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Spatial variability of soil attributes and modeling to estimate forage production and carrying capacity in Semi-arid

Variabilidade espacial dos atributos do solo e modelagem para estimar a produção de forragem e a capacidade de suporte no Semiárido

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Abstract: The objective of this study was to evaluate the spatial variability of soil attributes and the use of modeling to estimate forage production and carrying capacity (CC) in a semi-arid region. Data were analyzed using geostatistical methods, including semivariograms analysis and mapping of each soil chemical attribute. Forage production was simulated at 99%; 95% and 90% guarantee levels, considering areas suitable for mechanized forage production, native pasture areas, irrigable areas and, ephemeral wetland areas. The exponential model best fit the attributes of organic matter, potassium, phosphorus, and pH, while the spherical model was optimal for base saturation, stoniness index, slope index, and general index. The Gaussian model provided the best fit for the cost index. Phosphorus had the lowest range (235 m) and demonstrated a strong spatial dependence (<25%). The highest forage production occurred in irrigable areas, with yields of 112,270.00, 178,661.00, and 215,455.00 kg year^{-1} at the 99%, 95%, and 90% guarantee levels, respectively. The 90% guarantee level enabled a 31% higher CC than the 99% level, with the highest CC observed in mechanized areas—accounting for about 71.8% of the property's total CC due to greater forage production. Modeling effectively quantified areas capable of producing forage, with lower guarantee levels supporting higher forage production and carrying capacity.

Keywords: Carrying capacity; soil fertility; geostatistical techniques; forage biomass.

Resumo: O objetivo deste estudo foi avaliar a variabilidade espacial dos atributos do solo e o uso da modelagem para estimar a produção de forragem e capacidade de suporte (CS) no Semiárido. Os dados foram analisados usando métodos de geoestatística, incluindo semivariogramas e o mapeamento de cada atributo químico do solo estudado. A produção de forragem foi simulada para os níveis de garantia de 99; 95 e 90%, considerando áreas aptas à produção de forragem mecanizada, áreas de pastagem nativa, áreas irrigáveis e áreas de vazante. O modelo exponencial melhor se ajustou para os atributos matéria orgânica, potássio, fósforo e pH, enquanto o modelo esférico se ajustou para os atributos saturação por base, índice de pedregosidade, índice de declividade e índice geral. O modelo gaussiano melhor se ajustou para o índice de custo. O menor alcance (235 m) foi obtido para o fósforo, que apresentou um grau de dependência espacial classificado como forte (<25%). A maior produção de forragem foi obtida na área irrigável, com valores de 112.270,00; 178.661,00 e 215.455,00 kg ano^{-1} para os níveis de garantia 99; 95 e 90%, respectivamente. O nível de garantia de 90% possibilitou CS 31% superior à garantia de 99%, sendo maior a CS observada nas áreas mecanizadas, representando cerca de 71,8% da CS da propriedade, devido à maior produção de forragem. A modelagem permite quantificar eficientemente a área capaz de produzir forragem, sendo que menores níveis de garantia possibilitam maior produção de forragem e maior capacidade de suporte.

Palavras-chave: Capacidade de suporte; fertilidade do solo; técnicas geoestatísticas; biomassa forrageira.

1. Introduction

The semi-arid region is characterized by a hot and dry climate with scarce and unevenly distributed rainfall throughout the year. Due to this irregular rainfall distribution, production systems tend to expand the herd during the rainy season to take advantage of increased forage biomass and reduce it during the dry season when biomass diminishes. Unfortunately, this adjustment in stocking rates is often done empirically, leading to pasture and soil degradation.

Therefore, the planning of rural properties is crucial for enhancing pasture and herd productivity. For properties that implement pasture-based animal production systems, planning should rely on information such as herd dynamics projections, critical limits of nutritional requirements for plants and animals, and expected levels of pasture productivity throughout the year. This approach helps optimize the biological efficiency of the production system.

Precision agriculture has proven to be a valuable tool for managing and making decisions on properties, improving resource use efficiency within production systems[(1)]. This technology comprises a set of tools that assist producers in managing soil, crops, herds, and inputs, thereby increasing productivity and profits while reducing negative environmental impacts[(2)].

The use and refinement of precision agriculture techniques offer significant benefits in agricultural planning, resulting in measurable improvements that make properties more technically, economically, and environmentally efficient[(3)]. However, the adoption of precision agriculture tools remains limited in semiarid regions. Precision agriculture is rarely discussed for smallholder farmers with limited financial resources due to the high cost of the required equipment. For these producers, precision agriculture should adopt a more holistic approach to help manage forage production and soil variability, thereby enhancing productivity[(4)].

This study aimed to evaluate the spatial variability of soil attributes and the use of modeling to estimate forage production and carrying capacity (CC), considering different guarantee levels (99; 95 and 90%) in a semi-arid region.

2. Material and methods

The experiment was conducted at Fazenda Remédio in Quixeramobim, CE, Brazil, located at 5°13’59.07” W and 39°25’53.96” S. The climate of the region is BSwh type (hot and dry semi-arid), according to the classification of Köeppen[5]. The property has a total area of 313.0 hectares.

