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Stabilized Forage Guarantee System: defining a forage storage capacity to stabilize livestock production in vulnerable ecosystems[1]

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ABSTRACT - Livestock production in semi-arid areas has been unpredictable due to climate variability, mainly rainfall. This study aims to simulate rangeland production variability affected by rainfall over time and relate it to an adjusted carrying capacity, using forage stock to maximize the potential of production of the system to a specific guarantee level. Regression analysis of forage biomass against rainfall was performed for ecological sites in the Brazilian semi-arid region to generate probability distribution curves for the historical rainfall for each location using Monte Carlo approach. Forage biomass variability estimated over time was used as input to the model. The system optimizes forage use at a sustainable stocking rate and uses forage surpluses in good years to fill deficits during adverse years, due to a certain level of guarantee. As a rule, smallholder farmers would need to maintain a storage of around 1,500 kg ha^{-1} of DM of forage to maintain an adjusted carrying capacity of 0.11 animal units ha^{-1}, with a guarantee of 95% in the long term, stressing the forage storage capacity as a central component of the model. Since farm size influences forage production capacity and mainly forage stock capacity, recommendations to cope with this paradigm are suggested.

Key words: Forage supply. Guarantee concept. Sustainable livestock production. Monte Carlo approach. Semi-arid regions.

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INTRODUCTION

Semi-arid regions around the world are characterized by high annual evapotranspiration and irregular rainfall (GIRES *et al*., 2014; SILVA *et al*., 2016), resulting in a negative water balance in most part of the year. Along with this imbalance, there is also a poor distribution of rainfall within and between years, making pattern prediction difficult. Despite that, yearlong variation provides an opportunity for water accumulation, even with negative water balance, as most of the time there is less uncertainty between the years in the prediction of water availability in the long term.

Large climate variability associated with high pressure on natural resources due to inadequate agricultural practices and animal stocking rates contributes to degradation of many rangeland areas (HU *et al*., 2019; RAHMANIAN *et al*., 2019). Thus, it is necessary to understand all processes involved in the sustainability of vulnerable ecosystems to sustain animal/agriculture productivity and feasibility. To make this scenario more complex, the demand for high biological responses aggravates the risk, due to the direct relationship between production and water availability (LUKOMSKA; QUAAS; BAUMGÄRTNER, 2014).

Livestock production is a major agricultural activity in semi-arid regions (COUTINHO *et al*., 2013), so there is a need for better use of available natural resources, such as establishing a rangeland production pattern in response to rainfall (LUKOMSKA; QUAAS; BAUMGÄRTNER, 2014), and defining animal stocking rate. This is challenging, considering the erratic pattern of rainfall (SILVA *et al*., 2011), which affects rangeland forage production, and in turn, animal carrying capacity.

The definition of potential stocking rate in a semi-arid area needs to consider the uncertainty of weather conditions as well as factors related to pasture conditions and use. The use of stochastic models, including Monte Carlo approach, seems to be a valuable tool to study the risk associated with such uncertainty (URBANUCCI; TESTI, 2018).

In this context, the objective of this study was to simulate fluctuations in rangeland production over time and relate it to an economic and biological adjusted animal carrying capacity, using storage strategies to maximize the potential of the production system to a guarantee level.

MATERIAL AND METHODS

Characterization of ecological sites studied

The study was conducted considering data from three sites representative of the Brazilian semi-arid region, Ouricuri-Pernambuco (-7° 57’ 18” S; -40° 4’ 59.88” W), Quixadá-Ceará (- 4° 58’ 40.8” S; -39° 1’ 7.68” W) and Sobral-Ceará (-5° 37’ 19.2” S; -40° 6’ 57.96” W) (Figure 1). The criteria for choosing the places considered the rainfall history, type of soil and type of Caatinga, as well as the morphological and structural characteristics of the vegetation (IBGE, 2012), seeking the floristic representation of the region. The average rainfall was 622.2 mm (average of 25 yrs.), 735.0 mm (average of 39 yrs.), and 892.4 mm (average of 39 yrs.), respectively (FUNCEME, 2018; INMET, 2018), and the local soils are predominantly Ferralsols, Planosols and Luvisols (IUSS WORKING GROUP WRB, 2015). Forage biomass (FB) and rainfall data were obtained from the literature (Table 1).

