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CERRADO SOIL QUALITY UNDER DIVERSE FARMING SYSTEMS IN FAMILY AGRICULTURE

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ABSTRACT:

Family farming (FF) is a fundamental pillar of food security and social well-being, as it integrates social, cultural, and environmental dimensions. Despite its recognition since the 1990s, the sector faces persistent technological and policy challenges, particularly in the Cerrado biome. This study evaluated soil quality under pasture and native Cerrado vegetation in the state of Tocantins, Brazil. Undisturbed and disturbed soil samples were collected from the 0.00 – 0.10 m and 0.10 – 0.20 m layers of a dystrophic Lithic Ustorthents. Laboratory analyses were performed to quantify physical, hydrological, and biochemical parameters, including total organic carbon (TOC), soil bulk density (BD), porosity (PT), water storage capacity, and aggregate stability. A Visual Evaluation of Soil Structure (VESS) was also performed for detailed diagnostics. Data were subjected to analysis of variance (ANOVA), and means were compared using Student's t-test at a 5% probability level ($p < 0.05$). The native Cerrado exhibited significantly higher TOC, reflecting greater organic matter input. In contrast, the pasture showed higher BD values than the Cerrado, indicating soil compaction and reduced porosity, which compromised water infiltration. Water storage capacity was 50% lower in the pasture, highlighting reduced water retention. Furthermore, the VESS method classified the Cerrado as "friable" (score 1.5) and the pasture as "firm" (score 2.5), aligning with the quantitative data. Thus, the native Cerrado maintains superior edaphic conditions, with greater structural stability and carbon reserves. Conversely, pasture management involving fire and trampling promoted soil compaction and degradation, underscoring the need for interventions such as crop rotation or integrated crop-livestock-forestry systems (ICLFS) to restore soil health. The VESS method proved effective for low-cost, participatory monitoring that could be readily adopted by family farmers.

Keywords: Soil compaction; Organic matter; Water retention; Aggregate stability; Participatory monitoring.

QUALIDADE DE SOLOS DO CERRADO EM ÁREAS DE AGRICULTURA FAMILIAR SOB DIFERENTES SISTEMAS DE USO E MANEJO

RESUMO

A Agricultura Familiar (AF) constitui um pilar fundamental para a segurança alimentar e a reprodução social, integrando dimensões produtivas, culturais e ambientais. Apesar de seu reconhecimento a partir dos anos 1990, persistem lacunas tecnológicas e políticas, especialmente no Cerrado. Este estudo avaliou a qualidade do solo sob pastagem e Cerrado nativo no estado do Tocantins. Nas áreas avaliadas, amostras de solo indeformadas e deformadas foram coletadas nas camadas de 0,00 - 0,10 e 0,10 - 0,20 m de um Neossolo Litólico distrófico. Em laboratório, estas amostras foram previamente preparadas e utilizadas para a quantificação dos parâmetros físicos, hídricos e bioquímicos, tais como carbono orgânico total (COT), densidade do solo (Ds), porosidade (Pt), armazenamento de água e estabilidade de agregados, realizando também a Avaliação Visual da Estrutura

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do Solo (VESS) para diagnóstico detalhado. Os dados foram submetidos à análise de variância (ANOVA) e as médias comparadas pelo teste t de Studant ao nível de 5% de probabilidade (p < 0,05). O Cerrado nativo apresentou teores significativamente superiores de COT, refletindo maior aporte de matéria orgânica. A pastagem, por outro lado, exibiu maior valor de Ds em relação ao Cerrado, sugerindo compactação do solo e consequentemente menor porosidade, comprometendo a infiltração hídrica. A lâmina de água armazenada foi 50% menor na pastagem, evidenciando perda de capacidade de retenção de água. Além disso, a avaliação visual (VESS) possibilitou classificar o Cerrado como friável (escore 1,5) e a pastagem como firme (escore 2,5), correlacionando-se com os dados quantitativos. Assim sendo, o Cerrado nativo mantém condições edáficas superiores, com maior estabilidade estrutural e reserva de carbono. O solo sob pastagem, com queima e pisoteio promoveu compactação e perda de qualidade do solo, exigindo intervenções como rotação de culturas ou integração lavoura-pecuária-floresta (ILPF). O método VESS mostrou-se eficaz para monitoramento participativo, podendo ser adotado por agricultores familiares com baixo custo.

