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Drivers of degradation of pastures in the Cerrado north of Minas Gerais - BR

Vetores de degradação das pastagens no Cerrado norte mineiro – Minas Gerais - BR

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Abstract

The Brazilian Cerrado Biome is a strategic region for livestock, with a high concentration of pastures and cattle. Approximately 30% of these pastures have some degree of degradation, especially in semi-arid regions. The northern region of the state of Minas Gerais portrays this context well. Therefore, identifying the degradation vectors is a fundamental step in agro-environmental planning. This study aims to develop a model to evaluate the vectors of degradation of pastures in Cerrado north of Minas Gerais. The methodological structure was based on i) mapping of the pasture degradation index (PDI) using remote sensing techniques, ii) setting up a database with predictive variables representing socioeconomic, relief and climatic aspects, and iii) elaboration of a model to evaluate the vectors of pasture degradation with multiple linear regression. The PDI mapping showed that the pastures in all municipalities present some degree of degradation. Eighteen municipalities (21%) have moderately degraded pastures and 66 municipalities (79%) predominantly have pastures with mild degradation levels. According to the statistical model, the degradation of pastures is explained by climatic vectors, specifically by air temperature, seasonality of precipitation and annual precipitation ($R^2 = 0.50$, p-value < 0.001). The management of pastures in the region must consider these environmental factors, aiming at a more sustainable livestock in the Cerrado of northern Minas Gerais.

Keywords:
Remote sensing, degradation index of pastures, Savannah.

Resumo

O Cerrado é o bioma brasileiro é uma região estratégica para a pecuária, com alta concentração de pastagens e rebanho bovino. Aproximadamente 30% das pastagens do Cerrado possuem algum grau

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de degradação, essencialmente em regiões semiáridas. O norte do estado de Minas Gerais retrata bem este contexto. Portanto, a identificação dos vetores de degradação é vital para o planejamento agroambiental. O objetivo desse trabalho foi elaborar um modelo para avaliação os vetores da degradação das pastagens no Cerrado norte mineiro. A estrutura metodológica foi baseada em: I) mapeamento do índice de degradação de pastagens (IDP) por meio de técnicas de sensoriamento remoto, II) montagem de um banco de dados com variáveis preditoras representando os aspectos socioeconômicos, de relevo e climáticos, e III) elaboração de um modelo para avaliação dos vetores da degradação das pastagens com regressão linear múltipla. O mapeamento de IDP mostrou que todos os municípios do Cerrado norte mineiro apresentam algum grau de degradação. Dezoito municípios (21%) possui pasto moderadamente degradados e 66 (79%) com níveis leves. O modelo elaborado mostrou que a degradação das pastagens no norte de Minas Gerais pode ser explicada por vetores climáticos, especificamente por temperatura do ar, sazonalidade da precipitação e precipitação anual (R^2 = 0.50, valor-p < 0.001). O manejo das pastagens na região deve considerar esses aspectos ambientais, objetivando uma pecuária mais sustentável no Cerrado norte mineiro.
Palavras-chave:
Sensoriamento remoto, índice de degradação de pastagens, Savana.

I. INTRODUCTION

Brazil is the second-largest beef producer and meat exporter in the world, with the Cerrado biome being its main area of production, housing approximately 44% (~75 million animals) of the country's livestock (SANTOS et al., 2022). The Cerrado is strategically important for Brazilian livestock due to its favorable edaphoclimatic conditions (PEREIRA et al., 2018). However, livestock productivity in the Cerrado is low, primarily because of the extensive use of land required to maintain cattle herds (PARENTE et al., 2019; ZALLES et al., 2021). The expansion of pastures in the Cerrado has been unplanned and poorly managed, resulting in increased pasture degradation and the decline of grass supply for livestock (SANTOS et al., 2022). Studies have indicated that around 30% of pastures in this biome show some degree of degradation (AGUIAR et al., 2017; PEREIRA et al., 2018; PARENTE et al., 2019; VELOSO et al., 2020; SILVA et al., 2022).