To characterize the spatial variability of soil chemical attributes (pH, potassium, phosphorus, base saturation, and organic matter), georeferenced soil samples were collected within a rectangular grid measuring 300 m x 175 m. The sampling design considered the exploratory use of the soils, resulting in 62 samples across the entire property. Based on the soil analysis, fertilizer requirements were estimated to align soil levels with the recommendations outlined in Bulletin 100 from the Instituto Agronômico de Campinas[6].

Samples were collected according to exploratory land use. The mesh was generated using AutoCAD® Civil 3D® software. To locate the points generated in the mesh, a GPS navigation model GARMIN® GPSmap 62 sc was used. Samples were collected using an auger with an average depth of 20 cm. The data were subjected to geostatistical analysis to determine the best-fitting model, addressing the spatial variability of soil attributes. Semivariograms were obtained, and each chemical attribute was mapped using the Kriging method. Spatial dependence was analyzed using GS+ Version 5 software[7], which calculates the sample semivariance, as described by Vieiras *et al.*[8]:

$$y(h) = \frac{\sum_{i=1}^{n(h)}[z(xi+h)z(xi)]^2}{2n(h)}$$

where: n(h) is the number of sample pairs [z(xi); z(xi + h)] separated by vector h, being z(xi) and z(xi+ h), observed numerical values of the analyzed attribute, for two points xi and xi+ h, separated by vector h.

The degree of spatial dependence (DSD) was calculated, defined as the proportion between the nugget and the sill effect. The classification followed the criteria of Cambardella *et al.*[9], where values <25% indicate strong spatial dependence, between 25 and 75% indicate moderate spatial dependence, and >75% indicate weak spatial dependence.

$$DSD = [C_0/(C_0+C1)]*100,$$

where: DSD represents the degree of spatial dependence; C0 is nugget effect and C0 + C1 is sill.

Mathematical models were fitted to the semivariograms, allowing the visualization of the nature of spatial variation in density. The following mathematical models were used to fit the semivariograms:

For the exponential model: $\gamma(h) = C_0+C[1-\exp(-h/A_0)]$.

For the Gaussian model: $\gamma(h) = C_0+C[1-\exp(-h^2/A_0^2)]$.

For the espherical model: $\gamma(h) = C_0+C[1.5(h/A_0)-0.5(h/A_0)^3]$, for $h \le A_0$ or $\gamma(h) = C_0+C$, for $h>A_{0.}$

Where: $\gamma(h)$ = semivariance for interval distance class h; h = the lag distance interval; C_0 = nugget variance ≥ 0; C = structural variance ≥ C_0 and A_0 = range parameter.

To improve decision-making in property planning, it was necessary to quantify the volume of existing reservoirs on the property. For this, a topographic survey of the entire area was conducted using a pair of GPS TechGeo® receivers, GTR G^2 geodesic model, whose data, after being processed by the Brazilian Continuous Monitoring Network of the Brazilian Institute of Geography and Statistics, achieved a precision of 10 mm ± 1 ppm.

After the survey, a point cloud was generated and processed in a geographic information system to create a digital terrain model from which contour lines were produced. The storage volume of the reservoirs was then calculated using a quota–volume diagram.

With this data, a hydrological study was conducted for all the reservoirs on the property. The maximum volume of each reservoir was calculated, and the watershed area was delineated, with its slope and length measured. To estimate water flow within the watershed, the areas of native pastures, forests, and nonvegetated land were quantified using soil maps[10]. The volume generated by these flows and the evaporation from the reservoirs were then estimated[11].

Using the hydrological model and the region's precipitation history, reservoir behavior was simulated over time to quantify areas designated for irrigation and ephemeral wetlands.

For the irrigation areas, the average water requirement for a forage crop was set at approximately 100 m^3 ha^{-1} day^{-1}. Using this daily volume, the water requirement of the crop was calculated for a 150-day period (August to December), which is the peak demand period due to the region's dry conditions. With this information, the volume that could be extracted from the reservoirs was calculated, providing guarantee levels of 90; 95 and 99%. To determine the irrigated area supported by each reservoir at these guarantee levels, the following equation was used:

$$\text{Area(ha)} = (\text{VExt}/\text{VExi}*\text{NID}),$$

where: VExt: Extracted volume (m^3 x $ha^{-1}day^{-1}$); VExi: Required volume (m^3); NID: Number of irrigation days (days).

In addition to estimating the irrigated area, the ephemeral wetland area was also calculated. The water surface area was estimated based on the stored volume using the quota/volume/area diagram. Ephemeral wetland areas for each reservoir were determined through regression analysis. This area varied with the water surface level, which was related to the quota. For calculating ephemeral wetland areas, the reference becomes the quota referring to the water surface. The area was estimated as the difference between the quota of the water surface and the subsequent quota, defined as the water surface quota plus 1 m.

The ephemeral wetland areas were defined as areas used during the dry period of the year, contributing to the area available for forage production. Based on this data, the average annual ephemeral wetland area available for each reservoir was calculated. The hydrological model was used to simulate the behavior of ephemeral wetlands over a 40-year period (1974–2013)[12]. A probability test was then applied to determine the average ephemeral wetland areas with guarantee levels of 90, 95 and 99%, which correspond to the percentage of time during which the reservoirs provide areas for forage production.