Palavras-chave: Compactação do solo; Matéria orgânica; Retenção hídrica; Estabilidade de agregados; Monitoramento participativo

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INTRODUCTION

Family farming (FF) plays a crucial, multifaceted role in society. Beyond its core function of food production, it is fundamental to social reproduction. Savoldi and Cunha (2010) highlight that FF FF facilitates the transmission of material and cultural heritage through a variety of family and individual strategies. This process not only sustains family legacies but also contributes to the continuous development of agricultural activities (Abramovay, 1997; Delgado et al., 2017).

Historically, the characterization and true value of family farming (FF) were often undervalued. Until the 1990s, FF was frequently described using pejorative terms such as "small-scale production," "subsistence agriculture," "low-income producer," or "rural poor," reflecting a perspective that neglected its true potential and complexity. However, a critical re-evaluation of these terms began in the 1990s, leading the concept of "family farming" to gain national prominence and recognition. This neglect, in its various aspects, persists particularly in the Cerrado region, where FF is still fundamentally characterized by a limited technological profile (Abramovay, 1995; Abramovay, 1997; Schneider and Cassol, 2014; Brasil, 1964; Brasil, 2006; Brasil, 2017).

This technological gap is directly tied to the lack of access to public policies for technical assistance and rural extension (ATER). A significant limiting factor is the lack of formalized land tenure in the region, which acts as a major barrier to accessing these resources. This shortage of technical and legal support results in a series of environmental problems that often go unnoticed or are inadequately managed, thus intensifying the deforestation of native areas and soil degradation (FAO/INCRA, 2000). The conversion of natural ecosystems, such as native forests, for agricultural use has been widely documented to cause a rapid decline in soil productivity, loss of organic matter, accelerated acidification, crusting, and erosion. Deforestation and inappropriate agricultural practices are among the most common causes of soil degradation, as they drastically increase soil bulk density and decrease its water infiltration capacity (Delgado et al., 2017; Grisa, 2017).

Furthermore, eroded soils have a greater potential for carbon loss, which contributes to increased concentrations of greenhouse gases and accelerating soil acidification. This degradation, in turn, results in ecological changes, nutrient imbalances, and the destruction of the soil's natural buffering capacity. In addition, soil erosion facilitates the movement of soluble and particulate nutrients, such as nitrogen and phosphorus, which leads to the pollution of water bodies and ultimately causes the eutrophication of aquatic ecosystems (Ferreira et al., 2020; Pereira et al., 2021; Antoneli et al., 2021; Arneiro et al., 2021; Junior, 2022).

Beyond the environmental impacts, these challenges also contribute to a range of social problems. The degradation of natural and water resources threatens food security, particularly for millions of families on marginal lands, and reduces essential ecosystem services. The inability to acquire inputs often leads to extractive farming practices, perpetuating a cycle of poverty. However, this cycle can be mitigated through adequate public policies and efficient technical guidance (Lal, 2001; Ferreira et al., 2020; Sirqueira et al., 2022; Back, 2023)

In this context, promoting soil quality assessments in family farming areas within the Cerrado is essential. Such evaluations not only provide important diagnostic data for more effective technical assistance and rural extension, enabling targeted interventions, but also directly help these farms enhance their agricultural productivity. This is achieved through the implementation of practices that optimize nutrient availability, improve soil structure, and increase water use efficiency. Therefore, this study aimed to evaluate the quality of a soil under different land use and management systems in family farming areas of the Tocantins Cerrado, establishing a soil quality index (SQI) through visual assessments.

MATERIALS AND METHODS

The study was conducted on a private family farm in the rural area of Paraíso do Tocantins, Tocantins state (TO). The region has a climate with two distinct seasons: a rainy season from October to March, with an average precipitation of 1200 mm, and a dry season during the remaining months. The average annual temperature ranges from 22 to 27°C (Malheiros, 2016), and the climate is classified as Aw according to the Köppen-Geiger classification (Alvares et al., 2013; Cardoso et al., 2014).

Based on the soil map of Tocantins state, the region's soil is classified as a petroplinthic Dystrophic Lithic Neosol (RLd), which is equivalent to a dystrophic Lithic Ustorthents (IBGE, 2007). The soil has a medium, gravelly texture with a gently rolling and flat topography. Up to a depth of 0.2 m, the soil's particle size distribution is sandy-loamy, consisting of 82.0% sand, 13.2% silt, and 4.8% clay.