Pasture degradation can be caused by natural factors, as well as by socioeconomic and management aspects (SANTANA SANTOS; GUIMARÃES, 2017; PEREIRA et al., 2018). The topography influences the distribution of pastures, with flat areas undergoing more intense use and seeing a higher occurrence of degradation. Areas with steep slopes are more susceptible to erosion, weakening the sustainability of pastures (SANTANA SANTOS; GUIMARÃES FERREIRA, 2017). Additionally, the orientation of the relief face impacts pasture quality, as North-facing slopes receive higher solar radiation levels, affecting soil moisture levels (SOUZA et al., 2019). Climatic variables like precipitation and temperature also play a crucial role in pasture quality (SLOAT et al., 2018; VELOSO et al., 2020). Under extreme conditions of high temperatures and water scarcity,

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the photosynthetic activity of pastures is expected to decrease, leading to a sharp reduction in biomass levels (PFEIFFER et al., 2019). Furthermore, the socioeconomic aspect — particularly rural poverty — directly affects the producer's ability to invest in improving pasture conditions (PEREIRA et al., 2018).

Although the primary vectors of pasture degradation are known, studies have focused on isolated analyses thus far (PEREIRA et al., 2018; STANIMIROVA et al., 2019). However, a proper assessment of pasture degradation requires the integration of multiple variables, especially in environments of high physical and social heterogeneity like the Brazilian Cerrado. The northern region of Minas Gerais is one of the most heterogeneous areas of the Cerrado, characterized by distinct climatic seasonality, diverse relief, and transitions between different vegetation types (SILVA, 2016; COSTA, 2021).

The use of multiple linear regression models has been suggested as a suitable approach for such heterogeneous socio-environmental conditions (ESPINDOLA et al., 2021; RIGHI et al., 2023). Nonetheless, few studies have applied statistical methods to understand pasture degradation patterns in the Cerrado (PEREIRA et al., 2018). The use of modeling through multiple linear regressions can be essential for a more sustainable agriculture. It offers decision-makers a comprehensible model to understand the effects of predictor variables on a specific dependent variable. This study aims to develop a multiple linear regression model to identify the main vectors influencing pasture degradation in the northern region of the Cerrado in Minas Gerais.

II. MATERIALS AND METHODS

Study area

The analyzed pastures are in the North portion of the state of Minas Gerais, between coordinates 14° 32' and 17° 38' of latitude, and 45° 37' and 41° 29' of longitude (Figure 1c, d). There are 89 municipalities in the region, 84 of which are located on the edge of the Cerrado, the predominant biome in the region. Pastures (especially brachiaria) are the land activity with the greatest territorial expression, at around 23% (SILVA et al., 2022).

The Aw type climate and the transition to Bsh type is predominant in the region (SÁ JÚNIOR et al., 2012), and seasons are well-defined, wet (April–September) and dry (October–March). Precipitation is unevenly distributed, with an amplitude of ~1000 mm/year. The areas with lower precipitation (< 925 mm/year) are located mostly in the extreme North, where the air temperature presents higher figures (24–25°C) (FICK;

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HIJMANS, 2017). Furthermore, the study area is a zone of transition with the Caatinga biome, in a semi-arid climate.