Tanzania grass (*Megathyrsus maximus* cv. Tanzânia) was selected for the irrigable areas, while Canarana grass (*Echinochloa* sp.) was chosen for the ephemeral wetland areas. Additionally, areas suitable for mechanized forage production and native pasture areas were considered.

To define the mechanized forage production areas, the stoniness index (StI), the cost index (CI) with fertilization, and the slope index (SI) were developed. These were combined using a weighted average to generate a new index called the general index (GI). The StI, CI, and SI were assigned weights of 0.5; 0.3, and 0.2, respectively.

The values for calculating the weighted average were assigned based on factors that most limit mechanized harvesting. The StI received the highest weight because it is the greatest limitation for agricultural mechanization. Thus, the GI was used to delineate mechanized forage production areas and legal reserve areas in compliance with current environmental legislation. The native pasture area was determined after mapping the mechanized forage production areas, legal reserve areas, permanent preservation areas, and areas designated for irrigation.

For production in mechanized areas, between 1974 and 2013, the productivity of buffel grass (*Cenchrus ciliares*) was estimated through a regression, obtaining the productivity of the grass (kg DM ha^{-1} $cycle^{-1}$) from precipitation information, data obtained by Dantas Neto *et al*.[13]. Subsequently, the equation obtained from the regression in three months of precipitation was applied, where these months form a crop production cycle. As there were years where the average precipitation was around 700 mm and the rains extended to approximately six months of the year, six months of precipitation were used to compose two forage productions in the rainy season and later extrapolated to forty simulation years.

Native pasture productivity was estimated using data from Araújo Filho *et al*.[14]. A regression analysis based on precipitation data for a single growth cycle (February to July) was conducted, providing annual production estimates that were extrapolated over the 40-year simulation period.

Using the calculated forage production data, the property's CC (in animal units) was calculated using the following equation:

$$CC=[FP/365)*FUE]/(450*2.6\%),$$

where: CC: Carrying Capacity; FP: Forage Production (kg DM $year^{-1}$); FUE: Forage use efficiency (buffel grass 60%; Caatinga area 30%; ephemeral wetlands area 60% and Irrigated area 65%).

Based on these calculations, the CC of the property was determined, and precipitation data for 40 years were simulated to assess how the property's stocking rate would change during the simulation period.

3. Results and discussion

For the chemical attributes Organic Matter (OM), Potassium (K), Phosphorus (P) and pH, the model that best fitted the semivariograms was the exponential (Table 1). The Base Saturation (BS), stoniness index (StI), slope index (SI) and general index (GI) were best by the spherical model, while the cost index (CI) showed a better fit to the Gaussian model (Table 1). The semivariograms for soil chemical attributes are shown in Figure 1, and those for cost, stoniness, slope and general indices are shown in Figure 2. Various studies have demonstrated that the exponential and spherical models are the ones that best fit the chemical attributes of soil. The spherical model is characterized by reaching a plateau at a finite distance, indicating continuous phenomena, while the exponential model has a greater range compared to the spherical model under similar conditions[(15)].

Greater ranges were observed for the slope index, cost index, organic matter content and potassium content. The lowest range was obtained for the phosphorus content, suggesting that the range value used in geostatistical assessments for future projects on properties with similar requirements, as in the present study, should not be less than 235 m. The range variable refers to the distance where the sampled points are correlated, being important for the correct planning and evaluation of an irrigation system[(16)]. Through this, it is possible to determine to what extent a variable has spatial dependence, that is, from that point onwards the spatial behavior becomes independent[(17)].

Table 1. Parameters of models fitted to semivariograms for chemical attributes of the property's soil and cost, stoniness, slope and general indices

Variable	Model	Nugget Effect (C0)	Sill (C0+C1)	Range Ao (m)	DSD (C0/C0+C1)	R^2
			Chemical attributes			
Organic matter	Exponential	23.00	53.00	1600.00	43%	0.602
Potassium	Exponential	1.50	2.80	1350.00	54%	0.777
Phosphor	Exponential	1.00	2013.00	235.00	0%	0.582
pH	Exponential	0.20	0.30	600.00	67%	0.405
BS	Spherical	60.00	165.00	980.00	36%	0.334
			Indexes			
Cost	Gaussian	0.05	0.07	1750.00	64%	0.833
Stoniness	Spherical	0.02	0.057	446.00	31%	0.180
Slope	Spherical	0.01	0.01	2650.00	46%	0.821
General	Spherical	0.01	0.02	650.00	50%	0.343

BS: base saturation; DSD: degree of spatial dependence.

The degree of spatial dependence (DSD) was classified as strong (DSD<25%) only for phosphorus and moderate (DSD between 25 and 75%) for other soil chemical attributes and for all indices evaluated (Table 1). According to Cambardella *et al.*[(9)], variables with DSD classified as strong are more affected by the inherent properties of the soil, specifically factors related to soil formation, while variables with moderate DSD are associated with soil homogenization. In this context, the results obtained in the present study were satisfactory for establishing appropriate models.

