1}, equivalent value between 50 and 80% of total plant biomass when its canopy reaches the ceiling LAI (Pedreira et al., 2009).

The frequency of FDEc depends on the overall average productivity as well as its seasonal and interannual variation as well as the magnitude and variation of feed demand. Feed demand was set to constant along the year for this study (Figure 4). Higher stocking rates are associated with greater feed demand (Figure 5) and, therefore, increases the probability of FDEc, computed as events per year, for a given herbage accumulation rate time series.

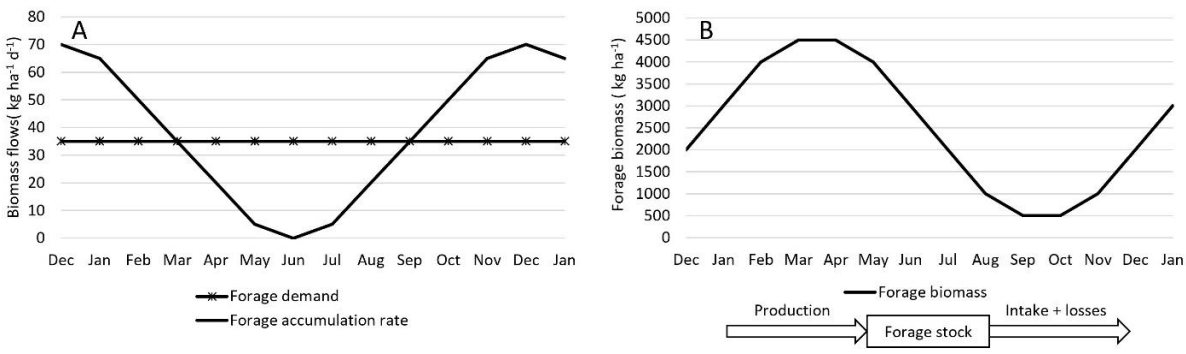

Figure 4. Forage accumulation and demand rates (kg ha^{-1} d^{-1}) throughout the year for a hypothetical condition (A); Forage biomass (kg ha^{-1}) trajectory throughout the year (B) for the hypothetical conditions presented in (A).

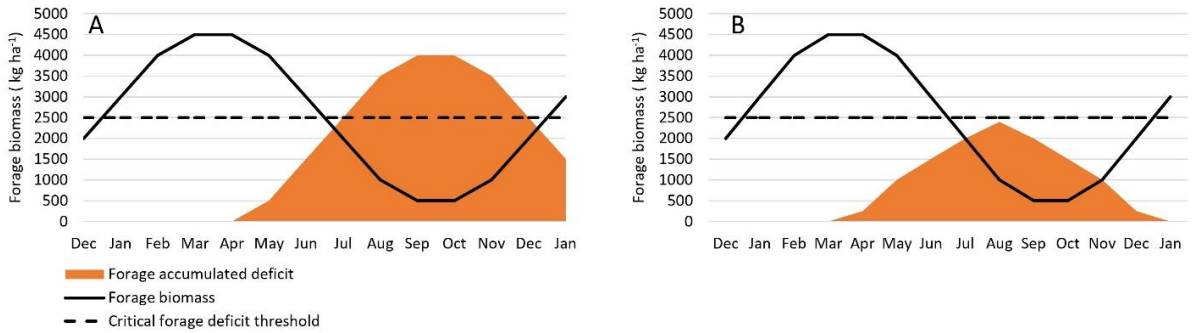

Figure 5. Cumulative forage deficit (CFD) and forage biomass for two stocking rates. In (a) the stocking rate generates a critical forage deficit event by exceeding the cumulative forage deficit threshold (CFDT) of 2500 kg. ha^{-1}, while in (b) the deficit is not critical as it does not exceed maximum transferable biomass.

4.2.5.1. Upper limit Stocking Rate

Upper limit stocking rate (SR_{upper}) indicates the pasture production potential and the carrying capacity of systems with variable stocking rate, i.e. not subject to forage deficit events. Thus, SR_{upper} is defined herein as the average stocking rate attainable when all forage available produced is harvested at potential grazing efficiency (PGE), as in a put and take pasture management system.

The annual herbage accumulation rate (HAR) required per AU ($HARR_{AU}$) was computed using Equation 2. We considered daily forage dry matter intake of 8.8 kg of dry matter per Animal Unit per day (kg AU^{-1} day^{-1}) (Allen et al., 2011) and PGE = 60%. We used average of 365.25 days per year.

Equation 2

$$HARR_{AU} = \frac{ADMI_{AU} * 365.25}{PGE} = \frac{8.8 * 365.25}{0.6} = 5357 \text{ kg AU}^{-1}\text{yr}^{-1}$$

The SR_{upper} was then determined as the average annual herbage accumulation rate (HAR) of a given site produced by CROPGRO-PFM divided by $HARR_{AU}$ $(Equation\ 3)$.

Equation 3

$$SR_{upper} = \frac{HAR}{HARR_{AU}}$$

4.2.5.2. Critical Stocking Rate

Critical stocking rate (SR_{crit}) is defined as the attainable upper limit stocking rate before exceeding a given FDEc probability, P(FDEc). In practice it represents the carrying capacity of managed pastures, limited by seasonal and interannual variations of forage production. In this work we have assumed P(FDEc) < 20% per year, which is the probability level traditionally used in for climatic risk

crop zoning. P(FDEc) depends on the time trajectory of HAR and stocking rates (SR), so we will represent this probability as $P(FDE_c|\boldsymbol{HAR}, \boldsymbol{SR}, CFDT, Prob)$,

where CFDT is the cumulative feed deficit threshold as previously defined, and; $Prob$ is the probability level (assumed 20% herein). We use bold letters for representing vectors.

SR_{crit} is estimated through an iterative method based on a sensitivity analysis of stocking rates and interpolation, as described in the algorithm in the pseudocode in Figure 6.

$\mathbf{rSR} = [1, 0.95, 0.9 \ldots 0.5]$ # defines a vector of decreasing proportions of SR_{upper}

$SR_{\text{upper}} = fSR_{\text{upper}}(\boldsymbol{HAR})$ # estimate SR_{upper} for a given HAR

$\boldsymbol{SRV} = rSR_i * SR_{\text{upper}}$ *# Vector of stocking rates to compute* $P(FDE_c)$

Loop through **rSR** until a predefined level of $P(FDE_c)$ is reached

$i = 0$

repeat

$\mathrm{i} = \mathrm{i} + 1$ *# increase the rSR index*

$SRV_i = rSR_i * SR_{\text{upper}}$ *# Determines the ith SR level to compute* $P(FDE_c)$

$P_i = P(FDE_c|\boldsymbol{HAR}, SRV_i, CFDT)$ *# determine* $P(FDE_c)$ *for the* i^{th} *level of SR*

stop searching if SRV_i produced a $P(FDE_c)$ lower than the predefined probability or

the vector was entirely searched

until ($P_i < 20\%$ or $i = length(rSRi)$)

if (i < length(rSRi))

$\mathrm{SRCrit} = interpolate\left(20\%, P_i, P_{i+1}, SR_{f,i}, SR_{f,i+1}\right)$ # linearly interpolate SR

else

$\mathrm{SRCrit} < \mathrm{rSR}_{\mathrm{lenght(i)}}$

Figure 6. Pseudocode of the algorithm to determine the critical stocking rate (SR_{crit})

The impact of stocking rates on forage consumption and deficit estimated by the method are also illustrated in Figure 7.