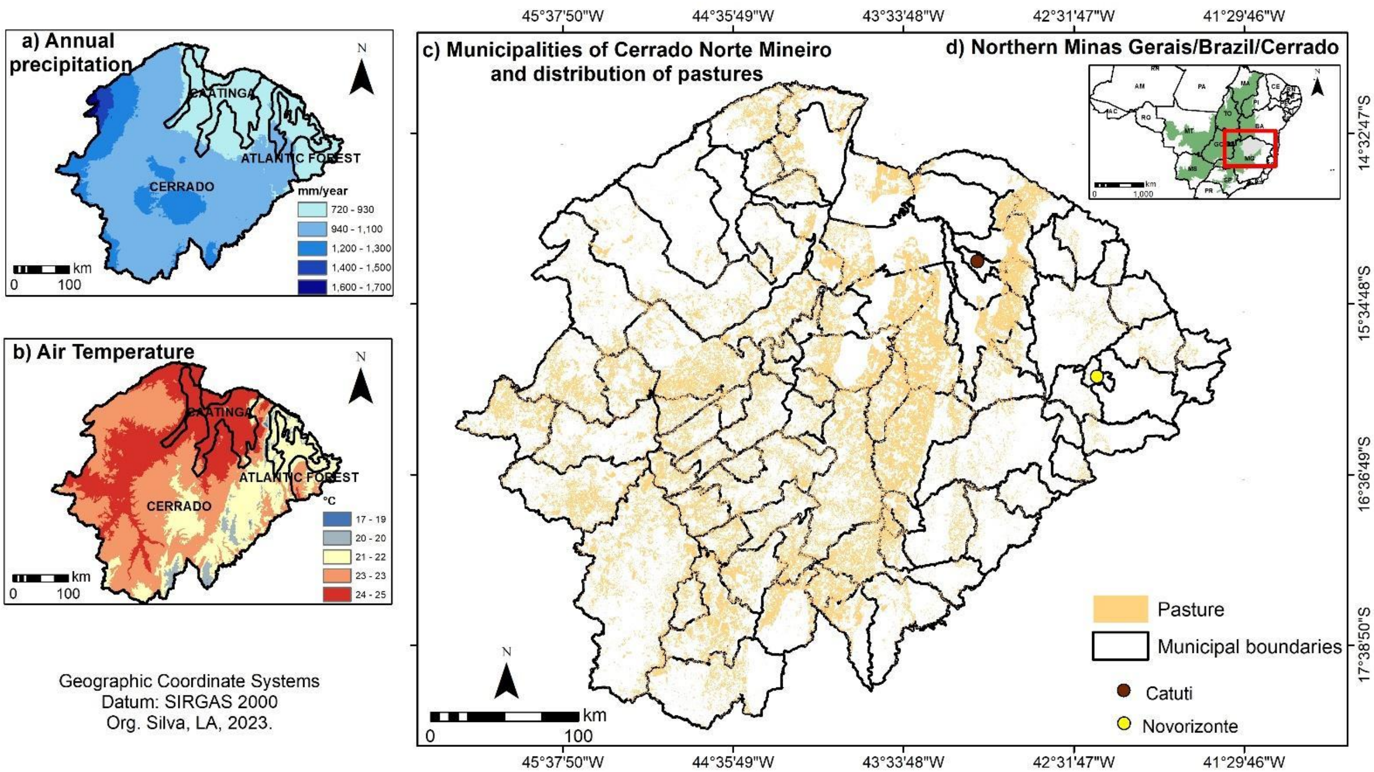

Figure 1 - Location of the study area. a) Annual precipitation (1970–2000); b) Average air temperature (1970–2000); c) Municipalities of the northern Cerrado in Minas Gerais and pasture distribution; d) Location of northern Minas Gerais in the southeastern portion of Brazil and the eastern Cerrado. The red dot indicates the municipality of Catuti, holding the highest PDI value, while the yellow dot points at Novorizonte, with the lowest PDI for the analyzed period.

Data base

The database was structured considering the limits of pastures in the Cerrado North of Minas Gerais. Normalized Difference Vegetation Index (NDVI) data was utilized for pasture degradation mapping, as well as a set of predictive variables of relief, climatic and socioeconomic factors. The boundaries of the pastures were determined by the Image Processing and Geoprocessing Laboratory (LAPIG) of the Federal University of Goiás (UFG) (LAPIG, 2019). This map defines boundaries of Brazilian pastures based on the Machine Learning algorithms of the Google Earth Engine platform. This resulting product is the most detailed map of pastures in Brazil, and it is freely available, with a spatial resolution of 30 m. The limit used in this study utilizes data from 2019.

Pasture degradation was mapped with MOD13Q1, a product of the Moderate-Resolution Imaging Spectroradiometer (MODIS) sensor, with a pass every 16 days and a spatial resolution of 250 m (DIDAN, 2015).

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MOD13Q1 calculates the photosynthetic capacity of vegetation using the Normalized Difference Vegetation Index (NDVI). For this analysis, 23 images from 2019 were used, covering all months of the year.

Relief data was obtained from the Digital Elevation Model (DEM) Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 90 m. Data on altitude, slope and standard deviation of slope was then extracted from the DEM. For the climate vectors, the variables of air temperature, annual precipitation and precipitation seasonality were collected, corresponding to a 30-year climatological normal (1970–2000), with a spatial resolution of 1 km (FICK; HIJMANS, 2017).