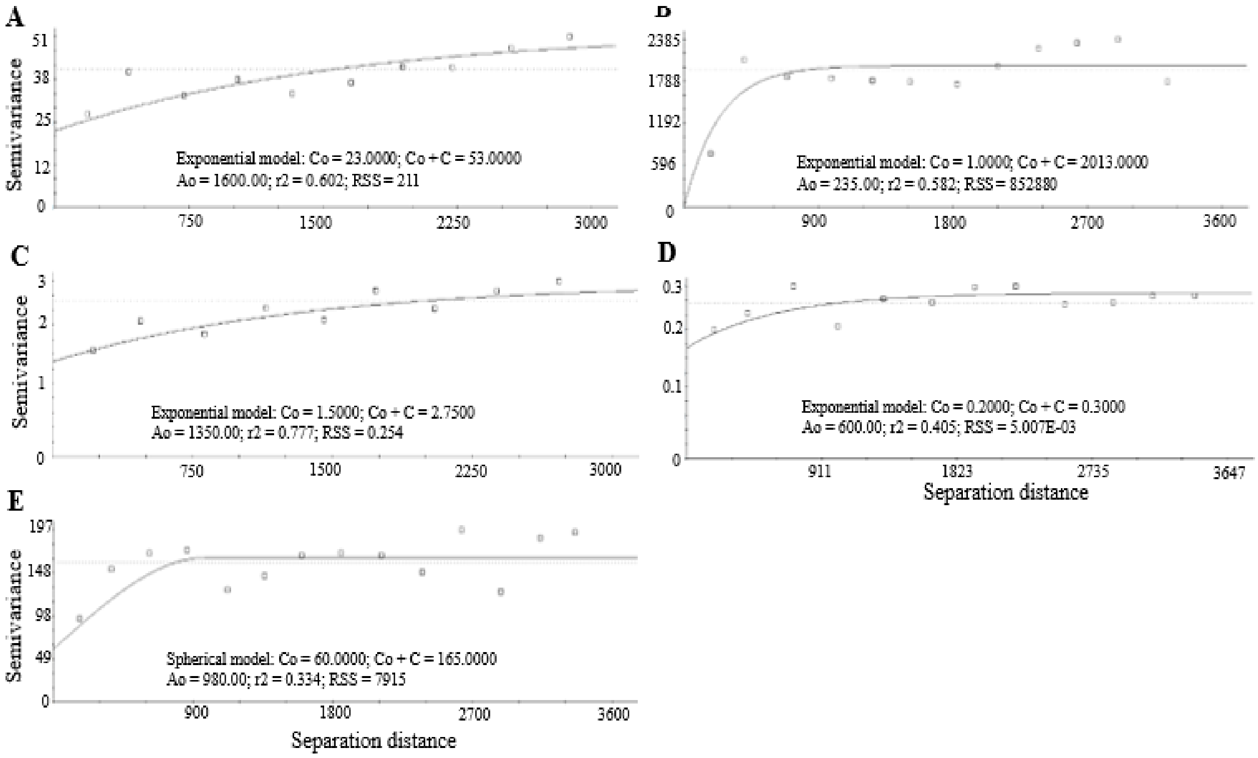

Figure 1. Experimental semivariogram for soil chemical attributes: (A) OM; (B) P; (C) K; (D) pH and (E) BS.

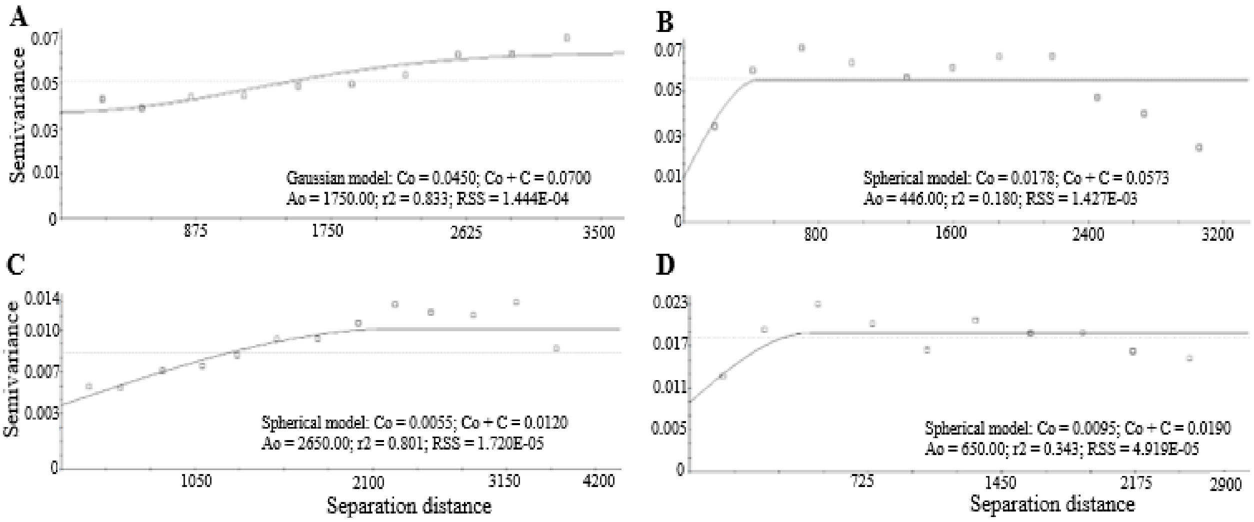

Figure 2. Experimental semivariogram for indices: (A) CI; (B) StI; (C) SI; (D) GI.