Forage biomass accumulation data (FB; kg DM ha^{-1} yr^{-1}) in exclusion areas (sites without the occurrence of herbivory for at least two years) and rainfall (mm yr^{-1}) occurring in the same evaluation period were used to develop a regression equation as a function of rainfall to obtain estimated annual forage biomass (AFBe) using the SPSS software ($P < 0.05$ by F-test) (Figure 2).

FB corresponds to the total amount of forage produced throughout the rainy season (harvested at the ground level), which starts in Jan-Feb in the locations studied, and usually lasts until July. Rainfall corresponds to the annual rainfall (usually concentrated in the rainy season in the studied locations).

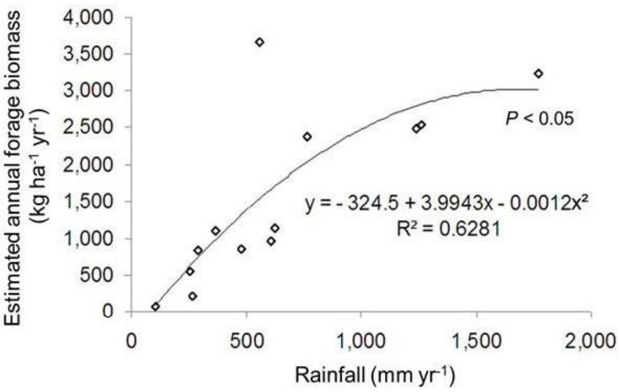
Figure 1 - Cities in Northeastern Brazil (circles) representative of the semi-arid region. AL - Alagoas; BA - Bahia; CE - Ceará; PB - Paraíba; PE - Pernambuco; PI - Piauí; RN - Rio Grande do Norte; SE - Sergipe

Table 1 - Cumulative rainfall (mm yr-1) and forage biomass* (kg DM ha-1 yr-1) of the natural vegetation of the Caatinga, according to data compiled from the literature for three municipalities in the Brazilian semi-arid region

Year	City	Cumulative rainfall	Forage Biomass	Source
1993	Ouricuri-PE	107.20	73.40	Araújo Filho *et al*. (2002)
1991	Ouricuri-PE	257.20	542.60	Araújo Filho *et al*. (2002)
1992	Ouricuri-PE	292.60	838.20	Araújo Filho *et al*. (2002)
1994	Ouricuri-PE	481.70	854.40	Araújo Filho *et al*. (2002)
1990	Ouricuri-PE	610.10	955.00	Araújo Filho *et al*. (2002)
1976	Quixadá-CE	561.00	3663.00	Araújo Filho *et al*. (1982)
1972	Quixadá-CE	763.00	2381.00	Araújo Filho *et al*. (1982)
1973	Quixadá-CE	1078.00	6937.00	Araújo Filho *et al*. (1982)
1975	Quixadá-CE	1240.00	2485.00	Araújo Filho *et al*. (1982)
1977	Quixadá-CE	1312.00	6201.00	Araújo Filho *et al.* (1982)
1974	Quixadá-CE	1773.00	3227.00	Araújo Filho *et al*. (1982)
1993	Sobral-CE	369.00	1108.20	Pereira Filho *et al*. (1997, 2007)
1988	Sobral-CE	1261.70	2537.80	Pereira Filho *et al*. (1997, 2007)

* Considered the maximum value of forage biomass obtained in that growing season. DM: Dry Matter; ha-1: hectare; yr-1: year

Figure 2 - Relationship between rainfall and estimated annual forage biomass (in DM)



The regression equation was used to obtain the AFBe for Sobral - CE, Quixadá - CE, and Ouricuri - PE, considering the variation in expected rainfall in these locations. For this purpose, historical data of total rainfall in the locations was obtained in the Ceará Foundation of Meteorology and Water Resources (Funceme), National Institute of Meteorology (Inmet), and Agrometeorological Monitoring System (Agritempo).

@RISK software, a component of the DecisionTools Suite 8.0.0 package (PALISADE CORPORATION, 2020), was used to generate probability distribution models for historical precipitation for each location. The generated probability density functions are important to determine the behavior of the distribution of the variable (rainfall) over time, and in this way it is possible to associate a probability value to the calculation of forage production estimate (rainfall dependent variable). The curves were chosen based on the chi-square test to represent the time series (SILVA *et al*., 2013).