The study consisted of an evaluation of two adjacent areas. One was a pasture of *Brachiaria brizantha* (synonym, *Urochloa mole* Stapf) with the presence of *Andropogon gayanus*, established for 20 years and managed primarily by burning. The other was an area of native Cerrado that had been free of human interference for more than 30 years.

In a completely randomized design (CRD), both undisturbed and disturbed soil samples were collected from the 0.00 - 0.10 m and 0.10 - 0.20 m layers. These specific depths were chosen because of their high susceptibility to physical, chemical, and biological changes influenced by the root systems of plants over time

Undisturbed soil samples were collected using volumetric rings (4.8 cm diameter x 5.0 cm height), totaling 24 samples (1 sample × 2 layers × 6 replicates × 2 treatments). In the laboratory, these samples were manually prepared to determine soil bulk density (BD), total porosity (TP), and volumetric water content for the evaluation of water storage.

Disturbed soil samples were collected using a spade for the determination of particle size fractions. A total of 12 samples were collected (1 sample × 2 layers × 3 replicates × 2 treatments). Each sample had approximate dimensions of 0.10 × 0.10 × 0.10 m and weighed about 1 kg.

The sand, silt, and clay contents were determined using the pipette method. First, 10 g of oven-dried fine earth (ODFE) was chemically dispersed using 1 N NaOH and physically dispersed for 12 hours with a mechanical shaker. The samples were then transferred to 500 mL graduated cylinders, and a 25 mL aliquot was extracted after the sedimentation time was calculated (Teixeira, 2017).

Total organic carbon (TOC, g kg^{-1}) was determined by muffle furnace incineration, as described by Teixeira (2017).

For the determination of soil bulk density (Ds or BD, g cm^{-3}) and total porosity (PT, %), undisturbed samples were oven-dried at 105°C for a minimum of 12 hours until a constant mass was achieved. The bulk density was then calculated as the ratio of the dry soil mass to the volume of the sampling ring (Teixeira et al., 2017).

Soil water storage was calculated by integrating the volumetric water content (θ, $m^3\ m^{-3}$) over the soil depth (z, m) using the trapezoid rule (Libardi, 2005).

Aggregate stability was determined using the method described by Kemper and Chepil (2015). Aggregates with a diameter between 1 and 8 mm were selected for sieving. The sieve sizes used for fractionation were 8 mm, 3 mm, 1.4 mm, and 1 mm.

Qualitative assessments of soil structure were performed by assigning a numerical score based on the principles of the Visual Evaluation of Soil Structure (VESS) (Ball et al., 2007) and Visual Soil Assessment (VSA) (Shepherd, 2009) methods. This approach to quantifying soil quality followed the protocol described by Penning et al. (2015).

The scores used to evaluate and classify visual soil quality followed the guidelines established by Ball et al. (2007). A Score 1 (Friable) was assigned to aggregates that break easily with fingers. This indicates a very good soil structure with good aggregation and aeration, which promotes water infiltration and root development. A Score 2 (Intact) was given when aggregates were easily broken by hand, indicating a good structure but with greater resistance to rupture than a friable soil. Finally, a Score 3 (Firm) was used when most aggregates required effort to be broken by hand. This suggests a more compact or less aggregated structure that can restrict water infiltration and root penetration, thereby increasing the risk of surface runoff and erosion (Mueller et al., 2013).

The data were subjected to analysis of variance (ANOVA), and the means were compared using a Student's t-test ($p < 0.05$). All statistical analyses were performed with SigmaPlot 11 software (Systat Software, 2008).

RESULTS AND DISCUSSION

Total organic carbon (TOC) contents were significantly higher in the native Cerrado compared to the pasture area (Table 1).

Table 1. Total organic carbon (TOC) of a Latossol under pasture and native Cerrado and under different soil layers in Tocantins, Brazil.

Treatments	TOC (g kg^{-1})	
	0.00 - 0.10 m	0.10 - 0.20 m
Pasture	37.10 b	35.87 b
Cerrado	57.46 a	61.25 a

Means followed by the same letter, within the same soil layer, do not differ significantly (Student's *t*-test, $p<0.05$).