For socioeconomic factors, the Gross Domestic Product (GDP) and the Municipal Human Development Income Index (MHDII) were used. The GDP for 2018 was obtained from the municipal survey (SIDRA, 2018), while the MHDII was obtained from the 2010 demographic census (IBGE, 2010). All predictors were extracted and organized for the limits of the municipalities of the Cerrado North of Minas Gerais.

Mapping of Pasture Degradation

The mapping of pasture degradation was prepared using 23 NDVI images from 2019. The images were pre-processed through the removal of pixels with negative values. These pixels indicate the presence of shade and water; therefore, they do not represent the reality of the pastures. Subsequently, monthly averages were calculated from January to December using 2 images per month. All average images were compiled into an annual median image (SANTOS et al., 2022). The Pasture Vegetation Cover (PVC) was obtained from this image according to Equation 1 (OLIVEIRA et al., 2020; SANTOS et al., 2022):

$$PVC = \frac{NDVI - NDVImin}{NIVImax - NDVImin} \quad (1)$$

Where NDVImin is the lowest NDVI value in pasture areas, which are intended for areas with exposed soil matrix; NDVImax is the highest NDVI value, for areas with higher biomass content and high photosynthetic activity. Then, four classes of pasture degradation were stratified: Absent Degradation (PVC > 0.6), Light Degradation (PVC of 0.5 to 0.6), Moderate Degradation (PVC of 0.5 to 0.4) and Severe Degradation (PVC < 0.4).

The purpose of the study is to analyze the degradation of pastures at the municipal level. Therefore, the Pasture Degradation Index (PDI) was calculated for the municipalities in the Cerrado North of Minas Gerais, weighing the pasture area (km²) of the classes obtained from the PVC against the total pasture area in the municipality (Equation 2).

$$PDI = \frac{(A1*P1)+(A2*P2)+(A3*P3)+(A4*P4)}{analyzed\ pasture\ area} \quad (2)$$

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Where A1 is the class area of no degradation, A2 is an area of weak degradation, A3 is an area of moderate degradation and A4 is an area of severe degradation. P1, P2, P3 and P4 are the weights for each class, ranging from 1 to 4 (ANDRADE et al., 2013). Obtaining the PDI by municipality enables the evaluation of the figures through a multiple linear regression.

Statistical Analysis: Selection of Pasture Degradation Vectors

The PDI data (dependent variable) and the predictor variables were placed in a regression matrix to carry out the statistical analyses. Correlation analysis was applied to this matrix in order to remove predictors with redundant information. The chosen correlation cutoff was the Pearson method, using a threshold > 0.75. After removing variables with r above 0.75, a multiple linear regression model was set up from the remaining predictors. In this model, the degree of multicollinearity was evaluated using the variance inflation factor (VIF). Values < 5 indicate low multicollinearity (ALIN, 2010), not affecting the interpretability of the model.

Finally, a procedure called stepwise was employed. The premise of this process is that the regression model is adjusted considering all predictor variables, and from the F-test with p-value < 0.05, the less important variables (p-value > 0.05) are removed from the model (MASS package) (RIPLEY et al., 2013). The final adjustment of the modeling was carried out with all the significant variables (p-value < 0.05) of the first stage and chosen from the Akaike information criterion (AIC) (AKAIKE, 1974). With the most important variables in the final model, a simple regression against the PDI was applied to identify the target-to-target linear behavior. All statistical procedures were performed in the R software (R core Team, 2022).

III. Results

Pasture Index Degradation

All municipalities in the Cerrado North of Minas Gerais showed some degree of pasture degradation (Figure 2a). Approximately 21% of the municipalities declined, while ~79% had slightly degraded pastures. The extreme North of the region had the municipalities with the highest PDI, with Catuti having the absolute highest, at 2.97 (Figure 2). This region is marked by the presence of the Cerrado/Caatinga transition zone, an area of semi-arid climate (SILVA et al., 2021). This range has high temperatures (above 23°C), low volume of rainfall (less than 908 mm/year) and greater seasonal variations in precipitation.

