Grassland Degradation Estimates through Field Data in the state of Goiás, Brazil

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Abstract

Grasslands play a critical role in global food security, biodiversity, and ecosystem services, particularly in tropical regions where they serve as the primary base for livestock production. However, grasslands are increasingly vulnerable to degradation due to poor management practices such as the Cerrado biome in Brazil. This study focuses on grasslands in Goiás, a state located in central-western Brazil, which relies heavily on pastures for its agricultural economy. We present a comprehensive field-based assessment of grassland degradation in Goiás, aiming to estimate pasture degradation area according to three categories: non-degraded, in process of degradation, and severely degraded. A three-stage cluster sampling design was employed to evaluate 460 field points, incorporating visual assessments of key variables using a novel Pasture Assessment Score (PAS) system developed specifically for this study. The scores were analyzed using Multiple Correspondence Analysis (MCA) to reduce dimensionality and identify clusters corresponding to degradation levels. Monte Carlo simulations were used to estimate confidence intervals for each degradation class, with standard errors ranging from 3.1% to 4.5%. The results revealed that 39.35% of the pasture area in Goiás was classified as non-degraded, 31.98% as being in process of degradation, and 28.67% as severely degraded. This study highlights the need for targeted management interventions and improved monitoring frameworks to mitigate grassland degradation. Future works should focus on integrating field data with satellite-derived indices to improve mapping accuracy, and enable large-scale, high-frequency monitoring and detection of early-stage degradation for more effective land management strategies.

RESEARCH ARTICLE

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Abstract

Grasslands play a critical role in global food security, biodiversity, and ecosystem services, particularly in tropical regions where they serve as the primary base for livestock production. However, grasslands are increasingly vulnerable to degradation due to poor management practices such as the Cerrado biome in Brazil. This study focuses on grasslands in Goiás, a state located in central-western Brazil, which relies heavily on pastures for its agricultural economy. We present a comprehensive field-based assessment of grassland degradation in Goiás, aiming to estimate pasture degradation area according to three categories: non-degraded, in process of degradation, and severely degraded. A three-stage cluster sampling design was employed to evaluate 460 field points, incorporating visual assessments of key variables using a novel Pasture Assessment Score (PAS) system developed specifically for this study. The scores were analyzed using Multiple Correspondence Analysis (MCA) to reduce dimensionality and identify clusters corresponding to degradation levels. Monte Carlo simulations were used to estimate confidence intervals for each degradation class, with standard errors ranging from 3.1% to 4.5%. The results revealed that 39.35% of the pasture area in Goiás was classified as non-degraded, 31.98% as being in process of degradation, and 28.67% as severely degraded. This study highlights the need for targeted management interventions and improved monitoring frameworks to mitigate grassland degradation. Future works should focus on integrating field data with satellite-derived indices to improve mapping accuracy, and enable large-scale, high-frequency monitoring and detection of early-stage degradation for more effective land management strategies.

KEYWORDS

Cerrado — forage production — land degradation — pasture management — pasturelands — visual scores

1 | INTRODUCTION

Grasslands are among the most extensive terrestrial ecosystems, covering approximately 40% of the Earth's land surface (Blair et al., 2014; Eze et al., 2018) and providing critical ecosystem services, including carbon sequestration, water regulation, and habitat for a diverse array of plant and animal species (Parente et al, 2024; Parr et al., 2014; Grace et al., 2006). Their global importance is further underscored by their role in supporting food security, as they form the backbone of livestock production, supplying forage for nearly 1.3 billion people worldwide (Blair et al., 2014; FAO, 2021). Despite their ecological and economic significance, grasslands are often overlooked in land management and conservation policies, making them highly vulnerable to degradation (Bardgett et. al, 2021). Continuous pressure to increase productivity and lack of proper management leads to soil degradation, biodiversity loss, and reduced forage availability (Bardgett et. al, 2021; Dias Filho, 2015). Tropical grasslands, in particular, play a significant role in the global food supply (Boval and Dixon, 2012). Regions such as the Brazilian Cerrado face increasing demands for livestock grazing (Dias et al. 2016), and understanding and mitigating degradation processes is essential to ensuring long-term sustainability. This study focuses on grasslands precisely because they are frequently neglected in broader environmental assessments, yet remain critical to global biodiversity, carbon storage, and food security.

The Cerrado biome, a biodiversity hotspot and vital water source, spans central Brazil, including Goiás, a key state in the country's agricultural sector. Goiás heavily relies on pasture-based livestock production, contributing significantly to national beef output. However, improper management and low soil fertility have heightened pasture degradation, posing ecological and economic risks. Brazilian tropical pastures, typically comprised of grasses and legumes for livestock grazing, are inherently diverse but often grow on soils that require nutrient replenishment due to their low natural fertility and rapid organic matter mineralization, which are further impacted by improper pasture management (Lopes et al., 2024). Characterizing these pastures is crucial for guiding appropriate management strategies that foster sustainable production systems, preserve environmental resources, and mitigate pasture degradation (Magalhães et al., 2020). This characterization often requires assessing both productive and qualitative aspects of pastures, which can be challenging and resource-intensive.

Pasture degradation in Goias is primarily driven by a combination of overgrazing, inadequate nutrient replenishment, dominance of invasive plant species, which compete with forage grasses, reducing pasture productivity and livestock performance, and poor soil management. These processes lead to soil compaction, reduced forage productivity, biodiversity loss, and increased vulnerability to erosion. Over time, degraded pastures exhibit lower carrying capacity, directly impacting livestock production and the region's economy. This highlights the urgent need for thorough field assessments to better understand degradation patterns.

This study uses a detailed field-based approach to provide estimates of pasture degradation across Goias, Brazil. By presenting a comprehensive dataset on key variables influencing forage productivity and land health, it offers a robust foundation for understanding the extent of degraded areas and supporting targeted management and restoration strategies.

2 | METHODS

2.1 | Study Area

The study covers the entire state of Goias, Brazil, located in the central-western region and spanning 340,242.860 km2 (IBGE, 2023). Goias lies predominantly within the Cerrado biome, accounting for approximately 17% of the biome extent (IBGE, 2024). The target population includes all pasture areas in Goias, which occupies around 40.27% (over 13.7 million hectares) of the State area (Lapig, 2024). These pastures include both native and cultivated pastures (Figure 1).