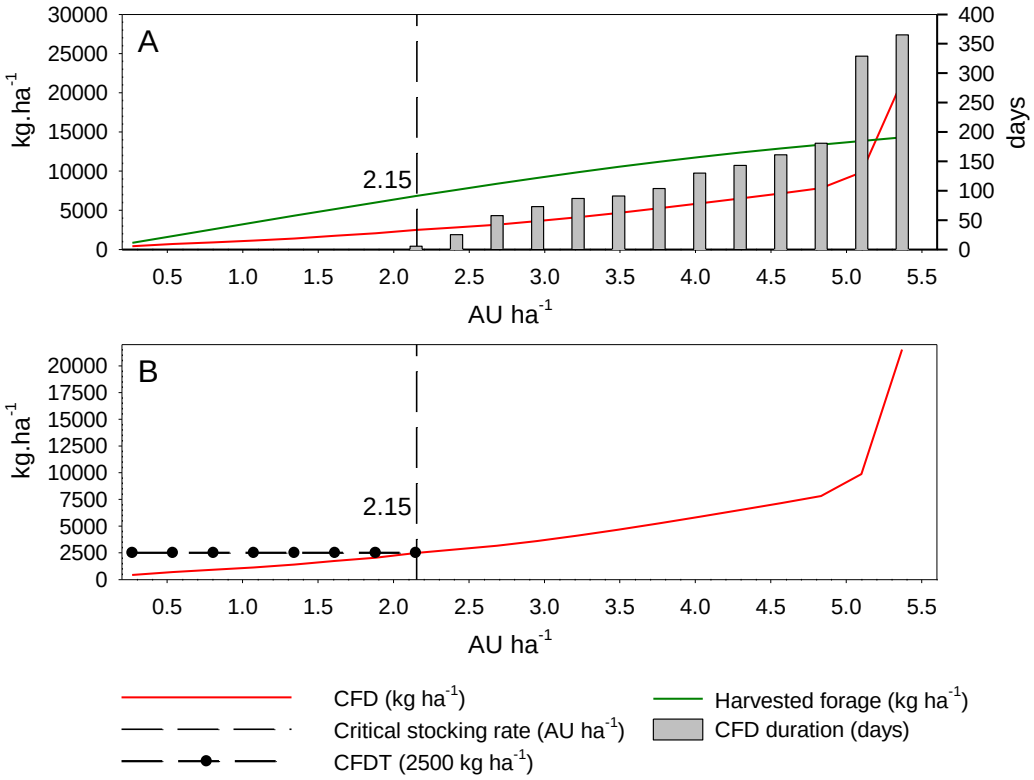

Figure 7. Sensitivity analysis for a given forage production (harvested forage) and cumulative forage deficit (CFD) (kg ha^{-1}) at 20% probability of exceeding the cumulative forage deficit threshold (CFDT). Duration of critical forage deficit (days) as a function of stocking rate (AU ha^{-1}) (A); The critical stocking rate (2.15 AU ha^{-1} in this example) is determined by the stocking rate value at which the CFD exceeds the maximum transferable biomass value of 2500 kg ha^{-1} (CFDT) (B).

4.2.6. Scenarios definition

The scenarios were built to represent the different productivity levels of beef cattle systems (Potential, water-limited potential or attainable). In DSSAT, we built the following 3 scenarios for simulating growth and forage production of Marandu palisadegrass: 1. Yp, with no water and N stress; 2. N400+ret, under water and N effect and following Primavesi et al. (2001), Oliveira et al. (2004) and Pequeno et al. (2014) recommendations, using the dose of 400 kg N.ha. y^{-1} as urea applied in the following day after each harvest; and 3. N50+ret, under water and N effect and according to Oliveira et al. (2004), fertilized with 50 kgN.ha. y^{-1} as urea applied in March and December of each year (Table 3).

In both scenarios fertilized with urea (N400+ret and N50+ret) were added 50 kg N ha^{-1} y^{-1} to represent atmospheric N deposition, in aqua ammonia form, split-applied in the beginning and end of

the rainy season (Resende, 2001), plus 75% of total extracted N in harvested herbage (Dubeux et al., 2006; Saraiva, 2010; Souza et al., 2018), to represent N return rates from animal feces and urine.

To accomplish the N return rates, we did a first simulation of rainfed scenarios to calculate 75% of N amount in plant harvested (inorganic form). This was assumed to return in organic form, and those amounts were then entered into the second run for N400+ret and N50+ret scenarios. The organic N was applied after each grazing date as liquid manure form, with assumed 5% N concentration. To do this, we converted plant mineral N equivalent to organic N by multiplying plant N extracted as feces in each cycle by a conversion factor of 20.

Table 3. Conceptual definition of simulated scenarios and influence of water and nitrogen in each of them

Scenarios	Scenario	Yield level	Water effect	N effect	Source
Yp	Potential intensive	Potential	No	No	Van Ittersum and Rabbinge, 1997
N400+ret	Rainfed intensive	Water-limited potential	Yes	Yes	Resende, 2001; Primavesi et al. 2001; Oliveira et al. 2004; Dubeux et al. 2006; Saraiva 2010; Pequeno et al. 2014; Pequeno et al.2017; Sá Souza et al. 2018
N50+ret	Extensive	Attainable	Yes	Yes	Resende, 2001; Oliveira et al. 2004; Dubeux et al. 2006; Saraiva 2010; Sá Souza et al. 2018

The planting dates were the same for all scenarios simulated using CROPGRO-PFM, and grazing frequency was established as 42 days during the winter and 28 days for the other seasons.

The percentage leaf of the stubble (RSPLF), hypothetical number of leaves left on a primary tiller axis after harvest (MVS) and stubble height after harvest (RSHT) values in the MOW file were based on Pequeno et al. (2014). The stubble mass (MOW) values were fixed to 3000 DM kg. ha^{-1} in accordance with Pequeno et al. (2014), Santos (2016), Bosi et al. (2020).

The RTSEN species parameter (Fraction of existing root length which can be senesced per physiological day) was decreased from 0.008 to 0.005 to slow down the root senescence rate, especially in locations with longer water stress periods, avoiding forage death. In addition, the soil evaporation method was changed from Suleiman-Ritchie to Ritchie-Ceres, because comparison to unpublished daily ET data showed that the Suleiman-Ritchie method causes too much soil evaporation (Kenneth Boote, DSSAT, personal communication).

The Soil Root Growth Factor (SRGF) values, which range from 0 to 1, were estimated for each layer for all soil profiles according to its depth and root distribution for tropical grasses in soils without impeding soil layers (da Cunha et al., 2010; Prudente Junior, 2019; Stumpf et al., 2016). We altered the

proportion of stable C in soil organic matter (SASC) from 0.57 (Pequeno et al., 2018, 2014) to 0.80 (Cheryl Porter, DSSAT, Personal communication), in order to represent better common SASC values in tropical soils. Due to lack of information about inorganic N in initial condition (ammonium and nitrate), we assumed the same values from Pequeno et al. (2018) experiments. Thus, to achieve a system in equilibrium for each experiment, with more stable values of N and organic carbon in soil, we did an initial twenty-five-years spin-up simulation for all experiments before 01/01/1980 by repeating the first 25 years of weather data.

4.2.7. Yield-gap analysis

Using IBGE data from 2006 census and filtered for beef cattle, the actual stocking rate (Ya) calculated for each HCZ was the relation of total number of animal units (AU) of municipalities in each HCZ by total pasture area of respective HCZ (AU ha^{-1}). Wherever a municipality was covered by more than one HCZ, the majority HCZ was the one that covered more than 30% of the municipality's area.

The gap fractions were defined considering Ya levels as 100% when compared to simulated upper limit stocking rate and critical stocking rate levels of Yp, N400+ret and N50+ret scenarios.

For each level of primary productivity of Marandu palisadegrass (potential and attainable scenarios) the upper limit and critical stocking rates were estimated. The critical stocking rate expresses the productive potential and carrying capacity of pastures managed with a fixed stocking rate, in which the animal stocking is limited or defined by the critical periods of the year. The upper limit stocking rate expresses the productive potential and the carrying capacity of systems characterized by the use of a variable stocking rate, adjusted through the purchase and sale of animals, allowing a better use of the forage produced throughout the year. The differences between the upper limit and critical stocking rates, both within each scenario and between scenarios, were due to the simulated interactions of climate, soil, plant and animal, which were taken into account in the coupling of used models (Figure 8).