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The municipality with the least degraded pastures was Novorizonte (1.07), in the eastern portion of the region (Figures 1 and 2). This region is characterized by lower temperatures (20°C) and greater water availability, with a precipitation volume above 1000 mm/year.

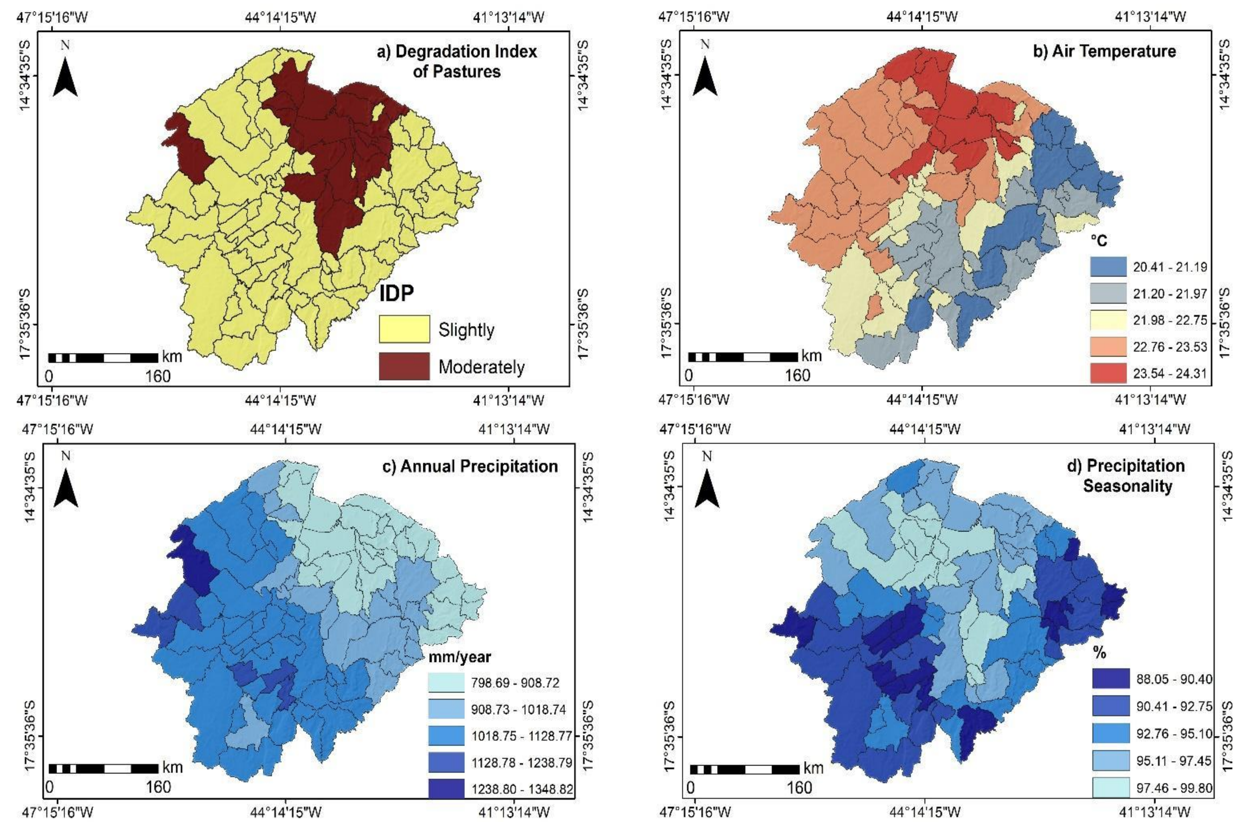

Figure 2 - Spatial distribution of a) Pasture Degradation Index (PDI) for the Cerrado North in Minas Gerais throughout 2019; b) air temperature (1970–2000); c) annual precipitation (1970–2000); d) seasonality of precipitation (1970–2000).