The variability maps of soil chemical attributes and cost, stoniness, slope, and general indices revealed variations in the studied attributes across the area (Figure 3).

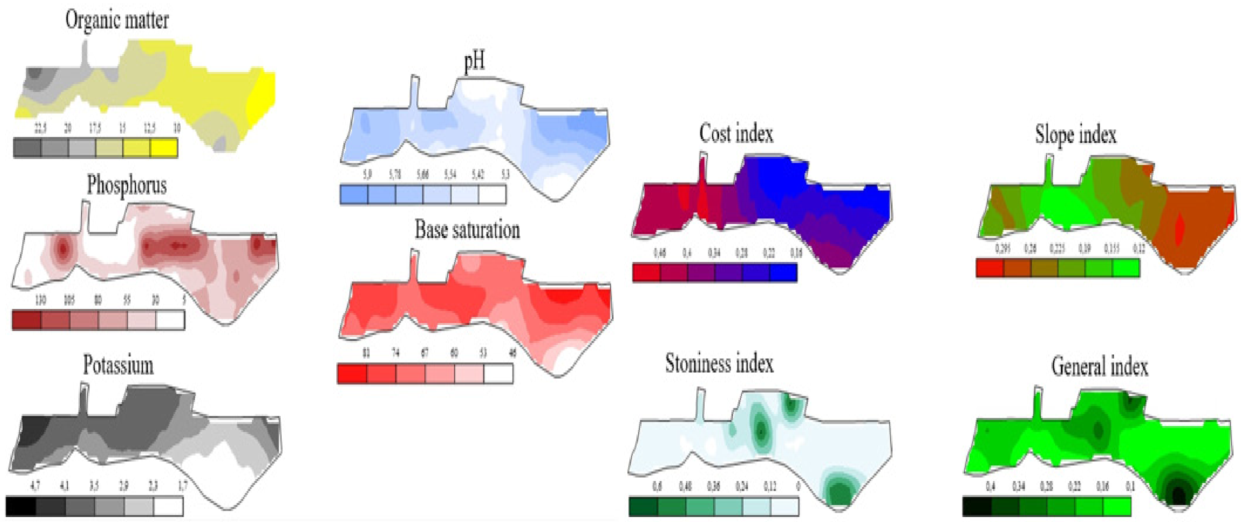

Figure 3. Spatial variability maps of soil chemical attributes and indices.

The creation of variability maps for soil chemical attributes and indices assessed in this study is crucial for identifying specific zones that require management. These maps enable the targeted application of inputs to improve soil fertility homogeneity. This information is particularly relevant for the implementation of precision agriculture techniques, as fertilizer application recommendations can be tailored to nutrient levels in each soil patch[15; 17; 18]. With these maps, it becomes possible, for example, to identify areas requiring soil correction, such as those with low pH (acidic soil) or low base saturation, thereby improving conditions for agricultural practices.

With the lowest guarantee level (90%) the property's reservoirs provide enough water to irrigate an area of 11.07 ha (Table 2). The greatest contribution came from water from the "Barragem" reservoir, allowing to irrigate an area equivalent to 69.44; 63.83 and 60.25% of the total area for levels 99; 95 and 90% guarantee respectively. Based on the irrigable area data for each reservoir, the total forage biomass (TFB) was estimated for the different guarantee levels adopted (Table 2). In the area subject to irrigation, the highest TFB, regardless of the guarantee level, was verified for the "Barragem" reservoir, which was already expected considering that this allowed a greater irrigable area.

For the ephemeral wetland production areas, larger areas were observed, regardless of the level of guarantee adopted, for the "Sede" reservoir, while the "Barragem" reservoir did not contribute with any area (Table 2). Thus, the higher TFB was estimated for "Sede" reservoir, with 3,110; 3,780 and 4,008 kg year^{1} for 99; 95 and 90% guarantee levels, respectively.

Table 2. Irrigated and ephemeral wetland areas for each reservoir, along with the production of total forage biomass (TFB) at different guarantee levels (G)

Reservoir	G 99%	G 95%	G 90%	G 99%	G 95%	G 90%
	Irrigated area (ha)			Ephemeral wetland area (ha)		
"Sede"	0.83	1.90	2.73	1.13	1.40	1.45
"Barragem"	4.00	5.86	6.67	0.00	0.00	0.00
"Volta"	0.93	1.42	1.67	0.14	0.19	0.29
TOTAL	5.76	9.18	11.07	1.27	1.59	1.74
	TFB (kg year^{-1})			TFB (kg year^{-1})		
"Sede"	16,224.00	36,993.00	53,215.00	3,110.00	3,870.00	4,008.00
"Barragem"	77,875.00	114,087.00	129,792.00	0.00.00	0.00.00	0.00.00
"Volta"	18,171.00	27,581.00	32,448.00	387.00	511.00	802.00
TOTAL	**112,270.00**	**178,661.00**	**215,455.00**	**3,497.00**	**4,381.00**	**4,810.00**

The fact that the "Barragem" reservoir did not contribute to the hydrological simulation in the ephemeral wetland area is due to its excellent inflow, which has kept its water level consistently near the maximum accumulation level over the years. When studying four types of reservoirs on a property in the municipality of Quixeramobim, Ceará. Souza *et al.*[19] and Andrade *et al.*[20] reported that the highest forage biomass was obtained from the with the greater irrigable area. This produced 369,058.78 kg year^{-1} from 7.78 irrigable ha, compared to 97,500.00 kg year^{-1} from 2.05 irrigable ha.