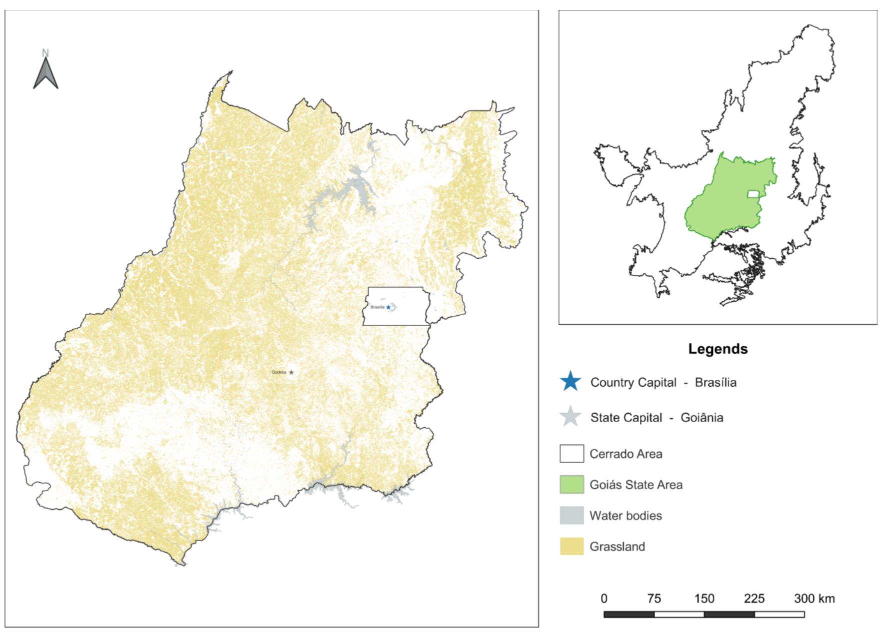


Figure 1. Study area showing the distribution of grasslands across the state of Goiás, Brazil, predominantly located within the Cerrado biome.

2.2 | Sampling Design

To obtain the final set of points that were visited and evaluated in the field, a cluster sampling approach was employed, structured into three distinct stages. The first stage involved a proportional and ordered systematic selection of primary units, defined as 100 x 100 km grids covering the state. The selection criteria are based on the proportion of pasture area within each grid.

In the second stage, a proportional and ordered systematic selection of secondary sampling units was conducted, represented by smaller grids of 10 x 10 km within the primary unit. The third stage involved a stratified, unbalanced selection of tertiary sampling units, defined by pixels (10 x 10 m) within the secondary unit. In this third stage, the tertiary units were selected from two strata: pixels within a buffer of no more than 250 m from any paved or unpaved road (buffer in) to avoid overly distant collections that would complicate access. In the second stratum, a smaller number of pixels, sampling points (SP), were chosen outside the 250 m road buffer (buffer out) to reduce biases of sampling points too close to roads where pastures are typically better managed (Figure 2). Additional random sampling was conducted from the pixels selected in the third stage to identify locations for soil and pasture sample collection. Methods for determining sample size and precision are available in Supplementary Material 2.

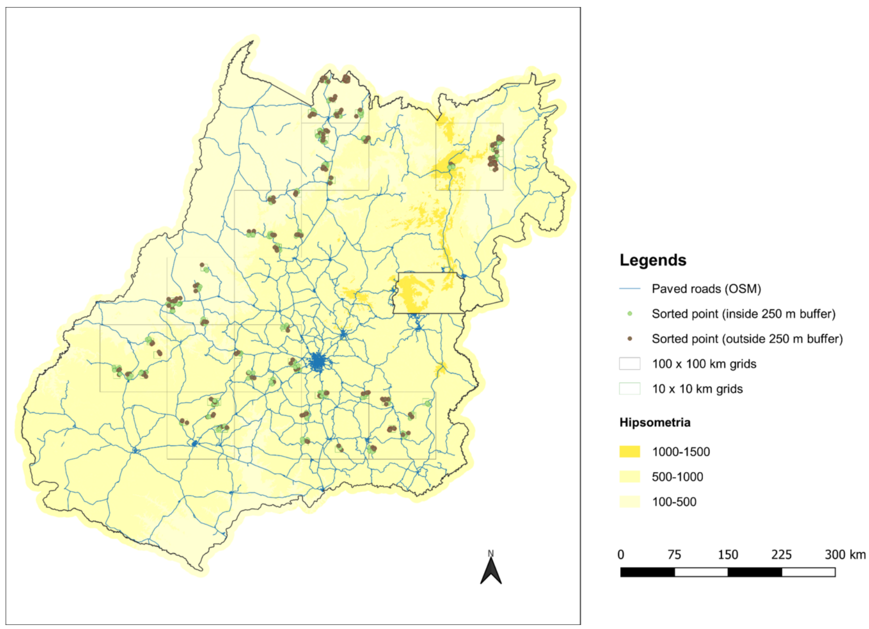


Figure 2. Sample design with 10 primary units (100 x 100 km) distributed within the state of Goiás, demarcated by square grids, and within each primary unit, six secondary units in smaller grids (10 x 10 km) with clustered colored circles where the tertiary units (pixels) were located.

2.3 | Field Protocol

The fieldwork in the state of Goiás was conducted within the framework of the MapBiomas initiative. The field campaigns were coordinated by the Remote Sensing and Geoprocessing Laboratory at UFG (LAPIG/UFG) in partnership with the School of Veterinary and Animal Science (EVZ/UFG) and the Forage Study Group (GEFOR/UFG). Data collection for the evaluation and characterization of pastures in Goiás occurred from January to May 2022.

For the fieldwork, teams were trained to systematically evaluate pastures following a field protocol that includes visual assessments of grassland using scoring, as well as forage and soil sample collection, drone imagery, and photos of the pastures. The sampling area (SA), sized at 900 m^2 within the pasture, was marked with the sampling point (SP) at its center, located by GPS.

The fieldwork in Goiás resulted in the assessment of 460 pasture points across the state. Within all visited points pasture productivity and degradation were assessed visually through the evaluation of different parameters. Forage samples were also collected from 136 points, and soil samples were taken from 115. Bromatological analysis was conducted on all collected forage samples, along with physical-chemical analyses of the soil samples. The pastures assessed through visual scoring were later classified into three degradation classes: 1) non-degraded (ND); 2) in process of degradation (PD); and 3) severely degraded (SD).

2.3.1 | Pasture Assessment Scores

Pasture Assessment Scores (PAS) used in this study were specifically developed to provide a rapid visual evaluation of pasture conditions without requiring destructive sample collection. Inspired by earlier methods described by Morley et al. (1964) that were later adapted by Campbell and Arnold (1973), the scoring system applied here is novel, with unique parameters designed to address the specific challenges of assessing large areas of tropical pastures. Using a 1-to-7 scale (Norman, 2010; Likert, 1932; Likert, 2010), three to four independent observers assigned scores at each sampling point to evaluate key variables related to pasture productivity and degradation, including 1) plant development stage (DV), 2) weed coverage (WC), 3) termites incidence (TI), 4) soil coverage (SC), 5) forage availability (FA), 6) green leaves availability (GLA), 7) pasture current condition (PC), 8) productive potential (PP), 9) pasture degradation (DG); and 10) management effectiveness (MN).