Pasture Degradation Vectors Selected by Multiple Linear Regression

The multiple linear regression model selected by the AIC showed that 50% of pasture degradation in the Cerrado North of Minas Gerais ($R^2 = 0.50$, p-value = < 0.001) was explained significantly (p-value = ≤ 0.01) by climatic variables. The variables were air temperature, annual precipitation and seasonality of precipitation (Figure 3 and Table 1). Among the climatic variables, air temperature and precipitation seasonality showed a linear behavior along pasture degradation (Figure 4). Therefore, the high temperatures and seasonality of rainfall distribution indicate high degrees of pasture degradation. On the other hand, precipitation showed an inverse pattern, as areas with higher precipitation maintain higher quality pastures.

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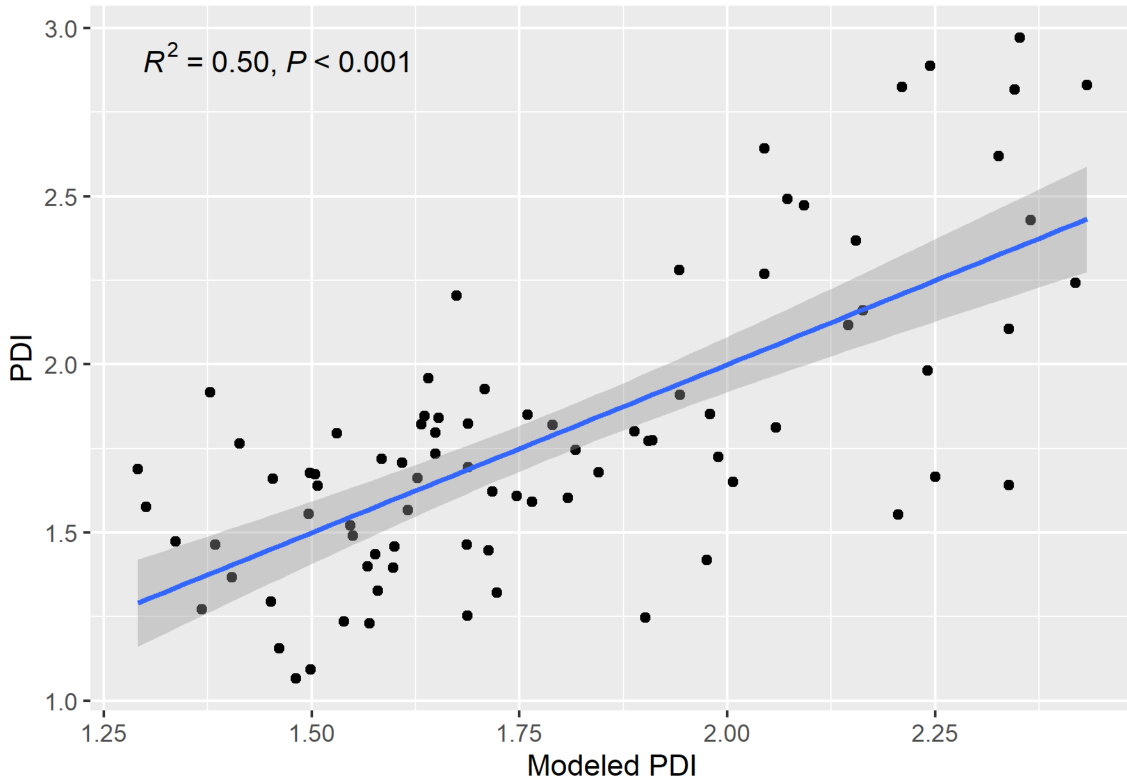

Figure 3 - Scatter plot showing the modeled and observed Pasture Degradation Index (PDI) values (R^2 = 0.50; p-value < 0.001; Shapiro-Wilk W = 0.99; and p-value = 0.63).

Table 1 – Parameters of the multiple linear regression model with the predictor variables selected by the AIC. F = test F; t = test statistics; p-value = probability of significance. F = 26.32.