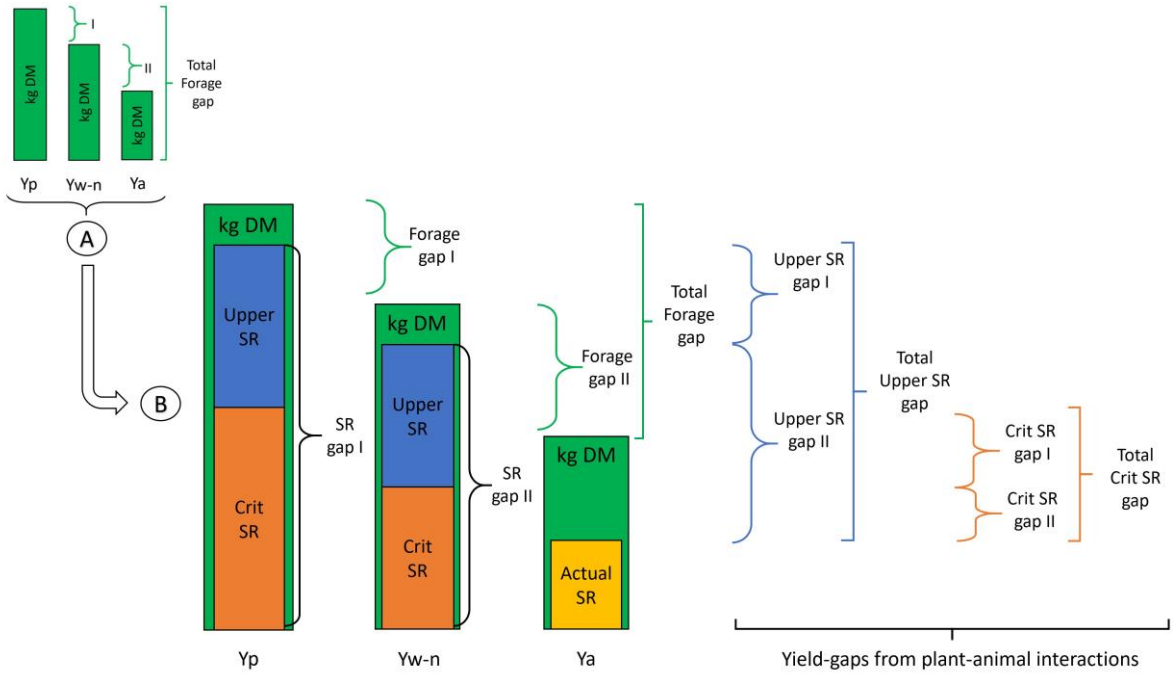

Figure 8. Pasture productivity levels - green bars - represented by the potential (Yp), attainable limited by water and / or nutrients (Yw-n) and actual (Ya) scenarios, and the gaps related to forage production (kg DM) (A); details of animal productivity levels (SR within the pasture productivity and the gaps associated with the upper limit stocking rate (Upper SR) - blue bars - the critical stocking rate (Crit SR) - orange bars - and actual or observed stocking rate (Actual SR) - yellow bar (B); detailing and differentiation of gaps between levels of productivity associated with plant production (Forage gap), upper limit (Upper SR gap) and critical (Crit SR gap) stocking rates (B).

4.2.8. Climatic risk analysis to forage production

The forage production variability and its associated climatic risk were estimated for the nine sites. For that, it was calculated the average annual herbage accumulation rate for whole period; the average herbage accumulation rate for the 3 months of the year with the lowest yields (commonly, 3 driest months of the year); the standard deviation of mean herbage accumulation rate for the 3 months with the lowest yields; the relative herbage accumulation rate, which was calculated by the relation of the lowest mean herbage accumulation rate (that for the 3 months with the lowest yields) by the average annual herbage accumulation rate.

Then, it was calculated the relative production risk at levels of 10 and 20%, that showed the proportion of years (%) in which the relative herbage accumulation rate was lower than 10 and 20% of the annual herbage accumulation rate.

4.3. Results

The simulated average of upper limit stocking rate of Yp scenario was similar in all locations, ranging between 6.08 AU ha^{-1} (Bom Despacho and Cordeiro) and 6.63 AU ha^{-1} (Aimorés, Alta Floresta, Aragarças, Diamantino, Figueirópolis D'Oeste, Itaperuna and Paranaíba) (Figure 9), and the average of critical stocking rate was 6.13 AU ha^{-1} excepting for Bom Despacho (3.84 AU ha^{-1}) and Cordeiro (5.19 AU ha^{-1}) values (Figure 10). The simulated average of upper limit stocking rate of N400+ret was similar in Alta Floresta, Cordeiro, Diamantino, Figueirópolis D'Oeste, Itaperuna and Paranaíba (4.96 AU ha^{-1}), 1.0 AU ha^{-1} more than values for Aimorés, Aragarças and Bom Despacho (3.98 AU ha^{-1}) (Figure 9). The highest critical stocking rate value of N400+ret was simulated for Cordeiro (2.03 AU ha^{-1}), followed by the average of Alta Floresta, Diamantino, Figueirópolis D'Oeste, Itaperuna and Paranaíba (1.55 AU ha^{-1}) and the lowest values were simulated for Aimorés, Aragarças and Bom Despacho (0.91 AU ha^{-1}) (Figure 10). The same pattern of N400+ret simulations was observed for N50+ret scenario, in which the average of upper limit stocking rate was similar in Alta Floresta, Cordeiro, Diamantino, Figueirópolis D'Oeste, Itaperuna and Paranaíba (3.10 AU ha^{-1}), 0.7 AU ha^{-1} higher than values of Aimorés, Aragarças and Bom Despacho (2.40 AU ha^{-1}) (Figure 9). Cordeiro also registered the highest critical stocking rate value of 1.86 AU ha^{-1}, followed by Alta Floresta, Diamantino, Figueirópolis D'Oeste, Itaperuna and Paranaíba with average of 1.40 AU ha^{-1}, and Aimorés, Aragarças and Bom Despacho with 0.91 AU ha^{-1} (Figure 10).

The simulated critical stocking rate values did not vary between the N400+ret and N50+ret scenarios for all sites. While the critical stocking rates of the Yp scenario were on average 4.41 AU ha^{-1} higher than the rates of the rainfed scenarios for all locations, except for Bom Despacho and Cordeiro, where this difference was on average 3.0 AU ha^{-1} (Figure 10).

The upper limit stocking rate of Yp scenario in Aimorés, Aragarças and Bom Despacho were on average 2.5 AU ha^{-1} higher than upper limit stocking rate of N400+ret scenario, whereas for other locations Yp generated upper limit stocking rate values 1.5 AU ha^{-1} higher than for N400+ret scenario. The upper limit stocking rate of N400+ret scenario were on average 1.77 AU ha^{-1} higher than upper limit stocking rate of N50+ret scenario for all locations. The biggest difference between N400+ret and N50+ret scenarios was simulated for Alta Floresta (2.2 AU ha^{-1}) (Figure 9).

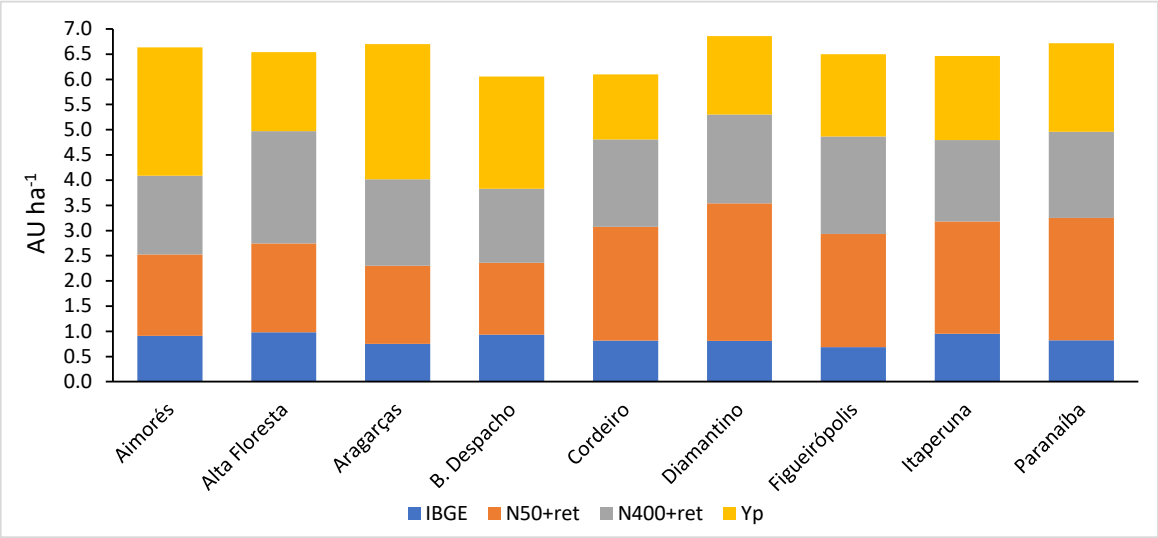

Figure 9. Simulated upper limit stocking rate levels (AU ha^{-1}) for Yp, N400+ret and N50+ret scenarios and actual stocking rate (Ya) from census (IBGE).