This tailored scoring approach provides a comprehensive framework for identifying degradation severity and estimating pasture productivity over a 12-month period. Lower scores generally indicate degraded conditions (except for DV, WD, and TI), while higher scores reflect well-managed pastures with high productivity and minimal degradation.

Designed for consistent *in situ* application, this scoring system enables timely and reliable pasture assessments, independent of seasonality or specific management techniques. A detailed description of the parameters and scoring criteria is available in Supplementary Material 1.

2.4 | Grassland Degradation Classification

Multiple Correspondence Analysis (MCA) was employed to examine associations among categorical variables, revealing structural patterns within the dataset. This method enables the projection of data points and variable categories into a lower-dimensional space (typically two or three dimensions), facilitating both visual interpretation and analytical insights (Figure 3). This analysis was chosen due to its suitability for handling categorical data, such as the scores assigned to different parameters during field assessments. MCA reduces the dimensionality of the dataset by summarizing the information contained in multiple categorical variables into a few principal dimensions, which capture the major patterns of variation in the data (Greenacre, 2017; Le Roux and Rouanet, 2010).

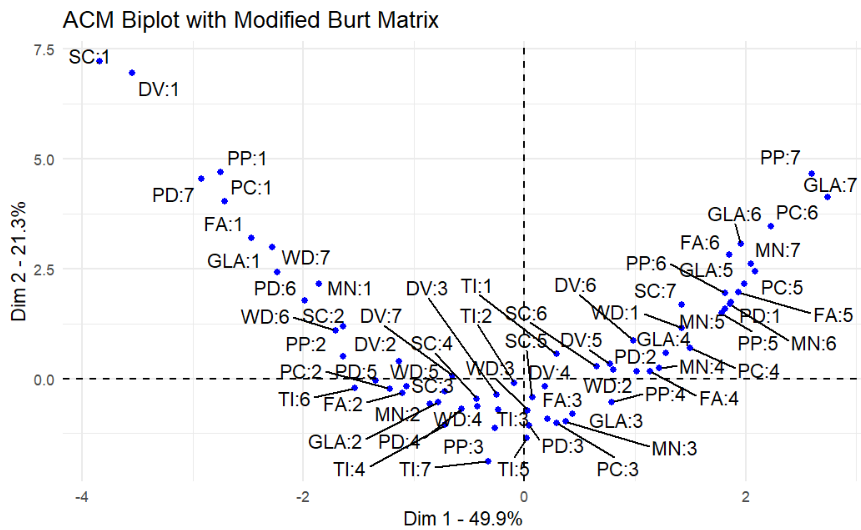


Figure 3. MCA Biplot of Grassland PAS using modified Burt Matrix, displaying the two main dimensions (Dim 1 and Dim 2) explaining 71.2% of the total inertia.

The input data consisted of individual evaluators' Pasture Assessment Scores (PAS) assigned at each SP for the various pasture productivity parameters described earlier. A Burt matrix was generated to represent all pairwise cross-tabulations of these variables, which served as the basis for the MCA computation. The analysis was conducted using the*mjca()* function from the *ca* package in R, and the results were visualized using the ggplot2 package to produce a biplot that displays the relationships between the score variables, where each score category is represented as a separate variable in the principal dimensions. The first two principal dimensions of the variables, which combined explained 71.2% of the total inertia (49.9% by Dim 1 and 21.3% by Dim 2), were retained for further analysis, as they captured the most significant patterns in the data. In Figure 4, it is possible to observe the ten variables that contribute the most percentage-wise in the first two principal dimensions and the sign of the weight in the coordinates.

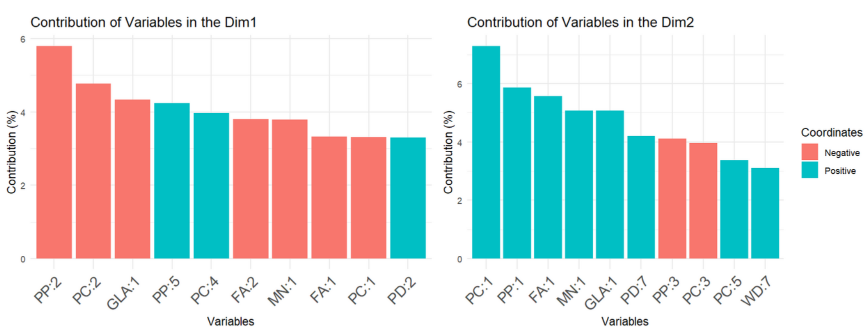


Figure 4. Ten variables that contribute the most percentage-wise in the principal dimensions Dim1 (left) and Dim2 (right), and the sign of the weight: positive (green) and negative (red) in the coordinates.

Considering the first two main dimensions, the variables were grouped based on their proximity in the reduced-dimensional space, with closer variables indicating similar pasture conditions. A hierarchical cluster analysis was then performed using the two principal dimensions. The categories of the variables, represented as coordinate pairs in this space, were grouped using Ward's method to identify structural patterns in the data (Ward, 1963). The resulting dendrogram illustrates the clustering process, identifying six distinct groups at a defined height threshold, as indicated by the dashed boxes (Figure 5). The six clusters identified in the hierarchical cluster analysis dendrogram were determined as the optimal number of clusters according to the gap statistic method (Tibshirani, Walther, and Hastie, 2001).

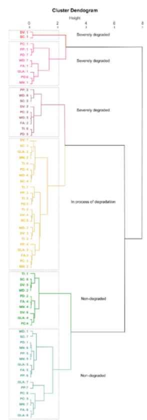
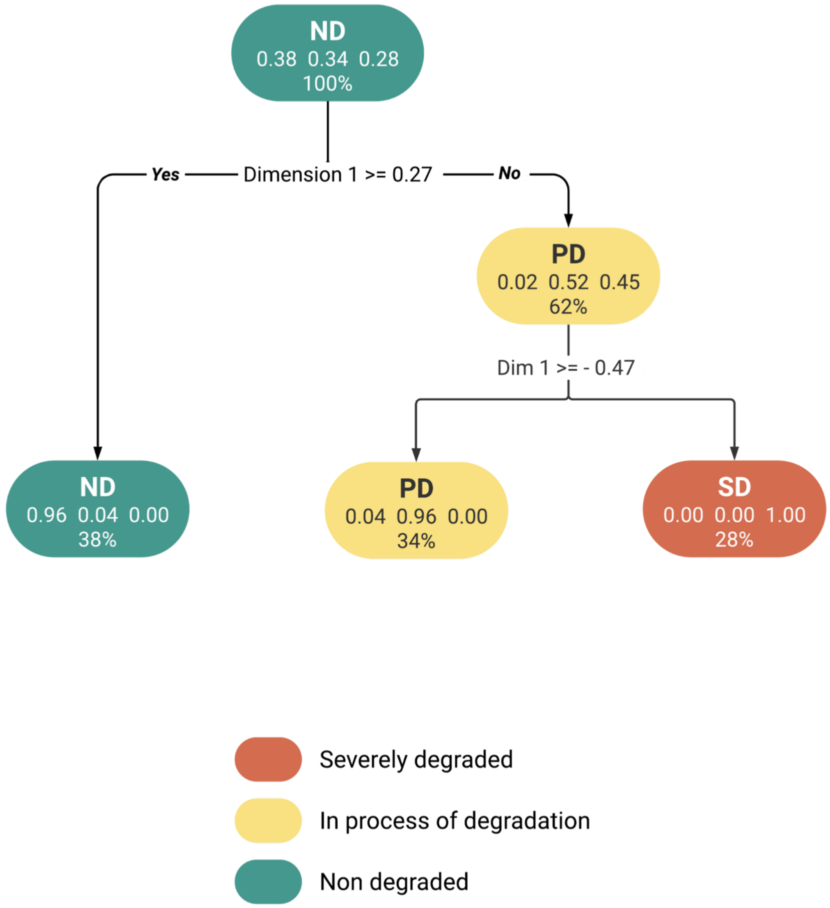