Expected rainfall data are used in the function that calculates the AFBe (kg DM ha-1 yr-1) (Eq. 1):

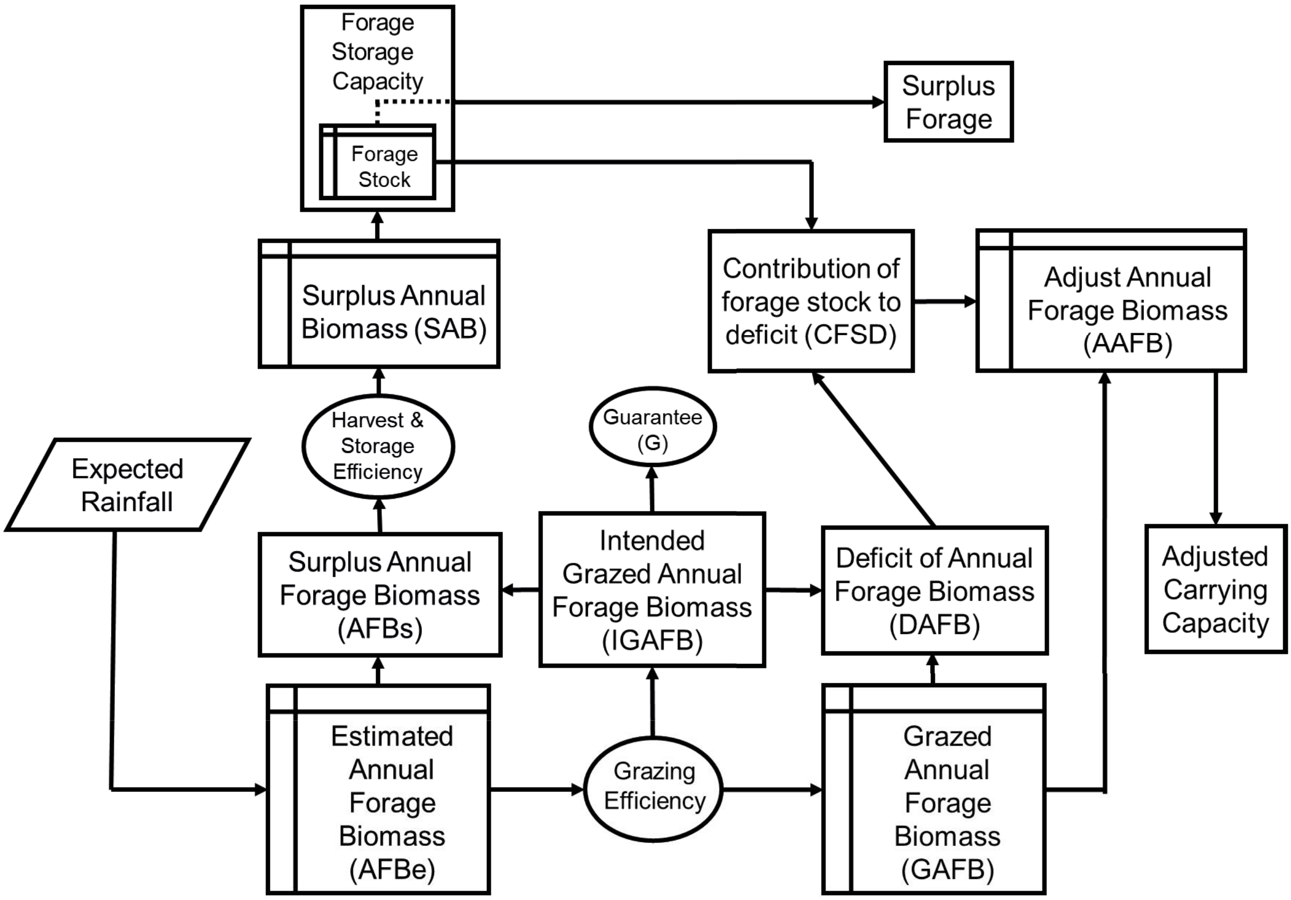
$$AFBe = -324.5 + 3.9943(PPT) - 0.0012(PPT)^2 \quad (1)$$

Where PPT is the annual rainfall (mm). The model uses a guarantee level (G), which is defined as the long-term probability of its success, equivalent to the frequency of years that the forage storage capacity (kg) is able to supply the deficit of annual forage biomass (AFBd) (SILVA *et al*., 2013).