	Estimated	Standard error	AIC	F	t	p-value
(Intercept)	-4.954	1.261			-3.930	<0.001
Air Temperature	0.193	0.038	-168.180	26.219	5.120	<0.001
Annual Precipitation	-0.001	0.000	-185.370	6.560	-2.561	0.01
Precipitation seasonality	0.034	0.013	-185.170	6.766	2.601	0.01

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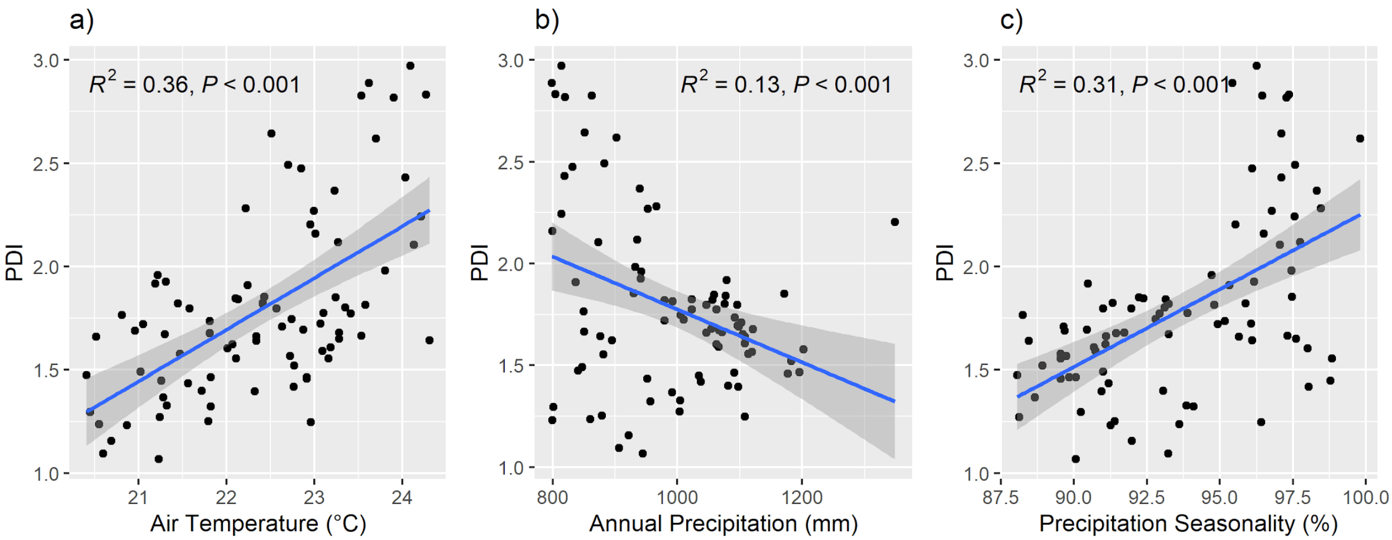

Figure 4 - Simple linear relationship between the most important predictor variables in the multiple linear regression model and the pasture degradation index (PDI) (air temperature, annual precipitation and precipitation seasonality).

IV. Discussion

Pasture Degradation Vectors in the North Cerrado of Minas Gerais

Pastures in the northern region of Minas Gerais show some degree of degradation, varying between light and moderate degradation. The results of this study are in line with research carried out in the Brazilian Cerrado, which pointed to the northern portion of the state of Minas Gerais as one of the pasture degradation hotspots (AGUIAR et al., 2017; PEREIRA et al., 2018; SANTOS et al., 2022). Natural characteristics of the northern region of Minas may lead to a predisposition to degradation of pastures. The climatic conditions of lower water availability and higher temperature are vectors that affect pasture conditions (FERNANDES et al., 2018). This explains the selection of climate predictors by the multiple linear regression model (Table 1, Figure 4).

The predictors selected by the regression model represent the edaphoclimatic conditions for the phenological development of pastures (SLOAT et al., 2018; VELOSO et al., 2020; SILVA et al., 2022). In regions of low rainfall and greater seasonal variability, pasture biomass levels decrease due to water restrictions (CLEMENTINI et al., 2020). Under these conditions, the rate of carbon assimilation by photosynthesis gradually decreases. At the same time, the higher temperature also affects the phenological and structural behavior of pastures, with an increase of potential evapotranspiration and aridity of the environment (HABERMANN et al., 2019).

Despite the non-selection of socioeconomic predictors in the regression model (Figures 3 and 4), studies in the Cerrado area showed evidence of a statistical correlation between degraded pastures and the human

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development index. The lack of access to technology or lines of credit, paired with a low investment capacity in pasture improvement are vectors that contribute to the maintenance of degraded pastures (PEREIRA et al., 2018; SANTOS et al., 2022). This situation contributes to worsen the social situation of the region, being one of the poorest in the state of Minas Gerais (IBGE, 2010).