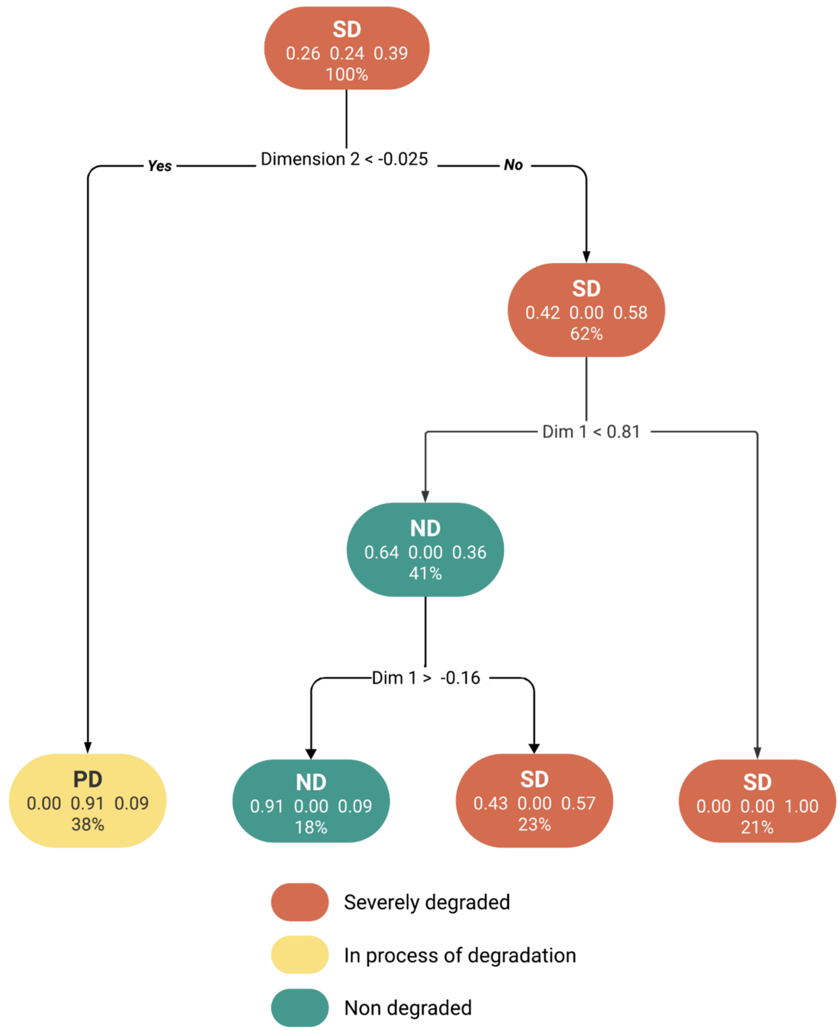
Figure 5 . Dendrogram illustrating the six distinct grouping of field variables.

The clusters exhibited clear patterns, with variables associated with better-managed pastures (*e.g.* , high forage availability, low weed presence, and high soil cover) forming distinct groups, while indicators of severe degradation (*e.g.* , high weeds presence, low soil cover, and low forage productivity) characterized others.

These groups were subsequently classified into three main grassland degradation classes: 1) non-degraded (ND), 2) in process of degradation (PD), and 3) severely degraded (SD), based on their characteristics and distribution of variables within the six clusters identified in the hierarchical cluster analysis. To model the relationship between degradation classes and the variables' principal dimension coordinates (Dim1 and Dim2), a decision tree was adjusted. In the adjustment of the decision tree, only the first principal dimension (Dim1) was relevant to explain the classification of the three degradation categories. The resulting tree model, shown in Figure 6, highlights key decision splits based on thresholds in Dim1. The terminal nodes display the predicted degradation class and corresponding percentages, indicando que 38% das variáveis foram classificados como ND, 34% como PD e 28% como SD. A precisão total do modelo de árvore foi de 97,05%, com apenas duas classificações incorretas entre as categorias ND e PD.

Since the proximity between the main coordinates of the field evaluations at each sampling point and the principal coordinates of the variables in the biplot (Figure 3) indicates an association between them, the decision tree model was once again applied to the principal coordinates of each evaluation across all field points (individuals). This approach allowed for the classification of degradation levels for each assessment based on its position within the factorial space. As a result, the model classified 37.31% of the field evaluations as non-degraded (ND), 34.84% as in process of degradation (PD), and 27.84% as severely degraded (SD). This classification was the basis for the degradation area estimates in Goiás.