The absence of anthropogenic activity in the native Cerrado provides a favorable environment for the maintenance of soil organic matter (SOM). This is primarily due to a continuous input of organic residues and a slow rate of decomposition (Guareschi et al., 2012). This finding is consistent with Jakelaitis et al. (2008), who studied the quality of topsoil under native vegetation, pasture, and cultivated areas. They observed that TOC contents decreased with a change in land use, with the highest values found in areas with native vegetation. According to the authors, this is attributed to the greater deposition of organic residues in soils under native forest cover.

A higher total organic carbon (TOC) content in native areas was also observed by Costa Junior et al. (2011) when compared to areas under cropland and pasture for 29 years. According to the authors, these agricultural areas have lower organic carbon contents due to a reduced input of organic material, specifically from the light fraction of organic carbon.

Soil bulk density (BD) was significantly higher in the pasture area compared to the native Cerrado. In contrast, total porosity (TP) was significantly greater in the Cerrado. This highlights important structural changes resulting from the conversion of native vegetation cover (Table 2).

Table 2. Bulk Density (BD) and Total Porosity (TP) of a Latossol under Pasture and native Cerrado and under different soil layers in Tocantins, Brazil.

Treatments	0.0 - 0.10 m		0.10 - 0.20 m	
	BD	**TP**	**BD**	**TP**
	g dm^{-3}	%	g dm^{-3}	%
Pasture	1.13 a	57.41 b	1.26 a	52.29 b
Cerrado	0.99 b	62.56 a	1.19 b	55.16 a

Means followed by the same letter, within the same soil layer, do not differ significantly (Student's *t*-test, $p<0.05$).

The lower bulk density (BD) values in the native Cerrado are attributed to higher organic matter contents and the absence of traffic from machinery, people, and livestock. This finding is supported by Carneiro et al. (2009), who state that different soil management practices alter BD compared to native forest areas, where the soil is maintained in its natural state. This occurs because vehicular and animal traffic compresses the soil, which increases its mass within the same volume, consequently raising density and reducing porosity. Similarly, Santos et al. (2011) found that intensive use of a brachiaria pasture resulted in lower values of macro- and micropores and, consequently, higher BD values, particularly in the surface layers. These findings corroborate the results obtained in our study.

Volumetric water content (θ, m^3 m^{-3}) and soil water storage (h, mm) were also significantly higher in the native Cerrado area (Table 3). These findings highlight the critical role of organic matter, porosity, and soil structure in the water storage process.

Table 3. Volumetric Water Content (θ) and Soil Water Storage (h) of a Latossol under Pasture and native Cerrado and under different soil layers in Tocantins, Brazil.

Treatments	0.0 - 0.10 m		0.10 - 0.20 m	
	θ $m^3\ m^{-3}$	**h** mm	**θ** $m^3\ m^{-3}$	**h** mm
Pasture	0.03 b	0.14 b	0.04 b	0.39 b
Cerrado	0.05 a	0.26 a	0.08 a	0.78 a

Means followed by the same letter, within the same soil layer, do not differ significantly (Student's *t*-test, $p<0.05$).

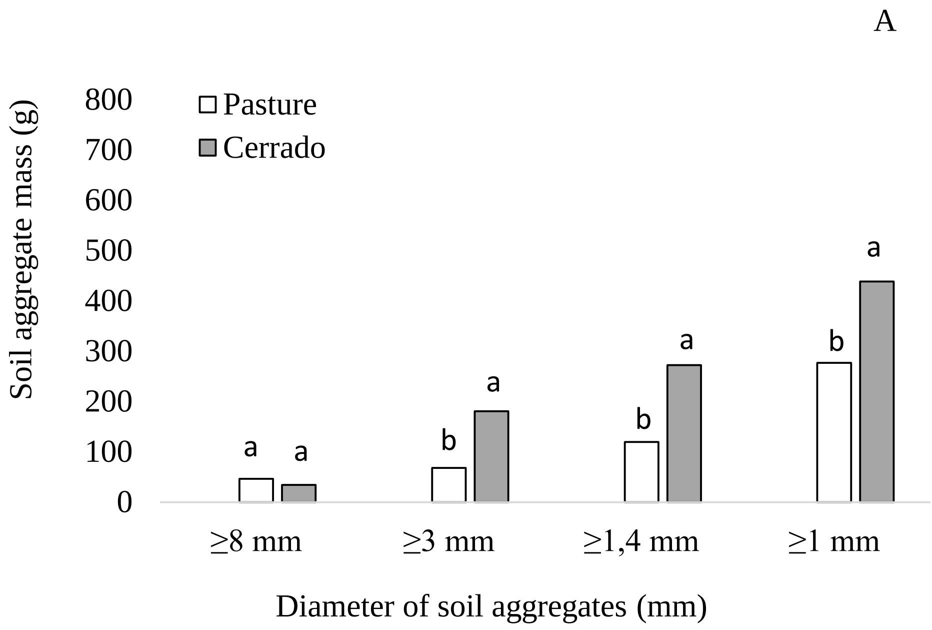
In the native Cerrado, the permanent soil cover, higher organic matter content, and greater porosity likely led to increased water infiltration. This, combined with the high hydration and water retention capacity of organic matter, may explain the greater volume of water stored in that specific treatment.