For example, AFBig for a 99% guarantee indicates the forage supply required to meet forage demand 99% of the time. In the present study, an AFBig for a 95% level of guarantee was considered in the stochastic model.

A grazing efficiency of 50% was considered for AFBg (AFBg = AFBe x 0.5). The remaining biomass (50%) was left in the area to support plant regrowth and microbial activity and to protect the soil from erosion. The forage allocated to intake by livestock was named grazed annual forage biomass (AFBg; kg of DM ha-1 yr-1), which is limited by the product of the grazing efficiency and AFBe. If AFBg is less than AFBig, there is forage deficit and forage is allocated to meet the deficit through a contribution of forage stock for deficit (CFSD; kg of DM ha-1 yr-1).

Figure 3 - Diagram of the Stabilized Forage Guarantee System



AFBe was evaluated against the user defined parameter, AFBig (kg of DM ha^{-1} yr^{-1}), which is the target annual forage production of the location that is needed to support a defined herd in the long term. When the difference between AFBe and AFBig was positive, the biomass was considered as surplus annual forage biomass (AFBs = AFBe - AFBig) and allocated to forage stock, considered the harvest and storage efficiency of 80%, due to possible losses of biomass during the utilization/harvesting process (e.g., loss of biomass through silage making), generating the surplus annual biomass (SAB; kg DM ha^{-1} yr^{-1}). The accumulated forage in forage stock will be used in subsequent years to supply AFBd, when it occurs. AFBd occurs when AFBg is less than AFBig (AFBd = AFBg – AFBig).

The adjusted annual forage biomass (AFBa = AFBg + CFSD) is a result of AFBg and CFSD (when AFBd occurs). The purpose of the Forage-Balance Guarantee System is to stabilize the AFBa in the long term for it to be quite similar to AFBg. The consequence of such a AFBa is to reach an adjusted carrying capacity (ACC), in animal units per year (AU yr^{-1}), associated with a determined guarantee (G) level, thus as an attempt to stabilize the AFBa.

The following information was used to determine the ACC variable (Eq. 2):

$$ACC = \left(\frac{AFBa}{BW \times DMI \times PER} \right) \quad (2)$$

Where, ACC: Adjusted Carrying Capacity (AU yr^{-1}), AFBa: Adjusted Annual Forage Biomass (kg of DM ha^{-1} yr^{-1}), BW: percentage of the body weight (2.45%) - based on NRC (1989), DMI: daily dry matter intake (kg DM day^{-1}) and PER: 365 days a year.

The forage storage capacity (FSC) is limited to the Physical Capacity of the Farm to store forage, to the economic capacity of the farmer to provide the logistics for it and the feasibility of AFBs to be mechanically harvested. Surplus forage (kg of DM ha^{-1} yr^{-1}) will be considered as the FSC that exceeds the forage storage capacity. Surplus forage can be used for: a) standing crop, just to be incorporated to the soil as organic matter; b) pasture for leasing; and c) forage biomass harvested to be sold as fresh forage or preserved forage (hay or silage).

ACC, in animal units (AU) (ACCau), was determined using Eq. 3:

$$ACCua = \left(\frac{BW^{0.75}}{450^{0.75}}\right) \times ACC \quad (3)$$

Where, ACCau: Adjusted Carrying Capacity in Animal Units, $BW^{0.75}$: Body Weight raised to 0.75 (kg), $450^{0.75}$: Animal Unit raised to 0.75 (kg), and ACC: Adjusted Carrying Capacity (AU yr^{-1}).

Application of the model to ecological sites studied

The model was used to simulate a dairy system in Ouricuri, Quixadá, and Sobral considering the rangeland as the only animal feed.

Using the model described in Figure 1, the following relationships were tested for each city, adopting a guarantee level of 95%:

Expected rainfall and estimated annual forage biomass;

Farm size, as a response of the stored forage;

Forage storage capacity and adjusted carrying capacity.