ND
0.38 0.34 0.28
100%
Yes
Dimension 1 >= 0.27
No
PD
0.02 0.52 0.45
62%
Dim 1 >= - 0.47
ND
0.96 0.04 0.00
38%
PD
0.04 0.96 0.00
34%
SD
0.00 0.00 1.00
28%
Severely degraded
In process of degradation
Non degraded


SD
0.26 0.24 0.39
100%
Dimension 2 < -0.025
Yes
No
SD
0.42 0.00 0.58
62%
Dim 1 < 0.81
ND
0.64 0.00 0.36
41%
Dim 1 > -0.16
PD
0.00 0.91 0.09
38%
ND
0.91 0.00 0.09
18%
SD
0.43 0.00 0.57
23%
SD
0.00 0.00 1.00
21%
Severely degraded
In process of degradation
Non degraded

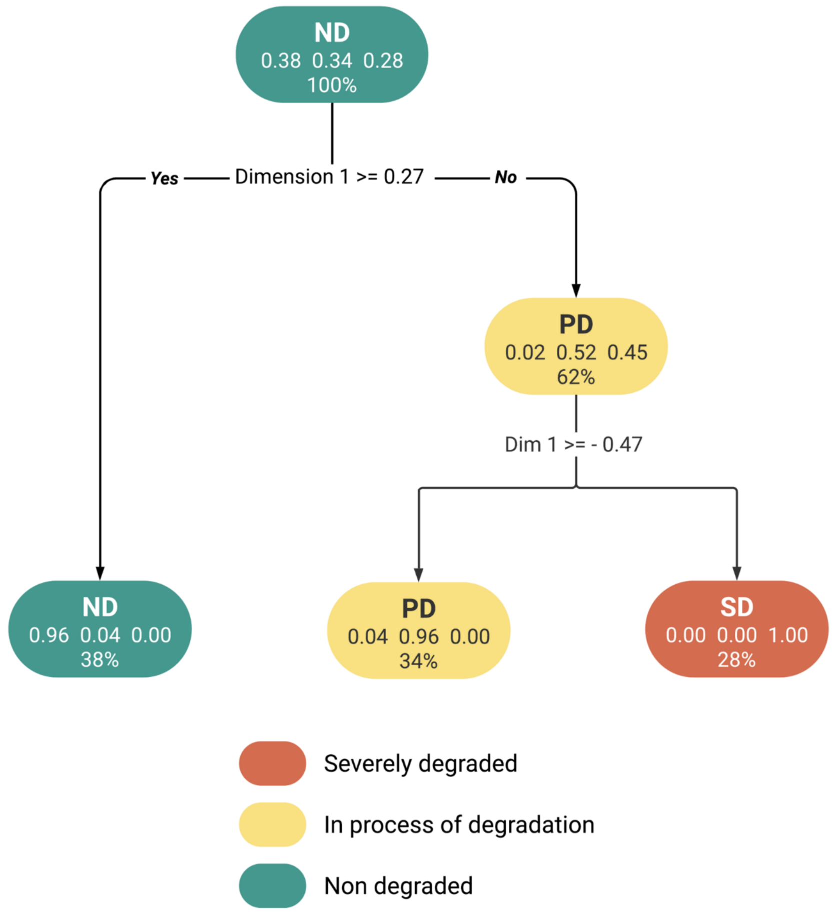


Figure 6 . Decision Tree Classification of Grassland Degradation Levels Based on Principal Dimensions

This method provides an intuitive and interpretable approach for associating field data with degradation levels based on key dimensions of variation. It provides valuable insights into the state of grasslands and serves as a foundation for targeted pasture management interventions aimed at reducing degradation and promoting sustainability.

2.5 | Area Estimates

To calculate area estimates in Goiás, we employed a robust statistical approach based on the Horvitz-Thompson estimator. This method calculates the mean or proportion of interest by assigning weights to each observation (?), reflecting its inclusion probability across multiple stages of the sampling design (Olofsson et. al, 2014; Stehman, 2014). The hierarchical structure of the sampling process included Pprimary sampling units (100 km x 100 km grids), S secondary sampling units (10 km x 10 km grids), and K tertiary sampling units (10 m x 10 m pixels) distributed across H strata. Within each tertiary unit, repeated observations were conducted, with the final sample size $n$representing the total number of observed tertiary units across all strata.

The estimates of means and proportions, denoted by $\widehat{\theta}$, were based on the Horvitz-Thompson estimator (Cochran, 1963):

$\widehat{\theta} = \frac{w_s \ \mathrm{y}_s}{w_s}$, where w_s is the weight of the ?-th observation and y_s is the value of the variable of interest for which the mean or proportion is being estimated. The initial weight w_{ijhk} is the inverse of the product of the inclusion probabilities of each sampling unit at each stage, given by:

$w_{\mathrm{ijhk}} = \frac{1}{p_{\mathrm{ijhk}}}$ where$p_{\mathrm{ijhk}} = p_i \times p_J \times p_{\mathrm{hk}}$,

Here, p_i is the inclusion probability at the first stage for$i \in \{1, ..., P\}$, p_J is the inclusion probability at the second stage for $j \in \{1, ..., S\}$, and p_{hk} is the inclusion probability at the third stage for $h \in \{1, ..., H\}$ and$k \in \{1, ..., K\}$. The final weight w_s is obtained by dividing w_{ijhk} by the number of repeated observations (n_{ijhk}) in the tertiary sampling unit, as follows:

$w_s = \frac{w_{\mathrm{ijhk}}}{n_{\mathrm{ijhk}}}$ forl ϵ $\{1, ..., n_{\mathrm{ijhk}}\}$.

where $s = s(i, j, h, k, l)$.

This method ensures that the sampling weights accurately reflect the probability of inclusion across all sampling stages, providing reliable and precise area estimates. Method for confidence interval calculation is available in Supplementary Material 3.

3 RESULTS

3.1 | PAS area estimates

The total pasture area corresponding to each parameter score was estimated using a statistically robust approach that incorporated sampling weights and spatial information, ensuring accurate extrapolations across the state. Each parameter was assessed using a standardized scoring system, with area measurements derived from a representative sample of pasture sites.

The estimated pasture area in hectares for each PAS, along with the associated standard error $se(\widehat{p})$, are presented in Table S.1 (Supporting information). These estimates provide a comprehensive quantification of pasture conditions across the state, highlighting variability in forage productivity, degradation status, and management effectiveness.

Figure 7 presents the distribution of estimated pasture area (in hectares) across different scores for the various pasture parameters assessed in Goias, Brazil. Each subplot represents a specific parameter, with the x-axis indicating the score (ranging from 1 to 7) and the y-axis showing the corresponding pasture area in thousands of hectares (k ha).

Figure 7 . Pasture area distribution and respective standard error across different scores in Goiás, Brazil.

For each parameter, the pasture area is highest at specific scores, indicating where most pastures fall in terms of condition. The results reveal distinct patterns across variables, highlighting the variability in pasture conditions. For instance, most pastures exhibit intermediate scores (2–4) for DV, indicating a predominance of pastures in active growth rather than those in early establishment or late senescence. Weed incidence (WD) is highest at lower scores (2–3), indicating that a significant portion of pastures experience low to moderate invasive species presence. Likewise, TI is most prominent at scores 1-2, indicating that termite distribution across Goiás pastures is generally low. It's important to note that the interpretation of these scores varies by parameter, as lower scores do not necessarily indicate poorer pasture conditions.

3.2 | Grassland degradation levels estimates

Following the classification of sampling points into three degradation categories (ND, PD, and SD), grassland degradation estimates were statistically derived through spatial extrapolation using sampling distribution and weights. The area estimates for each class, along with their respective percentages, standard errors, and confidence intervals, are summarized in Table 1. These estimates provide a comprehensive assessment of pasture degradation across Goiás, offering valuable insights into its spatial distribution and extent.