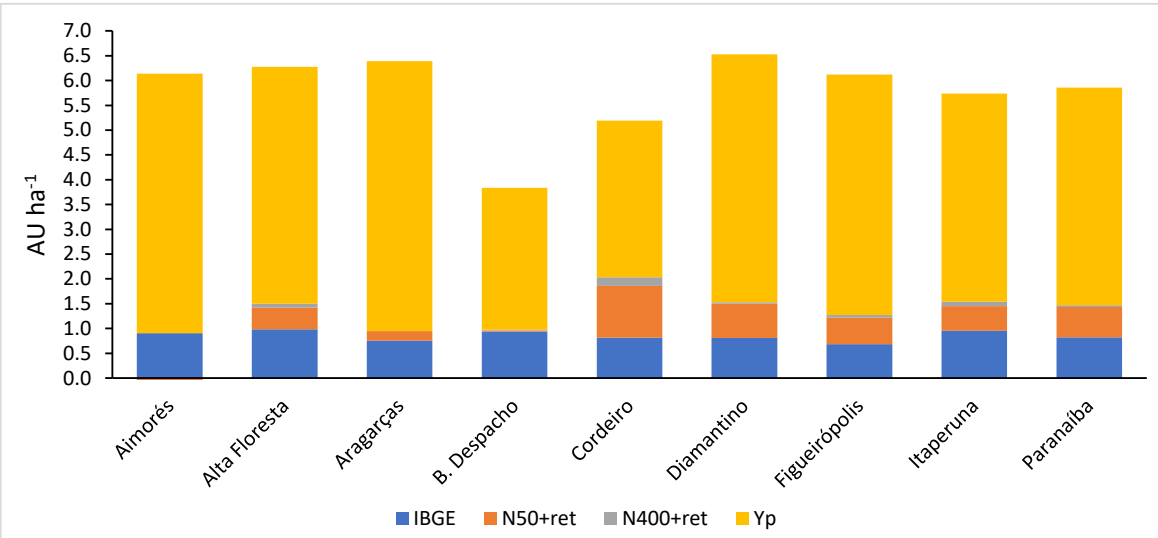

Figure 10. Simulated criticcal stocking rate levels (AU ha^{-1}) for Yp, N400+ret and N50+ret scenarios and actual stocking rate (Ya) from census (IBGE).

4.3.1. Climatic risk to forage production

Except for Bom Despacho and Cordeiro, in which the average annual herbage accumulation rate for the Yp scenario was 89.14 kg ha^{-1} d^{-1}, the other locations had an average annual herbage accumulation rate of 97.25 kg ha^{-1} d^{-1}.

The highest annual herbage accumulation rate averages of the scenarios N400+ret and N50+ret were simulated for Diamantino (77.79 and 51.98 kg ha^{-1} d^{-1}), followed by Alta Floresta, Cordeiro, Figueirópolis, Itaperuna and Paranaíba (71.57 and 44.53 kg ha^{-1} d^{-1}), and the lowest annual herbage accumulation rate averages of the scenarios N400+ret and N50+ret were observed in Aimorés, Aragarças and Bom Despacho (58.28 and 35.14 kg ha^{-1} d^{-1}, respectively).

For the scenario with no water limitation (Yp), lower SD values (3.68 kg ha^{-1} d^{-1}) were recorded, except for Bom Despacho, where the SD was 15.23 kg ha^{-1} d^{-1}. In addition, the location with the highest average herbage accumulation rate value for the Yp scenario during the 3 most critical (driest) months of the year was Alta Floresta (88.61 kg ha^{-1} d^{-1}), however, for the rainfed scenarios, the values were low and with high SD, when compared to rainfed scenarios from other locations.

Cordeiro and Diamantino had the lowest risks of reaching relative forage production below 10 and 20% of the average annual production, both for Yp and for rainfed scenarios. In rainfed conditions, both locations showed the greatest average annual herbage accumulation rate and, despite the middle SD values, Cordeiro and Diamantino were also the places with the greatest forage production during the 3 most critical months. While Aimorés, Aragarças and Bom Despacho presented the lowest values of average annual herbage accumulation rate and herbage accumulation rate of critical months, in addition to the highest production risks, with relative production values below 10 and 20% of the average annual production (Table 4).

Table 4. Average annual simulated herbage accumulation rate (Mean HAR), average herbage accumulation rate for the 3 months of the year with the lowest yields (Mean Lowest HAR), standard deviation for the average herbage accumulation rate of the 3 months (SD Lowest HAR) and relative production risk below 10 (Years below 10%) and 20% (Years below 20%) of the annual average of herbage accumulation rate

Location	Scenario	Mean HAR	Mean Lowest HAR	SD Lowest HAR	Years below 10%	Years below 20%
		---------- kg ha^{-1} d^{-1} ----------			-------- % --------	
Aimorés	Yp	97.3	69.57	3.52	0	0
	N400+ret	59.81	0.66	6.62	81	92
	N50+ret	37.07	-1.39	3.35	89	100
Alta Floresta	Yp	95.89	88.61	3.5	0	0
	N400+ret	72.9	6.00	10.65	70	78
	N50+ret	40.23	0.02	4.51	78	95
Aragarças	Yp	98.29	79.29	3.37	0	0
	N400+ret	58.88	-2.56	2.29	100	100
	N50+ret	33.73	-2.45	2.35	100	100
Bom Despacho	Yp	88.82	50.75	15.23	0	0
	N400+ret	56.15	-0.69	4.56	95	95
	N50+ret	34.61	-1.34	3.86	84	97
Cordeiro	Yp	89.45	55.88	3.85	0	0
	N400+ret	70.5	19.25	14.32	22	38
	N50+ret	45.1	9.98	7.87	19	54
Diamantino	Yp	100.64	83.09	4.03	0	0
	N400+ret	77.79	12.36	15.17	44	59
	N50+ret	51.98	6.95	9.93	50	78
Figueirópolis	Yp	95.3	76.30	3.67	0	0
	N400+ret	71.38	4.59	8.49	65	86
	N50+ret	43	0.23	3.85	81	97
Itaperuna	Yp	94.81	64.52	3.11	0	0
	N400+ret	70.34	13.73	17.1	43	68
	N50+ret	46.62	7.19	9.93	43	70
Paranaíba	Yp	98.54	66.87	4.44	0	0
	N400+ret	72.71	11.25	15.12	46	59
	N50+ret	47.7	5.45	7.98	51	68

4.3.2. Yield-gaps

The average of Ya values for each HCZ ranged between 0.94 AU ha^{-1} (Aimorés, Alta Floresta, Bom Despacho and Itaperuna) and 0.78 AU ha^{-1} (Aragarças, Cordeiro, Diamantino, Figueirópois D'Oeste, Itaperuna and Paranaíba) (Table 5).