Notably, the reservoirs have irrigation potential, producing a TFB ranging from 112,270 to 215,455 kg year^{-1} for irrigated areas and 3,497 to 4,810 kg year^{-1} for ephemeral wetland areas, with greater values estimated for lower guarantee levels (G90%), due the guarantee of 90% allows irrigating a greater area (Table 2). In all forage production areas, an increase in the TFB estimate was observed with the reduction in the guarantee level and, consequently, the property's carrying capacity was greater (Table 3).

Table 3. Production of total forage biomass (TFB) and carrying capacity (CC) in forage production areas at with different guarantee levels

Areas	G 99%	G 95%	G 90%	G 99%	G 95%	G 90%
	TFB (kg year^{-1})			CC (AU ha^{-1})		
Ephemeral wetlands area	3,497.00	4,382.00	4,810.00	0.50	0.60	0.70
Irrigable area	112,270.00	178,659.00	215,455.00	17.10	27.2	32.80
Mechanizable area	28,125.00	122,640.00	294,336.00	4.00	17.20	41.40
Native pasture area	110,114.00	157,305.00	277,906.00	7.70	11.10	19.50
TOTAL	254,006.00	462,985.00	792,506.00	29.30	56.10	94.40

The 90% guarantee level resulted in a 32% higher forage production compared to the 99% guarantee level, leading to a 31% greater CC when compared to the observed capacity for the greater guarantee level (Table 3). Lower guarantee levels, therefore, lead to higher forage production estimates, allowing for greater pasture CCs. The increased CC in mechanized areas is due to the higher estimated TFB, as CC is directly related to forage production[21;22]. The differences in TFB at various guarantee levels are significant, highlighting the importance of selecting an appropriate guarantee level for accurate production estimates and determining the area's CC.

The Figure 4 illustrates the response of forage production (Figure 4A), the contribution of each forage production area (Figure 4B), and the property's CC over the 40-year period (Figure 4C). Forage production from irrigated areas remained consistent throughout the simulation, as the volume extracted from the reservoirs was determined based on a 99% guarantee, ensuring efficient water supply for forage production 99% of the time (Figure 4A).

Interestingly, years with higher precipitation did not always correlate with greater TFB. This was particularly true for years with precipitation ranging from 600 to 800 mm (Figure 4A). The mean TFB was 117,016; 10,208; 432,493 and 510,997 kg DM year^{-1} for irrigable areas (99% guarantee), ephemeral wetlands areas, native pasture areas and mechanized areas, respectively, estimating a mean of 1,070,714 kg DM year^{-1}.

In years with lower precipitation, irrigable areas contributed more significantly to the TFB of the property (Figure 4B). This increased contribution is due to the storage of rainwater in reservoirs, which provides water for forage production during periods of low rainfall (Figure 4B). The contribution of each area to the property's forage production was as follows: 12.9; 1.1; 39.5 and 46.4% for irrigable areas, ephemeral wetlands areas, native pasture areas and mechanizable areas, respectively.