RESULTS AND DISCUSSION

Rainfall data in the three municipalities considered in this study (Figure 2) showed a similar pattern, fitting the Gamma distribution ($P < 0.05$), by Chi-square test. Studies point to the good fit of the gamma distribution to rainfall data (RODRIGUES; SANTOS FILHO; CHAVES, 2013). Despite similar rainfall patterns, differences in probability values of maximum and average rainfall were observed. Ouricuri (Figure 4A) showed the lowest average and the low probability of extreme events, Sobral (Figure 4C) showed an opposite pattern and Quixadá (Figure 4B), an intermediate response.

In general, the frequency of high rainfall values remained below the average, stressing the risk of using the average historical rainfall as a parameter to define public policies (Figure 2). In this way, the use of the median seems to be a better indicator of rainfall pattern for a long time for each city. So, for the mentioned cities, the parameters to be used are: 866.8; 718.1 and 601.7 mm, instead of 892.4; 735.0 and 622.2 mm, respectively.

Figure 5 illustrates the relationship between farm size and its forage storage capacity. The greater the forage storage capacity, the lower the pressure over land use and the smaller the farm size for the livestock production to become economically feasible. If the farmer is capable of enhancing forage production and storage, it will not be necessary to increase the pasture area every year to feed the animals. When considering the locations studied, Ouricuri showed a lesser potential AFBe, indicating that smallholder farmers need to store more feed. Otherwise, a larger farm size would be necessary to feed the same herd.

Forage storage capacity affected the adjusted carrying capacity (ACC) (Figure 5). As forage storage capacity increases, a higher ACC can be adopted, with a maximum 5.9 ha per AU in Quixadá and Sobral, when it is possible to store 8,000 kg feed. This ACC is approximately half of the cited carrying capacity of the Brazilian semi-arid region (10 ha AU^{-1}; (ARAÚJO FILHO, 2013)). Thus, it suggests that, when the farmer is capable of storing more feed, it is possible to increase the farm carrying capacity.

Figure 4 - Data fit to the theoretical (line) and actual (columns) probability density function of the whole year rainfall (mm yr^{-1}) in Ouricuri (A), Quixadá (B) and Sobral (C). The selected function was *Gamma*, by chi-square test ($P < 0.05$)