Table 5. Reference locations, their respective homogeneous climatic zones and the actual stocking rate (Ya) from IBGE census 2006 for each homogeneous climatic zone

Reference location	Homogeneous climatic zone	Ya
		AU ha^{-1}
Aimorés	8051	0.91
Alta Floresta	9081	0.98
Aragarças	8071	0.75
Bom Despacho	7061	0.93
Cordeiro	7071	0.82
Diamantino	9071	0.81
Figueirópolis D'Oeste	9061	0.68
Itaperuna	7051	0.95
Paranaíba	8061	0.82

Simulations in which the forage was harvested by the "put and take" method, without considering forage deficit events (seasonality), the upper limit stocking rates for rainfed scenarios showed greater exploitable gaps without the use of irrigation in Figueirópolis D'Oeste and Diamantino. Considering Ya values as 100%, N400+ret and N50+ret scenarios showed possibility to increase upper limit stocking rates in 611% and 328%, respectively, in Figueirópolis D'Oeste and increasing of 555% and 337%, respectively, in Diamantino. These percentages are equivalent, on average, to 4.34 AU ha^{-1} for N400+ret and 2.49 AU ha^{-1} for N50+ret. The locations with the smallest exploitable gaps in an intensive rainfed system (N400+ret) were Aimorés with 350% (3.18 AU ha^{-1}) and Bom Despacho with 310% (2.90 AU ha^{-1}), while the smallest exploitable gaps for the extensive system (N50+ret), were also for Aimorés that registered 178% (1.62 AU ha^{-1}) and Bom Despacho with 153% (1.43 AU ha^{-1}), in addition to Alta Floresta that registered upper limit stocking rate 179% (1.76 AU ha^{-1}) higher than actual stocking from IBGE census (Figure 11). For Yp, the largest simulated yield-gap was 849% (5.81 AU ha^{-1}) for Figueirópolis D'Oeste, and the smallest ones were 549% (5.12 AU ha^{-1}) for Bom Despacho, 566% (5.56 AU ha^{-1}) for Alta Floresta and 578% (5.51 AU ha^{-1}) for Itaperuna (Figure 12).

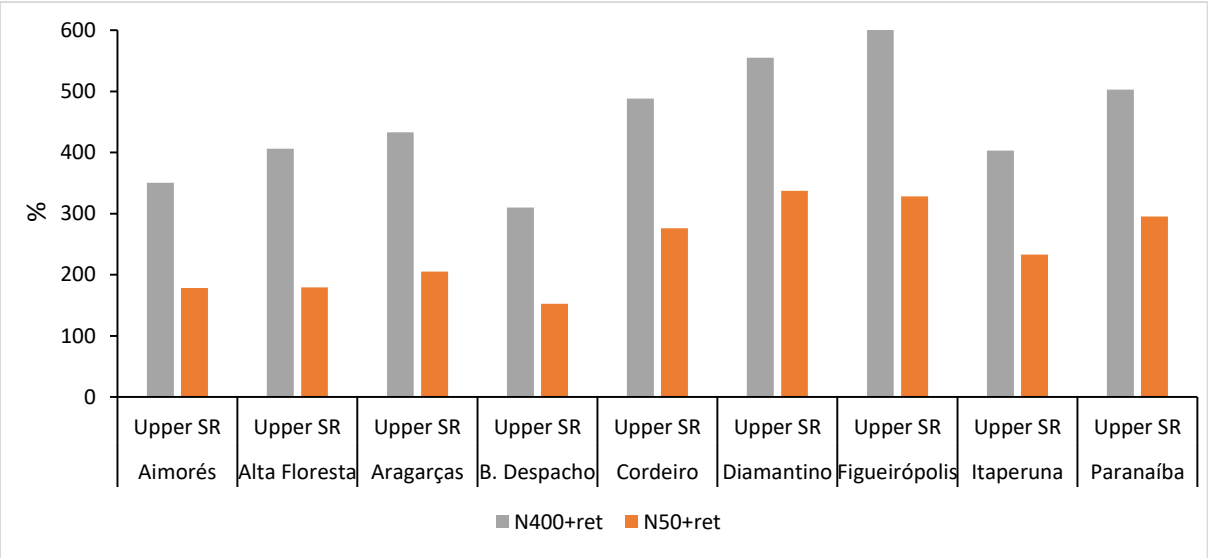

Figure 11. Percentage of upper limit stocking rate (%) of N400+ret and N50+ret scenarios above stocking rate from IBGE census (Ya) for all locations.

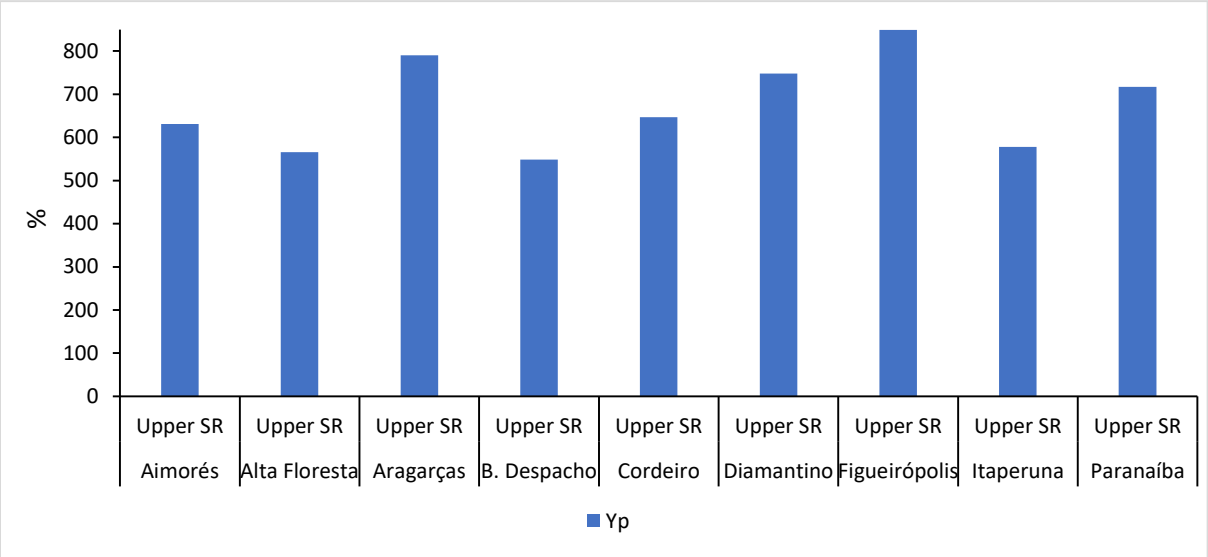

Figure 12. Percentage of upper limit stocking rate (%) of Yp scenario above stocking rate from IBGE census (Ya) for all locations.

Considering the critical period and the fixed stocking rate that would be critical for the herd, the largest exploitable gap in rainfed systems was simulated for Cordeiro, with a critical stocking rate 148% (1.21 AU ha^{-1}) above Ya for the most intensive scenario (N400+ret) and 128% (1.04 AU ha^{-1}) above Ya for the extensive scenario (N50+ret). The smallest gaps were simulated for Bom Despacho (5% for N400 + ret and 3% for N50 + ret), while in Aimorés, there was no yield-gap due to the simulated critical stocking rate data was 11% lower than the actual stocking rate of IBGE census (Figure 13). For Yp, the

largest yield-gap was 794% (5.44 AU ha^{-1}), observed in Figueirópolis D'Oeste, and the smallest yield-gap was 311% (2.91 AU ha^{-1}) for Bom Despacho (Figure 14).