Table 1 . Area estimation for degradation class within Goiás, Brazil.

Classe	Percentage (%)	SE.Per (%)	LI.Per (%)	LS.Per (%)	Area (ha)	SE.Area (ha)	LI.Area (ha)
ND	39.35	3.92	31.66	47.04	5,412,294	539,608	4,354,682
PD	31.98	2.66	26.77	37.19	4,398,206	365,643	3,681,560
SD	28.67	3.64	21.54	35.79	3,942,569	500,095	2,962,401

An estimated 39.35% of the total pasture area in Goiás, approximately 5.4 million hectares, was classified as ND, with a standard error of 539,608 hectares. Pastures classified as PD accounted for 31.98%, covering 4.4 million hectares. Meanwhile, SD pastures represented 28.67% of the total area, corresponding to 3.9 million hectares.

These results highlight the significant extent of grassland degradation across Goiás, emphasizing the need for targeted management interventions to prevent further deterioration. The high proportion of PD and SD pastures suggests that a considerable share of the state's pasturelands require recovery measures, such as improved soil management, rotational grazing, and the restoration of forage productivity. The spatial distribution of degradation classes provides critical insights for policymakers, land managers, and researchers, aiding in the development of sustainable pasture management strategies.

5 | DISCUSSION

The hierarchical clustering analysis of the pasture assessment scores reveals insightful relationships between key indicators of grassland productivity and degradation. The dendrogram (Figure 5) organizes these variables into six distinct clusters, indicating potential correlations and dependencies among them and reinforcing the complexity of degradation processes.

One of the key findings is the strong association between low soil coverage (SC score 1) and forage in the early vegetative stage (DV score 1). These pastures likely experience significant soil exposure, often indicative of biological degradation (Dias-Filho, 2015) or the aftermath of disturbances such as fire, both scenarios can be linked to severe degradation. Additionally, more mature forage development stages (DV scores 6–7) are associated with intermediate levels of degradation (PD). Prolonged forage growth without proper grazing management can result in reduced forage quality and the accumulation of senescent material, diminishing pasture productivity and livestock performance. Additionally, extended growing seasons in warmer environments accelerate plant growth, leading to reduced soil nitrogen availability and further declines in forage quality (Kirkman et al., 2023; Morris et al., 2022). This finding underscores the need to interpret forage development scores in the context of seasonal variations and grazing/management strategies to avoid misleading degradation assessments.

Another notable observation is the clustering of termite incidence with intermediate degradation levels (PD). This suggests that termite presence alone may not necessarily indicate severe degradation (Lima et al., 2011), challenging the common perception that links termite activity to declining pasture conditions. In contrast, some studies have shown that termites can positively contribute to soil health, improving organic matter content, aeration, and nutrient cycling (Traoré, et al., 2022; Chen et al., 2023). This pattern reinforces the idea that termite activity may serve as an ecological function rather than solely as a degradation indicator, warranting further investigation into its role in pasture dynamics.

Overall, the clustering results emphasize the interconnectedness of pasture condition parameters and the importance of a holistic approach to evaluating grassland degradation. They highlight the necessity of context-driven interpretations, considering regional variations in soil properties, climate, and pasture management practices to develop more effective and sustainable grassland management strategies.

The area estimates for individual parameters, as depicted in Table 1, reveal that approximately 63.6% of pastures in Goiás, equating to 8.7 million hectares, fall within intermediate condition scores (PC). However, the distribution of productivity potential scores (PP) further highlights that a substantial portion of the assessed areas could achieve higher productivity levels with appropriate management and recovery practices. Implementing weed control, adjustments to stocking rates, and soil correction measures, such as liming and fertilization, can address nutrient deficiencies inherent in tropical soils, thereby enhancing forage growth and quality (Dias-Filho, 2015; Lopes et al; 2024; Ortega et al., 2024). Effective pasture management is crucial for maximizing forage production and ensuring long-term sustainability (Cezimbra et al., 2021), particularly in tropical regions where soil fertility naturally declines over time without proper intervention (Rodelo-Torrente et al., 2022).

Although soil coverage estimates suggest that a majority of grasslands in Goiás maintain adequate biomass cover, forage availability scores reveal a concerning trend. Average scores range from 2 to 3, corresponding to approximately one to four tons of dry matter per hectare. This lower forage availability is likely linked to higher grazing pressure, which can hinder pasture recovery and reduce productivity over time (Lane, 2020; Silva et al., 2019). Adjusting livestock stocking rates is essential to align forage production with animal demand, promoting a sustainable pasture-livestock balance and preventing further degradation. Effective grazing management, such as rotational grazing, allows for periods of rest and regrowth, preventing overgrazing and maintaining pasture quality, therefore supporting the economic viability of livestock production (Lane, 2020).

Regarding the estimation of degraded areas in Goiás, our study revealed that around 28.67% of the grasslands exhibit severe degradation, and another 31.98%, are in the process of degrading. These categories combined represent over 8.2 million hectares, highlighting a critical challenge for pasture management in the region. Previous studies highlight the widespread nature of pasture degradation in the Cerrado region. Pereira et al. (2018) estimated that approximately 46% of Cerrado pastures exhibited some level of degradation. Similarly, Santos et al. (2022) reported that in 2018, over 3 million hectares (21.10%) of pastures in Goiás were classified as severely degraded, and another 6.4 million hectares (44.25%) were at intermediate levels of degradation. However, their analysis of pasture quality trends from 2010 to 2018 suggested a predominance of improvement within large properties, with Goiás being among the regions showing positive changes. Despite these localized improvements, our study reinforces that degradation remains a widespread and persistent issue, necessitating continuous monitoring.

A comparison between our field-based degradation estimates and the Pasture Vigor maps produced by LAPIG within the MapBiomas initiative (Atlas das Pastagens, 2022) reveals significant differences, particularly in the distribution of non-degraded and severely degraded areas. The Pasture Vigor maps classify Goiás' pasturelands into three vigor levels: high (4.61 million hectares; 33.48%), medium (6.06 million hectares; 44.06%), and low vigor (3.09 million hectares; 22.45%), with the latter serving as an indicator of severe degradation. In contrast, our field-based analysis suggests a larger proportion of severely degraded pastures. This suggests that remote sensing-based assessments may underestimate the severity of degradation, as satellite-derived indices can struggle to fully capture localized degradation processes, such as soil compaction and weeds coverage.

These differences underscore the importance of validating remote sensing-based assessments with ground-truth data to ensure accuracy and reliability in assessing pasture conditions. While satellite imagery provides broad-scale insights and facilitates continuous monitoring, it may overlook finer-scale degradation patterns that ground-truth data can detect. Therefore, combining both approaches is essential for a more comprehensive and reliable assessment of pasture degradation dynamics, ensuring that land-use policies and rehabilitation strategies are based on accurate, multi-source information.