The pasture area exhibited lower water content in the surface layers compared to the native Cerrado, a result attributed to the sparse ground cover. A similar situation was reported by Marchão et al. (2007), who found significant increases in soil bulk density and penetration resistance in pastures. They specifically noted that tussock-forming grasses, such as *Panicum maximum* (jack), have a greater potential to expose the soil. This exposure contributes to soil degradation and subsequently reduces water infiltration and retention.

In general, the native Cerrado soil exhibited a larger mean aggregate size when compared to the pasture area. Conversely, the management system with greater soil disturbance showed higher values for the percentage of smaller aggregates. These findings clearly indicate a relationship between aggregate stability and the intensity of soil mobilization generated by the management system (Figure 1).

Research by Harris et al. (2015) using the percentage of stable aggregates (>2 mm) as a soil quality indicator also found a decrease in stability across management systems, reporting values of 40%, 26%, and 19% for conservation systems, no-tillage, and tilled soils, respectively. Furthermore, Wendling et al. (2005) concluded that soil tillage decreased aggregate stability compared to native forest baseline values. While no-tillage did increase aggregation when compared to conventional preparation, the authors noted that it concurrently led to a decrease in biodiversity.

Aggregate size is a useful indicator for the visual assessment and determination of soil degradation or conservation status (Braida et al., 2011). In the evaluated layer, the presence of large clods, or structural units, with dimensions exceeding 7 cm is considered evidence of degradation. Such large structural units suggest excessive soil compaction caused by inadequate management practices, which leads to a slower regeneration potential. These compromised properties negatively influence overall soil health and are consequently detrimental to plant development (Freddi et al., 2015).



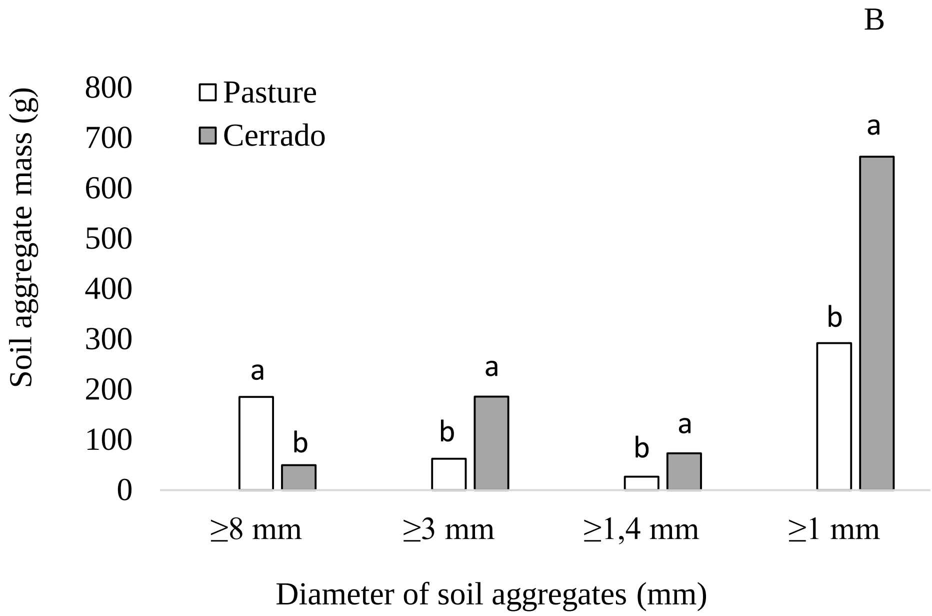


Figure 1. Aggregate size classes in the 0.0 - 0.1 m (A) and 0.1 - 0.2 m (B) layers of an Latossol under pasture and native Cerrado under different layers in Tocantins, Brazil.
Means followed by the same letter do not differ significantly according to the Student's *t*-test ($p < 0.05$).