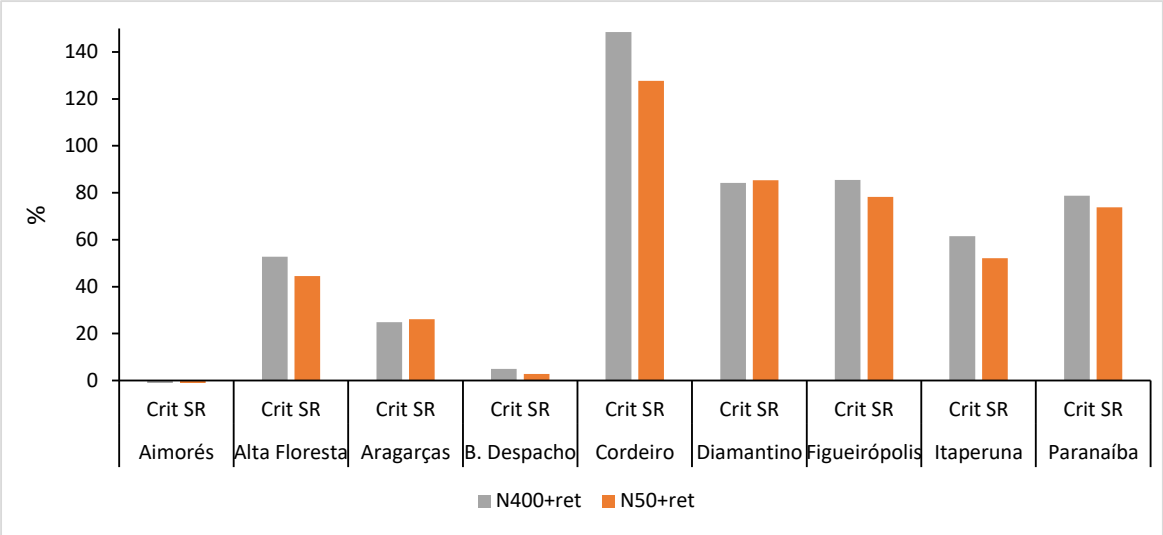

Figure 13. Percentage of Critical stocking rate (%) of N400+ret and N50+ret scenarios above stocking rate from IBGE census (Ya) for all locations.

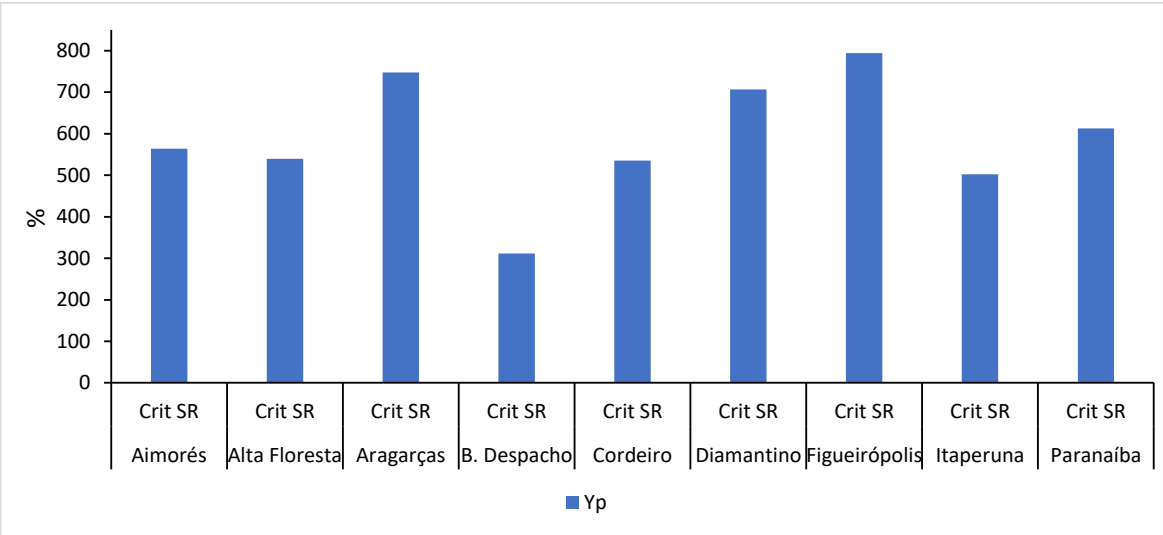

Figure 14. Percentage of Critical stocking rate (%) of Yp scenario above stocking rate from IBGE census (Ya) for all locations.

4.4. Discussion

4.4.1. Critical stocking rate

This study showed that, although the critical stocking rates were not far below the upper limit stocking rate values under potential conditions (0.50 AU ha^{-1} lower, except for Bom Despacho and Cordeiro), in rainfed simulations, the critical stocking rates showed greater declines in relation to their upper limit (3.30 for N400 + ret and 1.58 for N50 + ret) for all simulated locations. Moreover, the critical stocking rates did not respond positively to the increase in the fertilization level of rainfed scenarios N400+ret and N50+ret due to the seasonality of forage production. Due to changes in the growth rates of forage species, caused by fluctuations in climatic factors that determine plant production, there is a reduction in the supply of forage produced as well as in the quality of forage stored for animals, making it necessary to add supplementary nutritional sources that can guarantee the animal's performance continuously throughout the year, unless the animal stocking rate is reduced to achieve optimal carrying capacity of pasture (Hoffmann et al., 2014; Soares et al., 2015). Therefore, seasonality of forage production between the dry and rainy periods must be considered in the estimates and analyzes of the productive potential of livestock system, since the values of pasture carrying capacity are directly influenced by the variation in forage productivity and quality during the year.

Locations with milder minimum temperature records during the winter months, such as Bom Despacho (average of 10.3 to 11.3 °C between June and August) and Cordeiro (average of 12.7 to 13.3 °C between June and August), demonstrated greater forage production limitations, even in potential conditions and, consequently, resulted in the lowest values of critical stocking rate. These minimum temperature values were too close and sometimes, lower than the base temperature for vegetative development of this grassland. Pequeno et al. (2014) presented base temperature for Marandu palisadegrass of 11.1 °C, similar to values of 10.5 and 10.6 °C found by da Silva et al. (2012) and Pezzopane et al. (2018), respectively. Moreover, in tropical and subtropical regions, between latitudes 30 ° N and S, the temperature and water deficiency and their association are the main limiting factors of forage production, unlike what occurs in temperate regions, where sunlight starts to have great relevance, followed by temperature and water supply (McDowell, 1972).

4.4.2. Upper limit stocking rate

Regarding simulations following the “put and take” method, the upper limit stocking rate values were higher than the critical stocking rates, which was expected because these estimates do not consider forage deficit events. Therefore, the higher the levels of intensification on pasture

management (dose of fertilization and irrigation), the higher the upper limit stocking rates, mainly in the zones represented by Alta Floresta, Diamantino and Figueirópolis D'Oeste, where there is better water availability.

The HCZ represented by Alta Floresta was the region most responsive to the increase in the level of fertilization in rainfed conditions, starting from the most extensive to the most intensive scenario, in which larger increments in the upper limit stocking rate were simulated. However, according to the risk analysis to forage production in rainfed conditions, this region presented high risks due to seasonality marked by water deficiency. In addition, it can be considered a region more responsive to fertilization combined with irrigation, as it had the largest simulated forage production for the most critical months of the year in potential condition (Yp). This may be associated with the record of higher temperatures for this location, which associated with the availability of radiation and water, provided conditions for more stable forage production throughout the year. As reported by Santos et al. (unpublished data), Alta Floresta was the location of the Central Brazil region with less production seasonality in potential condition.

Meanwhile, the HCZ region represented by Bom Despacho, resulted in the lowest simulated forage production for the most critical months of the year, as well as the lowest upper limit and critical stocking rates in potential condition. Evidencing that, even using irrigation, this region presents a higher risk of decreasing pasture production in critical winter seasons due to low minimum temperatures, causing greater deficits for the maintenance of grazing animals. These results indicate that, in addition to the adoption of pasture intensification techniques that are necessary to close or reduce the yield-gaps in the Bom Despacho area, this region has a greater need for the adoption of supplementation techniques to increase stocking levels, when compared to the other areas analyzed in this study.