In summary, both the PAS area estimates and degradation levels estimates indicate that the majority of pastures in Goiás are in intermediate condition or in process of degradation. Addressing soil fertility, controlling invasive species, and optimizing grazing pressure are critical steps toward enhancing forage productivity and sustaining pasture health. These measures will strengthen the economic viability of livestock production in Goiás while promoting the long-term resilience of grassland ecosystems.

5.1 | Opportunities, challenges, and future steps

The use of a comprehensive, field-based scoring system combined with advanced statistical methods provides a novel framework for quantifying grassland degradation. One key opportunity lies in the scalability of this approach. By refining the methodology and applying it across other regions, researchers can build a broader database of grassland conditions, enhancing pasture management strategies. Additionally, the development of the Pasture Assessment Scores (PAS) tailored to tropical grasslands offers a transferable tool for evaluating pasture degradation and productivity and guiding sustainable practices in different landscapes and grassland typologies.

Despite these opportunities, several challenges must be addressed. The primary challenge is the resource-intensive nature of field data collection, which requires trained personnel, logistical coordination, and significant financial support. Variability in pasture conditions across large areas further complicates sampling design and may introduce biases in representativeness. The interpretation of degradation levels based on categorical variables, while effective, requires continuous refinement to ensure consistency across different regions and seasons.

Future steps should focus on refining the field protocol to enhance data collection efficiency, improve standardization across diverse landscapes, and incorporate more objective measures such as soil health indicators, biomass measurements, and grazing pressure. Expanding the PAS with these additional variables will improve the accuracy and robustness of the degradation classification system.

Additionally, conducting an accuracy assessment of pasture vigor maps using the field data from this study is essential to evaluate the reliability of remote sensing-based assessments and improve existing mapping methodologies. Integrating field data with satellite-derived data can enhance large-scale, high-frequency monitoring, reducing reliance on labor-intensive fieldwork while improving the precision of degradation detection. This approach also strengthens long-term surveillance efforts, supporting more effective conservation planning. Ultimately, establishing a comprehensive monitoring framework will contribute to mitigating grassland degradation and promoting more resilient and productive grazing systems.

6 | CONCLUSIONS

This study provides a comprehensive assessment of grassland degradation in Goiás, Brazil, through a field-based approach combined with robust statistical analysis. By employing a tailored scoring system for tropical pastures and applying Multiple Correspondence Analysis (MCA) and hierarchical clustering, we classified pastures into three degradation levels: non-degraded (ND), in process of degradation (PD), and severely degraded (SD). The results indicate that 39.35% of the pasture areas present low to no signs of degradation, while 31.98% are undergoing degradation processes, and 28.67% are already severely degraded, highlighting the widespread impact of pasture degradation across the state.

These findings reinforce the urgent need for targeted management interventions to restore degraded pastures and improve sustainability. The integration of field data with spatial modeling enhances the accuracy of area estimates, providing valuable insights for policymakers and land managers. Future research should refine assessment methodologies, incorporate remote sensing for large-scale monitoring, and explore the socioeconomic drivers of degradation in the region. The framework developed in this study provides a replicable approach for assessing grassland conditions, supporting global efforts in sustainable land management and degradation mitigation.

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FINANCIAL DISCLOSURE

None reported.

CONFLICT OF INTEREST

The authors declare no conflicts of interest regarding the publication of this article.