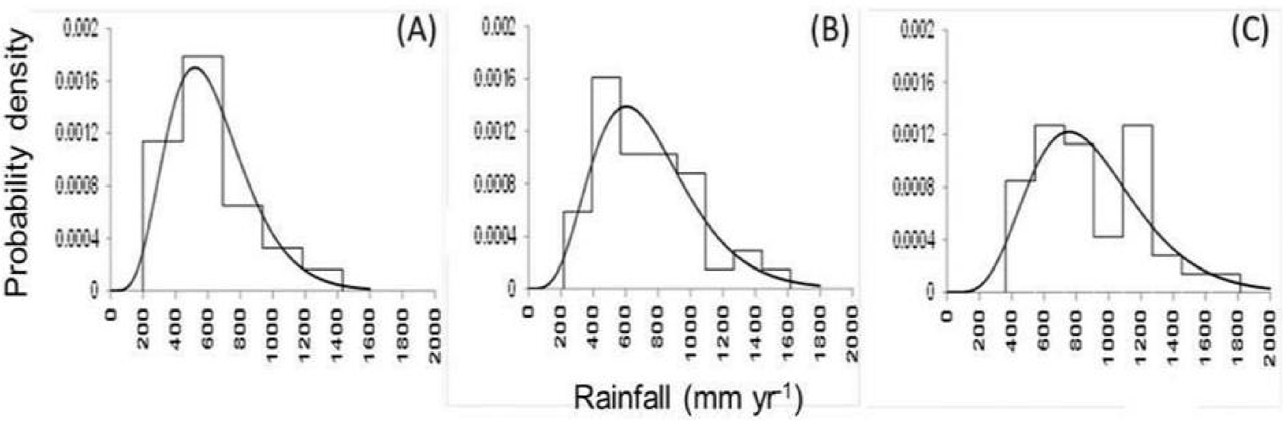


Figure 5 - Relationship between accumulation capacity (forage) and farm size

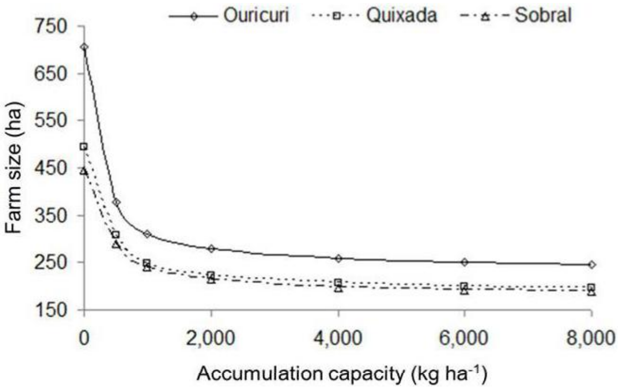
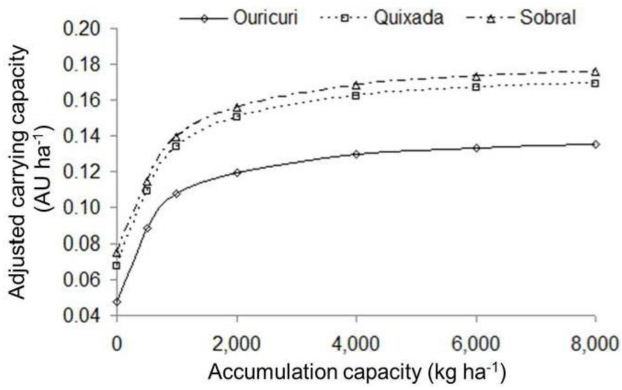


Figure 6 - Relationship between accumulation capacity and adjusted carrying capacity



The AFBe is affected by the type of probability distribution associated with rainfall, and the latter must be considered when planning the production system. Considering the relationship between AFBe and expected rainfall, the model showed a quadratic response ($P < 0.05$) (Figure 2). The maximum AFBe was 2,999 kg for the rainfall of 1,664 mm. This biomass response apparently discrepant from rainfall is a consequence of the prevalent soils in that region studied, associated with interactions with climate and the plants which evolved in this ecosystem.

Sobral and Quixadá showed a similar pattern in the relationship between forage storage capacity and farm size, although Sobral had higher rainfall than Quixadá (Table 1), which occurred because Sobral showed more years of rainfall above the maximum necessary to maximize AFBe.

The predominance of undeveloped and shallow soils (ALENCAR; ARAÚJO; COSTA, 2017; FARRICK; BRANFIREUN, 2015), with low water storage capacity and a great risk of runoff (ANDRADE *et al*., 2017), increases the negative impact of the lower rainfall. In turn, in years of above-average rainfall, its effect is usually limited by a fast soil saturation and an increase in runoff frequency (ANDRADE *et al.*, 2017), thus reducing the rainfall effectiveness for the water supply necessary for plant growth.

Greater response in ACC to increases in forage accumulation capacity was obtained up to 1,500 kg forage storage capacity (Figure 6). Afterwards, ACC showed an asymptotic response, increasing with forage storage capacity up to approximately 2,000 kg. After this point, there is no advantage in increasing ACC because of ecological aspects, including a lesser frequency of favorable climate conditions, which may limit plant growth.

Besides weather and soil factors, vegetation in this condition is also an important component. The herbaceous layer contains ephemeral plants as an important component, which in most cases finish their life cycle by the middle of the rainy season (OLIVEIRA; PRATA; FERREIRA, 2013), and their biomass production is greatly affected by the amount of rainfall. Additionally, the woody layer may become dormant, thus reducing the total amount of biomass (THOMA *et al*., 2016).

In addition to fluctuation in productivity caused by rainfall, a change in the floristic composition of the herbaceous layer in response to the rainfall volume was verified (OLIVEIRA; PRATA; PINTO, 2018). In years when rainfall oscillated above the historical average, herbaceous layer was mainly composed of forbs, as a rule. On the other hand, in years with rainfall below the historical average, grasses predominated in the composition of the herbaceous layer. Thus, the ecosystem resilience relies on adaptation to rainfall variation over the years, modulating plant growth and floristic composition according to the yearly rainfall, guaranteeing a minimum replenishment of reserves each year and a phytosociological equilibrium in the ecosystem.