4.4.3. Risks and yield-gaps

Aimorés and Aragarças were the locations with the largest gaps between potential scenario and rainfed intensive scenario, both for upper limit stocking rates and critical stocking rates. In addition, in rainfed conditions, Aimorés, Aragarças presented the greatest risks of relative production below 10 and 20% of the average annual accumulation rate. This demonstrates that these locations, despite having the greatest carrying capacities of this study under potential conditions (from 6.03 to 6.86 AU ha^{-1}), presented the greatest production risks in the most critical months of the year, under rainfed conditions. The average annual precipitation of these places was 941 mm for Aimorés and 1577 mm for Aragarças, however, it is worth remembering that the simulated soil for Aragarças was an

Entisols (Quartzipsamments), which has a sandy texture along the entire profile, making water holding capacity far below than the other simulated soils. Thus, the most accentuated water stress in these regions, due to the low volume and poor rainfall distribution, in addition to the physical properties of the soil, resulted in simulations of greater risks for plant production in rainfed scenarios, as well as for animal production, as these regions also showed the lowest critical stocking rate values (between 0.80 and 0.95 AU ha^{-1}).

Cordeiro and Diamantino were the locations with the highest productive potential, in terms of animal stocking in rainfed conditions (2.03 and 1.50 AU ha^{-1}, respectively), associated with the greatest rates of forage accumulation in the most critical months of the year and with the lowest risks of forage production.

4.4.4. Productive potential and yield gap analysis

According to the study about livestock intensification potential in Brazil, developed by Arantes et al. (2018), the Brazilian average potential cattle-carrying capacity of the pastures was 3.60 AU ha^{-1} and the potential of livestock intensification was, on average, 2.63 AU ha^{-1}. They estimated a pasture carrying capacity for Central-West of 3.45 AU ha^{-1}, values higher than those simulated in the current study, for zones covering Central-West region, considering critical stocking rate of rainfed intensive scenario (between 0.94 and 1.50 AU ha^{-1}). In addition, the authors reported potential for intensification between 1.1 and 3.3 AU ha^{-1} for Central-West and more than 3.4 AU ha^{-1} for East of Southeast region. While the potential increases in the critical stocking rate simulated in the current study, in areas within the central west, ranged between 0.19 and 0.69 AU ha^{-1}, and reached at most 1.21 AU ha^{-1} for East of Southeast region (Cordeiro), also considering the most intensive scenario in rainfed condition.

Arantes et al. (2018) estimated a yearly-based forage production by dividing dry matter yield in the growing period by 0.8 and a daily dry matter yield by dividing annual yield (kg DM) by 365 (day), thus, the stocking rate was calculated dividing daily dry matter yield by daily animal intake from one animal unit (i.e., 11.25 kg DM), considering a harvest efficiency of 50%, obtaining a daily demand of 22.5 kg DM AU^{-1}. However, the authors did not account the seasonality of pastures production, which might cause distortions in results of carrying capacity such as verified in their results to South region of Brazil, wherein potential carrying capacity ranged from 4.7 to 11.2 UA ha^{-1}. According to Allen et al. (2011), carrying capacity is the maximum stocking rate that will achieve a target level of animal performance, in a specified grazing system that can be applied over a defined time without deterioration of the grazing land. Moreover, studies in southern Brazil, where there is a predominance

of natural pastures, have shown that the carrying capacity of pastures throughout the year should not exceed 0.8 AU ha^{-1}, thus maintaining productive systems with positive animal performance (live weight gain), without degradation of pasture by overgrazing (Tanure et al. 2011; Mezzalira et al 2012).

Araújo (2018) performed a yield-gap analysis for Marandu palisadegrass pastures in the state of São Paulo, Brazil. The author also based on the protocol proposed by GYGA and used the CROPGRO-PFM to estimate forage production. It was found average efficiency of pasture production of 46% and an exploitable yield-gap of 5.8 Mg ha^{-1} ano^{-1}, suggesting a possible increase of 0.96 AU ha^{-1}, when compared to actual stocking rate of 1.33 AU ha^{-1} from IBGE census 2006. However, to determinate the real Marandu palisadegrass production and pasture carrying capacity, Araújo (2018) used Strassburg et al. (2014) equation which consideres the following inputs: daily feed intake per animal unit (constant, kg AU^{-1} d^{-1}), grazing efficiency (dimensionless) and stocking rate (AU ha^{-1}) from IBGE census 2006. Thus, it just the average annual production of Marandu palisadegrass was considered in both CROPGRO-PFM simulations and in estimates by Strassburg et al. (2014) method. Therefore, the effects of seasonal plant growth over pastures carrying capacity were not considered properly. According to Allen et al. 2011, carrying capacity is a useful concept when based on adequate historical data and experience, but is a number in a constant state of change, that both site-specific and varies from season to season and year to year.

Literature data, generally, originating from experiments developed in a specific area of the farm, generate results that do not represent the whole animal production system, as well as its variations throughout the year. As a result, a large part of productive potential estimates (AU ha^{-1}) on a regional scale have distortions in the final result.

The results of the current research indicated gaps in both plant production and pasture carrying capacity, influenced by temperature, radiation, CO_2 concentration, genetic characteristics (determining factors), water and nutrients (limiting factors). The difference between livestock systems and crop systems is that agricultural crops do not remain in the field all year long, subjected to periodic defoliation and under the influence of these factors (determining and limiting factors) that cause the seasonality of production, like it occurs in perennial tropical pastures.

4.5. Conclusions

Yield-gap analysis of pasture-based beef cattle livestock systems may be performed by protocols adapted from the GYGA protocols, that couples forage models and animal stocking rate models. This research indicated there are gaps in both plant production and pasture carrying capacity due to interactions between climate, soil, plant and animal. Studies with more robust protocols for the determination of yield potentials for pasture-based beef cattle livestock systems, provide greater

reliability for studies with yield-gap and climate risk analyzes, besides being fundamental for identifying regions with yield-gap and potentials to improve yield, for agroclimatic zoning surveys, for climate change impact projections and for better decision making within livestock activity in pastures.

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Annexes

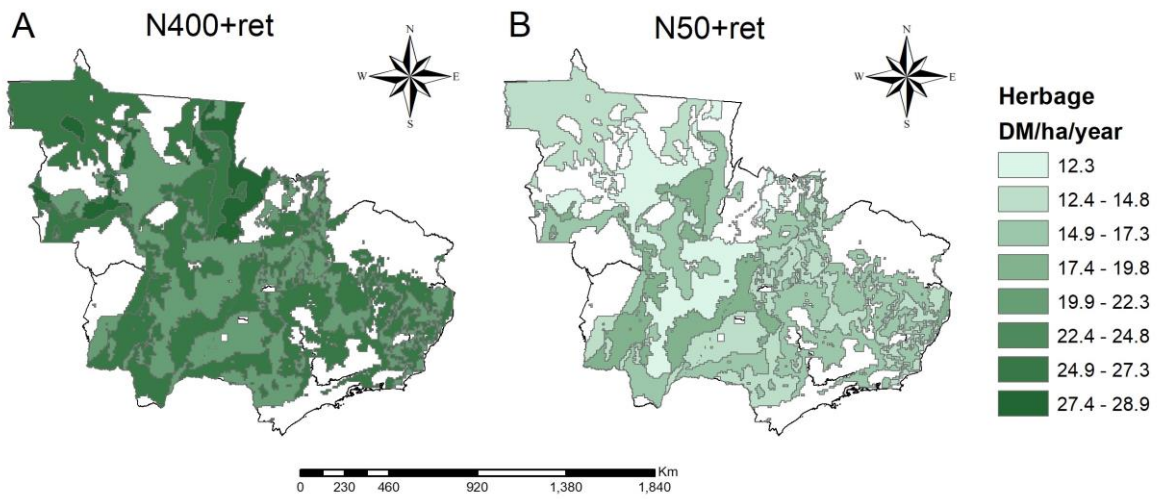

Figure 15. Average annual accumulated herbage (Mg ha^{-1} y^{-1}) between 1980 and 2016 of rainfed scenarios N400+ret (A) and N50+ret (B) simulated by CROPGRO-PFM for the nine homogeneous climate zones in Central Brazil.