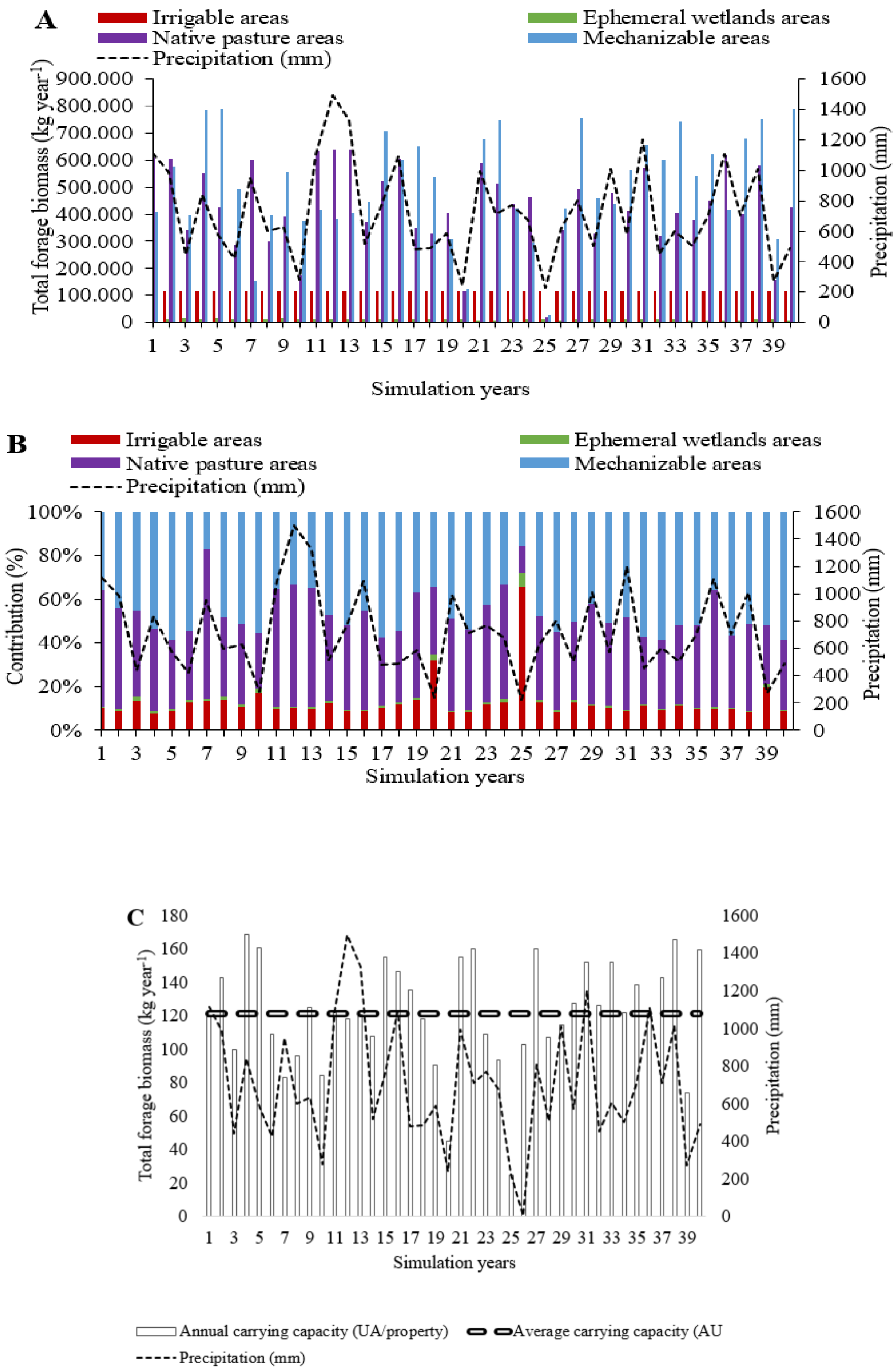

Figure 4. Forage production (A), contribution of forage production areas (B) and carrying capacity (C) over the simulated period.

The carrying capacity of the property ranged from 24.8 to 168.9 AU, with irrigable areas, ephemeral wetlands areas, native pasture areas and mechanizable areas contributing with 17.8; 1.4; 30.4 and 71.8% of the total, respectively.

4. Conclusion

The geostatistical data processing enabled the identification and differentiation of areas suitable for forage production and legal reserve areas on the property. The generation of maps facilitates more efficient planning and management of soil fertility. This hydrological study allows for the quantification of forage-producing areas, the estimation of the total forage biomass and the determination of the carrying capacity of the property, whose values vary with the guarantee level adopted.

Conflicts of interest statement

The authors declare no conflict of interest.

Data availability statement

Further information on the data and methodologies will be made available by the author for correspondence, as requested.

Author contribuitions

Conceptualization: R.G. Silva; M.J.D. Cândido. Data curation: R.G. Silva; E.R. Lima Junior. Formal analysis: E.R. Lima Junior; F.G.S. Alves. Investigation: E.R. Lima Junior; R.G. Silva. Methodology: E.R. Lima Junior; R.G. Silva. Funding acquisition: R.G. Silva; M.J.D. Project administration: M.J.D. Cândido. Validation and visualization: E.R. Lima Junior; F.G.S. Alves. Supervision: R.G. Silva; M.J.D. Cândido. Writing (original draft): E.R. Lima Junior; F.G.S. Alves. Writing (review & editing): R.G. Silva; M.J.D. Cândido; E.R. Lima Junior; F.G.S. Alves.

References

1. Antonini RC, Bortolotto RP, Zamberlan JF, Nora DD. Pasini MPB. Fiorin JE. Adoção e uso da agricultura de precisão na região das missões do Rio Grande do Sul. Holos. 2018;34(4):106-121. Available at: https://doi.org/10.15628/holos.2018.6297

2. Inamasu RY, Naime JM, Resende AV, Bassoi LH, Bernardi ACC. Agricultura de Precisão: um novo olhar. São Carlos: Embrapa Instrumentação, 2011. 334p. Available at: https://www.embrapa.br/busca-de-publicacoes/-/publicacao/916714/agricultura-de-precisao-um-novo-olhar

3. Bragagnolo J, Amado TJC, Nicoloso RS, Santi AL, Fiorin JE, Tabaldi F. Optical crop sensor for variable-rate nitrogen fertilization in corn: II - Indices of fertilizer efficiency and corn yield. Revista Brasileira de Ciência do Solo. 2013;37(5):1299-1309. Available at: https://doi.org/10.1590/S0100-06832013000500019

4. Alemaw G, Agegnehu G. Precision agriculture and the need to introduce in Ethiopia. Ethiopian Journal of Agricultural Science. 2019;29(3): 139–158. Available at: https://www.ajol.info/index.php/ejas/article/view/189563

5. Köppen W. Das geographische System der Klimate. In: Köppen W, Geiger R. Handbuch der Klimatologie, Berlin: Gebrüder Borntraeger; 1936. 44p.