The visual assessment of soil structural quality, performed using the VESS (Visual Evaluation of Soil Structure) method, identified clear differences in structure between the study areas. These differences were manifested as visible modifications in the organization of aggregates within the soil profiles (Table 4).

Soil Structural Quality (SSQ) is a critical indicator reflecting the soil's capacity to resist disaggregation and maintain its integrity. This structural integrity directly influences vital soil processes, including water infiltration and nutrient retention (Askari et al., 2013, 2015; Ball et al., 2007, 2013; Freitas et al., 2020).

The soil under native Cerrado exhibited a Score 1 (Friable) in the 0.00 to 0.10 m layer. This suggests the surface layer possesses excellent structural quality, characterized by easily disaggregating aggregates. The native vegetation, especially with good ground cover, protects the soil from raindrop impact, minimizing particle disaggregation and surface sealing, which in turn favors water infiltration. This high structural quality significantly contributes to a lower susceptibility to water erosion (Roger-Estrade et al., 2010).

In the deeper 0.10 to 0.20 m layer, the soil maintained a good structure, exhibiting a Score 2 (Intact). This score is associated with aggregates that are still easily broken by hand. Although less friable than the surface layer, a Score 2 remains favorable for the movement of water and air within the soil. The overall mean SSQ observed for the Cerrado soil was 1.5, which falls between very good and good quality. This strongly emphasizes the significant contribution of the native vegetation cover to the formation and long-term maintenance of stable aggregates (Askari and Holden, 2015; Das et al., 2014; Duval et al., 2013; Gong et al., 2015).

Table 4. Classification of Soil Structural Quality (VESS), mean scores, and required management actions for a Latosol under Pasture and native Cerrado and under different soil layers in Tocantins, Brazil.

Treatments	0.0 - 0.10 m	0.10 - 0.20 m	Mean SSQ
	Visual soil score	**Visual soil score**	
Pasture	2	3	2,5
Cerrado	1	2	1,5

Score 1 (Friable) is defined by aggregates that crumble easily with the fingers. Score 2 (Intact) applies when aggregates are easily broken by hand. Score 3 (Firm) represents the breaking of the majority of aggregates by hand, requiring moderate force. The source for these criteria is Ball et al. (2007).

The pasture soil exhibited a Score 2 (Intact) in the 0.00 to 0.10 m layer. While these aggregates are still easily broken by hand—indicating good structural quality—this score is slightly less friable when compared to the Cerrado soil in the same layer (Score 1).

In sharp contrast, the deeper 0.10 to 0.20 m layer showed a decline in quality, receiving a Score 3 (Firm). This score suggests a firm soil structure where the majority of aggregates require substantial force to be broken. This finding points to a less developed or more compacted structure at depth in the pasture compared to the Cerrado. In soils with such a firm structure, water infiltration is reduced, and the potential for surface runoff is likely to be greater.

The overall mean SSQ of 2.5 for the pasture indicates a structural quality ranging from good to firm. The pronounced degradation observed at depth (Score 3) likely reflects the effects of compaction processes combined with the less intense action of organic matter and roots in this layer.

The visual assessment provided a final, clear distinction between the two areas, classifying the native Cerrado as having superior structural quality with a mean score of 1.5, significantly lower than the pasture area's mean of 2.5 (Table 4). The superior score obtained in the Cerrado corroborates the association between higher total organic carbon (TOC), lower bulk density (BD), greater porosity, and increased water storage. While it is recognized that permanent pasture systems or no-tillage rotations *can* promote the formation of large, stable aggregates (Ferreira et al., 2010), the findings from the Cerrado study area remain superior. According to the same authors, the reduced soil disturbance and vigorous root systems of grasses are the mechanisms that allow for the formation of stable macro-aggregates and enhanced soil quality.

CONCLUSION

The integrated analysis, combining the Visual Evaluation of Soil Structure (VESS) with detailed physical, hydrological, and organic matter attributes, definitively showed that the soil under native Cerrado possesses superior overall quality compared to the soil under pasture. This comprehensive approach confirmed that the soil quality differences are substantial between the two land uses. Furthermore, the VESS methodology proved to be a highly sensitive tool for distinguishing subtle alterations in soil quality across different land use and management systems, highlighting its potential as a simple, effective diagnostic tool readily usable by family farmers.

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