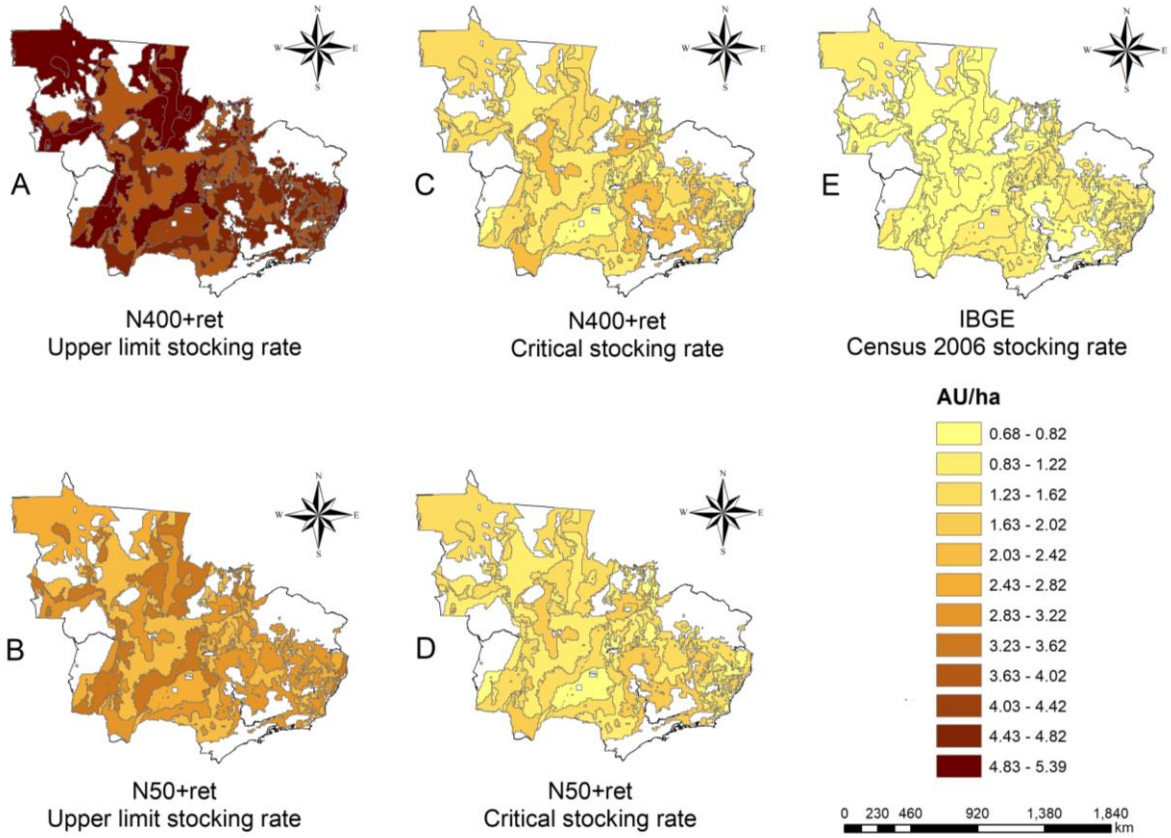

Figure 16. Upper limit and critical stocking rates (AU ha^{-1}) simulated for rainfed scenarios N400+ret (A and C) and N50+ret (B and D), and IBGE census 2006 stocking rate (E) for the nine homogeneous climate zones in Central Brazil.

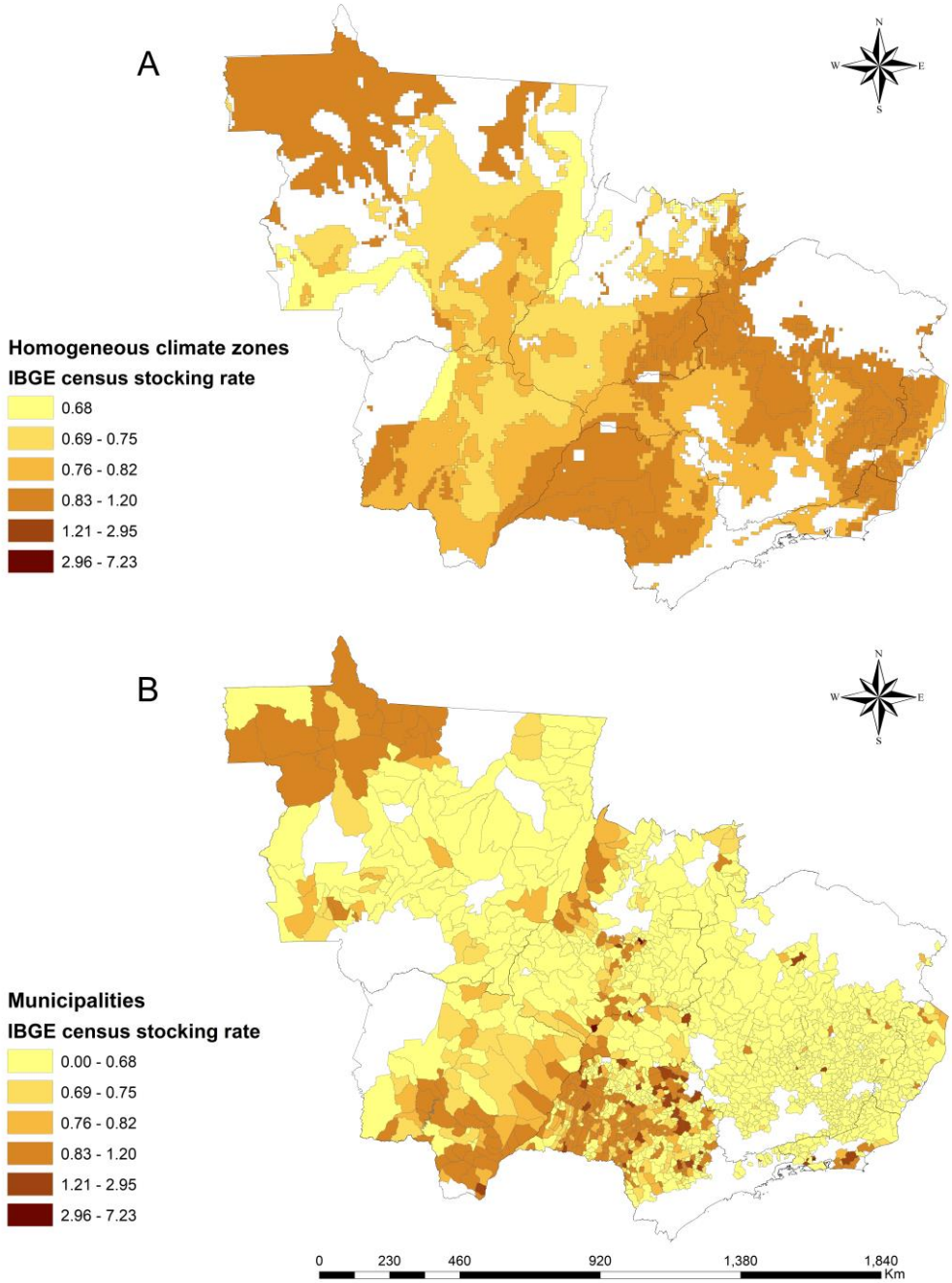

Figure 17. IBGE census 2006 stocking rate per homogeneous climate zone (A) and per municipality (B) in Central Brazil.

5. FINAL CONSIDERATIONS

This study suggests that the CROPGRO-PFM model has potential to be applied for new locations with climate and soil characteristics different from the conditions in which the model was originally developed. However, we recommend model evaluation with local testing which is important before generalizing too far. The calibrated model presented here is important for identifying regions with yield gap and with potentials to improve yield, for agroclimatic zoning surveys and for climate change impact projections for the agricultural sector, as well as for decision making for better management and planning of livestock activity in pastures.

It is possible to estimate yield-gap of pasture-based animal production systems in different edaphoclimatic conditions including the Brazilian Amazon, Cerrado and Atlantic Forest Biomes, by the developing a specific protocol of yield-gap analysis for beef cattle.

One of the main contributions of this study was to provide an overview of the livestock production system as a whole, through simulations of long-term forage production and animal stocking rates, that consider the effects of annual seasonality of production on pastures carrying capacity, thus, generating more consistent data.