In an attempt to recommend a forage storage capacity that optimizes the adjusted carrying capacity, the forage storage capacity value that provided a critical value of 90% of the maximum adjusted carrying capacity was estimated for each location (Figure 5), and the results were 1,556, 1,717 and 1,748 kg ha^{-1} for Ouricuri, Quixadá, and Sobral, corresponding to 0.12, 0.15 and 0.16 AU ha^{-1}, respectively. So, the smallholder farmers have a guarantee of 90% to use on the farm 8.3, 6.67 and 6.25 ha for each animal unit if maintaining such a forage storage capacity.

These values are quite below the range from 10 to 20 ha per AU recommended by Araújo Filho (2013), but it can be stressed that they were simulated considering the adoption of storage practices and indicates that there is a slight but not negligible variation in the potential for each location. In a general way, smallholder farmers should maintain a forage storage capacity equivalent to 1,500 kg ha^{-1} forage biomass to duplicate the adjusted carrying capacity, with a guarantee of 95%.

Considering that the average farm size in the Brazilian semi-arid region is 28.9 ha (FERNANDES; CARDOSO; QUEIROZ, 2020; IBGE, 2012), it should be enough to raise 3.5, 4.3 and 4.6 AU in Ouricuri, Quixadá, and Sobral, respectively. So, it is necessary to improve farm efficiency to make it feasible. One of the recommendations should be the diversification of forage resources, taking advantage of some privileged areas on the farm to make improved pastures and introducing exotic forages, like sugarcane, cut-and-carry grass and so on, as well as the adoption the multispecies grazing to cope with such a diversification.

Another possibility is the multiple use of rangelands to optimize land use, coupling livestock production with crops, forestry management, biodiversity conservation, water preservation, and recreation, thus improving ecosystem services. This can be obtained, in part, with improved and effective use of technology by smallholder farmers; for example, the use of machinery adapted to semi-arid conditions may have a positive impact on production systems with minor impact on costs.

Future implications

Studies have been conducted to establish a feasible stocking rate in rangelands to prevent degradation. Dieguez and Pereira (2020) proposed the Safe Stocking Rate concept, which assumes some adjustments in the stocking rate throughout the year to prevent degradation. This is an advance to the fixed stocking rate concept, which according to Derner and Augustine (2016) take out 10% to 33% of the ranch area to fallow, causing loss of forage in years of favorable weather, but it requires the movement of animals in or out of the farm along the year, which makes the management more complex.

On the other hand, the Forage-Balance Guarantee System may help smallholder farmers to overcome climate vulnerability in the long term, defining possible forage inputs in the system and maintaining the system carrying capacity, and the production stabilized over time. The results provided information on how smallholder farmers could increase the carrying capacity by adopting the concept of forage storage capacity in their property.

Regarding climate variability associated with semi-arid conditions, one of the possible risks is the occurrence of years of severe droughts in which the estimated annual forage biomass can be less than the minimum residual biomass to maintain the sustainability of the ecosystem. This should define a critical threshold to take out the livestock from pasture to be kept in a feedlot.

Another question that arises is the forage quality variation because of storage time. In the long term, even when using the best preservation techniques, it is not possible to maintain feed quality due to storage losses. This increases the need for extra supplements to maintain livestock production, which contributes to increasing the feeding cost and reducing the net income. Thus, the inclusion of this parameter in the model may allow system optimization, considering the need for balancing the nutrient to meet livestock requirements.

Finally, soil limitations to mechanization, such as rocky soils and slope, need to be considered, as these can limit the forage storage capacity of the farm, even in years of high rainfall.

CONCLUSIONS

1. The use of a model associated with the guarantee concept has proved to be useful to estimate adjusted annual forage biomass, even in regions with high rainfall variability;
2. Forage storage capacity is a central component of the Forage-Balance Guarantee System, contributing to stabilizing livestock production systems in the long run, considering a stated guarantee level, through its inverse relationship to land demand and stored forage;
3. The optimum level of forage storage capacity to guarantee livestock production in semi-arid regions like the studied ecological sites should be around 1,500 kg DM ha^{-1} yr^{-1}, but never exceeding 2,000 kg DM ha^{-1} yr^{-1}.

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