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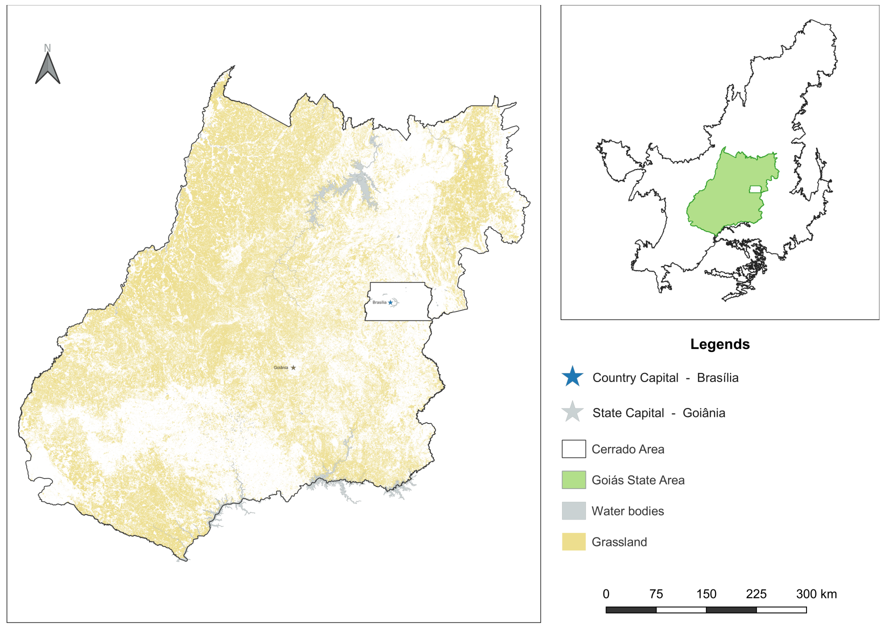
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Legends
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State Capital - Goiânia
Cerrado Area
Goiás State Area
Water bodies
Grassland
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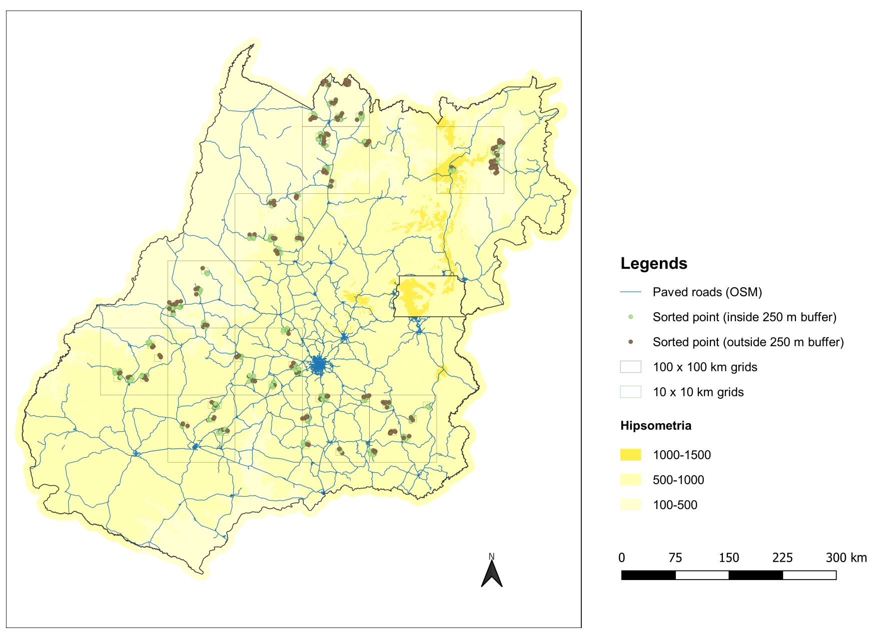
Legends
Paved roads (OSM)
Sorted point (inside 250 m buffer)
Sorted point (outside 250 m buffer)
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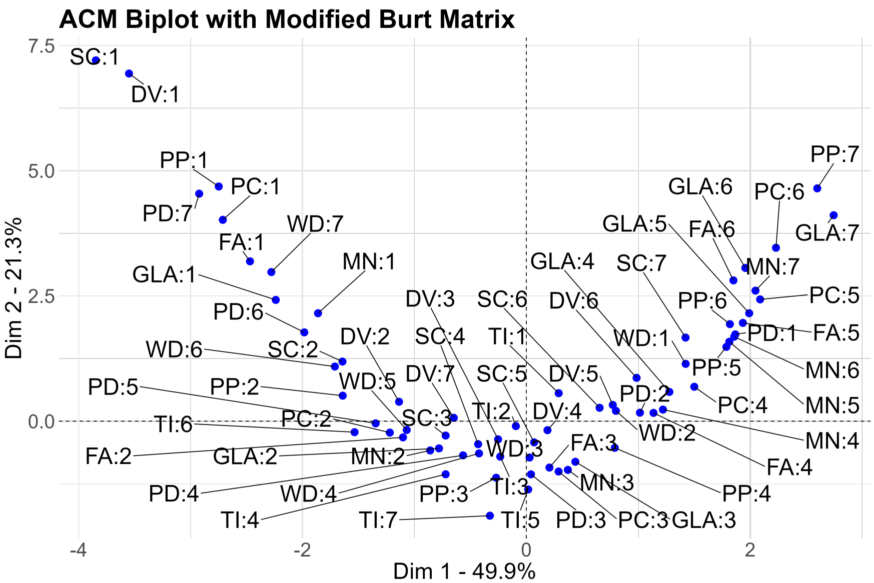
10 x 10 km grids
Hipsometria
1000-1500
500-1000
100-500
0 75 150 225 300 km
N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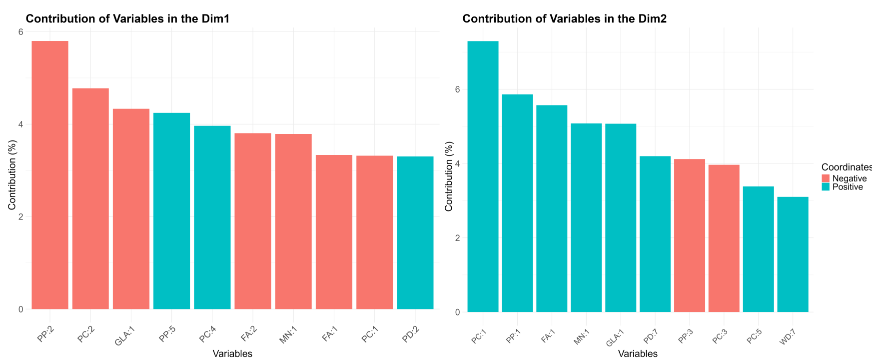
Dim 2 - 21.3%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Contribution of Variables in the Dim2
Contribution (%)
Variables
Coordinates
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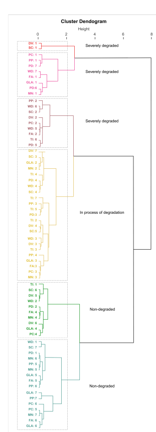
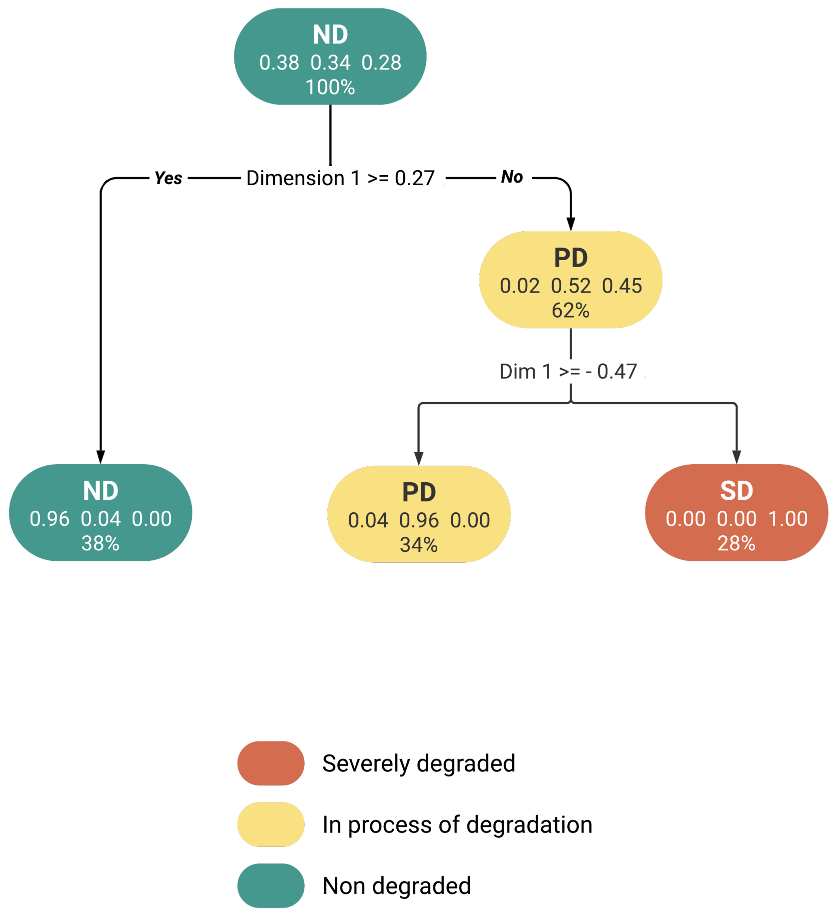

Cluster Dendrogram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100%
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No
PD
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62%
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ND
0.96 0.04 0.00
38%
PD
0.04 0.96 0.00
34%
SD
0.00 0.00 1.00
28%
Severely degraded
In process of degradation
Non degraded

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`Table S.1.xlsx` available at https://authorea.com/users/887364/articles/1265436-grassland-degradation-estimates-through-field-data-in-the-state-of-goi%C3%A1s-brazil