Environmental Implications of Pasture Degradation

Pasture degradation in the Cerrado presents serious environmental implications that affect several factors. Studies have pointed to a significant increase in soil loss by erosion, as well as a change in the dynamics of CO_2 emissions and an intensification of soil surface temperature.

Regarding the soil, predictive scenarios showed that degraded pastures drive soil losses (GALDINO et al., 2016). Studies carried out in the Cerrado of northern Minas Gerais support this conclusion, indicating continuous losses of over 45 Mg of soil in degraded pastures (OLIVEIRA; LEITE, 2018). These excessive soil losses, in turn, lead to the silt up of rivers, damaging water quality (SPERANDIO et al., 2012). This situation generates socio-environmental conflicts over the use of this resource in the region (SALIS et al., 2017). Over the last two decades, the North region of Minas has originated 33% of land conflicts registered in the state of Minas Gerais (FERREIRA et al., 2020), which reflects the harshness of the scenario.

The increase of CO_2 emissions is also expected with pasture degradation (ROSA; SANO; ROSENDO, 2014; SANTOS et al., 2023). This situation is more sensitive in the climatic conditions of the northern region of Minas. Semi-arid climate conditions with low precipitation and high temperature (Figure 2) are aspects capable of inducing aridity and affecting the quality of pastures. Studies show that pastures in the North of Minas Gerais present lower carbon fixation rates precisely in the Cerrado/Caatinga transition region (SILVA et al., 2022), which has semi-arid characteristics. Therefore, the results suggest that the municipalities of the Cerrado in the North of Minas Gerais can be considered a source of CO_2 emissions on a regional scale.

The expansion of pastures in the Cerrado North of Minas Gerais generally occurs due to the replacement of native vegetation of forests and savannahs (LEITE; SOUZA; SILVA, 2022). This conversion is pointed out in studies as one of the main degradation vectors of the Cerrado. The use of land as pastures increases the surface temperature, especially in some stage of degradation (SAMPAIO et al., 2007; FERREIRA et al., 2013). This situation is exacerbated in the North of Minas Gerais due to regional climatic conditions, mainly in areas with less precipitation (Figure 2).

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To minimize the impacts of pasture degradation on soil loss, CO_2 emissions and surface temperature in the Cerrado of northern Minas Gerais, it is essential to make both public and private investments in management plans aimed at improving the biomass levels of these pastures. Several studies have proven the benefits of well-managed pastures, with high levels of biomass, in mitigating these problems.

According to the relevant literature, well-managed pastures can significantly reduce the flow of sediments (GALDINO et al., 2016), in addition to maintaining carbon stocks in the soil comparable to those found in native vegetation (BRAZ et al., 2013; ROSA; SANO; ROSENDO, 2014). Therefore, they contribute to providing adequate humidity rates for the atmosphere by inducing surface wetting (ANDRADE et al., 2016). Therefore, the implementation of efficient management practices that lead to an increase in pasture biomass not only benefits soil conservation, reducing CO_2 emissions and surface temperature, but also contributes to the preservation of biodiversity and water resources in the region.

V. Conclusions

The results of this study showed that the pastures of all municipalities in the North region of Minas present some degree of degradation. 21% (18 municipalities) show moderate levels and 79% (66 municipalities) have slightly degraded pastures. In terms of implications, if pastures are not improved, economic and ecosystem losses can be intensified in the region.

The multiple linear regression model applied to evaluate the main vectors of pasture degradation showed that pasture quality is influenced by natural factors. The vectors that lead to a predisposition to degradation of pastures were climatic predictors, such as air temperature, seasonality of precipitation and annual precipitation. These predictors were more significant in explaining degradation levels, resulting in an R^2 of 0.50 (p-value < 0.001).

The integration of remote sensing techniques and statistics as the methodological structure of this work was essential, as it allowed the authors to observe spatial variations in pasture degradation levels and explain the main vectors. Therefore, the replication of this methodology with other regions is possible, mainly due to the ease of obtaining secondary data, and to the use of tools available in open source software.

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