6. Raij BV, Cantarella H, Quaggio JA, Furlani AMC. Recomendações de adubação e calagem para o Estado de São Paulo. 2.ed. Campinas: Instituto Agronômico; 1996. 285p.

7. Gamma Design Software. Geoestatistics for the environmental sciences. Version 5.1.1. Michigan, 2001. CD Rom.

8. Vieira SR, Hatfield JL, Nielsen DR, Biggar JW. Geostatistical theory and application to variability of some agronomical properties. Hilgardia. 1983;51:1-75. Available at: https://doi.org/10.3733/hilg.v51n03p075

9. Cambardella CA, Moorman TB, Novak JM, Parkin TB, Karlen DL, Turco RF, Konopka AE. Field-scale variability of soil properties in central Iowa soils. Soil Science Society of America Journal. 1994;58(5):1501-1511. Available at: https://doi.org/10.2136/sssaj1994.03615995005800050033x

10. Chow VT, Maidment DR, Mays LW. Hidrologia aplicada. Santafé de Bogotá: McGrawHill; 1994. 584p.

11. Penman HL. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences. 1948;193(1032):120-145. Available at: https://doi.org/10.1098/rspa.1948.0037

12. FUNCEME - Fundação Cearense de meteorologia e Recursos Hídricos. 2013. Disponível em: <http://www.funceme.br> Acesso em 01/02/2014.

13. Dantas Neto JD, Silva FAZ, Furtado DA, Matos JA. Influência da precipitação e idade da planta na produção e composição química do capim-buffel. Pesquisa Agropecuária Brasileira. 2000;35(9): 1867-1874. Available at: https://doi.org/10.1590/S0100-204X2000000900020

14. Araújo Filho JA, Gadelha JA, Crispim SMA, Silva NL. Pastoreiro misto em Caatinga manipulada no sertão cearense. Revista Cientifica de Produção Animal. 2002:4(1-2):9-21. Available at: https://periodicos.ufpb.br/index.php/rcpa/article/view/42662

15. Barbieri RS Unda SAB, Carrillo JEC, González AP, Montarani R. Spatial distribution of soil attributes in the region of El Oro, Ecuador. Colloquium Agrariae. 2020;16(4): 46-60. Available at: https://doi.org/10.5747/ca.2020.v16.n4.a382

16. Andrade ARS, Guerrini IA, Garcia CJB, Katez I, Guerra HOC. Spatial variability of the soil density in the irrigation management. Ciência e Agrotecnologia. 2005;29(2):322-329, 2005. Available at: https://doi.org/10.1590/S1413-70542005000200008

17. Dalchiavon FC, Rodrigues AR, Lima ES, Lovera LH, Montanari R. Variabilidade espacial de atributos químicos do solo cultivado com soja sob plantio direto. Revista de Ciências Agroveterinárias. 2017;16(2):144-154. Available at: https://doi.org/10.5965/223811711622017144

18. Dalchiavon FC, Carvalho MP, Andreotti M, Montanari R. Variabilidade espacial de atributos da fertilidade de um latossolo vermelho distroférrico sob sistema plantio direto. Revista Ciência Agronômica. 2012;43(3):453-461. Available at: https://doi.org/10.1590/S1806-66902012000300006

19. Souza FLS, Nunes FES, Lima Junior ER, Silva RTN, Fontenele RM, Andrade AGM. Relação dos reservatórios e capacidade de suporte em área irrigável numa fazenda em Quixeramobim-CE. In: Aguilera JG, Zuffo AM. Ensaios nas ciências agrárias e ambientais. Ponta Grossa: Atena editora; 2019. p. 152-157. Available at: https://atenaeditora.com.br/catalogo/post/relacao-dos-reservatorios-e-capacidade-de-suporte-em-area-irrigavel-numa-fazenda-em-quixeramobim-ce

20. Andrade AGM, Fontenele RM, Nunes FES, Lima Junior ER, Silva RTN, Souza FLS. Relação dos reservatórios utilizando garantias de uso de água para irrigação numa fazenda em Quixeramobim-CE. In: Aguilera JG, Zuffo AM. Ciências agrárias: campo promissor em pesquisa. Ponta Grossa: Atena editora; 2019. p. 152-157. Available at: https://atenaeditora.com.br/catalogo/post/relacao-dos-reservatorios-utilizando-garantias-de-uso-de-agua-para-irrigacao-numa-fazenda-em-quixeramobim-ce

21. Bernardino FS, Tonucci RG, Garcia R, Neves JCL, Rocha GC. Forage yield and performance of beef steers in a silvopastoral system: effects of forage offers and nitrogen fertilization. Revista Brasileira de Zootecnia. 2011;40(7):1412-1419. Available at: https://doi.org/10.1590/S1516-35982011000700003

22. Silva RG, Lopes MN, Araujo JC, Neiva JNM, Candido MJD. Orçamentação forrageira de longo prazo no semiárido. Revista Cientifica de Produção Animal. 2013;15(2):98-110. Available at: https://10.15528/2176-4158/rcpa.v15n2p98-110