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Aggregate stability of an Ultisol in regions of the brazilian Amazon

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ABSTRACT

The aggregate stability is essential for water infiltration, soil aeration and root penetration resistance, impacting water infiltration, moisture retention, soil aeration and root penetration resistance. Inadequate agricultural practices can limit root growth, cause compaction, reduce water infiltration and increase water erosion. This study evaluated the stability of aggregates of an Ultisol in the Amazon, including different ecosystems: natural forest, natural savannah, forest converted to pasture and savannah converted to pasture. Three soil depths were analyzed at 0.00 to 0.10 m, 0.10 to 0.20 m and 0.20 to 0.40 m. The properties evaluated included aggregate classes, geometric mean diameter, weighted mean diameter, dispersed clay, degree of clay flocculation, sensitivity index and organic matter. The results showed that the conversion of natural environments to pasture did not significantly affect aggregate stability indices, suggesting that proper pasture management can maintain the structural quality of the soil.

Keywords: Physical quality, Soil management, Ecosystems.

Estabilidade de agregados de um Argissolo Amarelo em regiões da Amazônia brasileira

RESUMO

A estabilidade dos agregados é essencial para a infiltração de água, a aeração do solo e a resistência à penetração das raízes, impactando a infiltração de água, a retenção de umidade, a aeração do solo e a resistência à penetração das raízes. As práticas agrícolas inadequadas podem limitar o crescimento das raízes, causar compactação, diminuir a infiltração de água e aumentar a erosão hídrica. Este estudo avaliou a estabilidade dos agregados em Argissolos Amarelos na Amazônia, incluindo diferentes ecossistemas: savana natural, floresta natural, savana convertida em pastagem e floresta convertida em pastagem. Foram analisadas três profundidades do solo (0,00 a 0,10 m, 0,10 a 0,20 m e 0,20 a 0,40 m). As propriedades avaliadas incluíram classes de agregados, diâmetro médio geométrico, diâmetro médio ponderado, argila dispersa, grau de floculação da argila, índice de sensibilidade e matéria orgânica. Os resultados mostraram que a conversão de ambientes naturais em pastagem não afetou significativamente os índices de estabilidade dos agregados, sugerindo que uma gestão adequada da pastagem pode manter a qualidade estrutural do solo.

Palavras-chave: Qualidade física, Manejo do solo, Ecossistemas.

1. Introduction

Aggregate stability is a fundamental indicator of processes related to soil degradation, since it impacts water infiltration, moisture retention, soil aeration and resistance to root penetration. Likewise, it influences surface sealing and erosive, water and/or wind processes (Vale Júnior et al., 2015). In addition, it is considered to be the parameter with the best correlation with soil erodibility (Reichert et al., 1993).

In the context of intensive cultivation, there is a decrease in soil organic matter content, which negatively affects aggregate stability. This reduction in aggregate stability leads to an increase in the relative proportion of microaggregates in the soil, whose stability is not significantly affected by management (Tisdall and Odes, 1982). As a consequence, soils with lower organic matter and less stable aggregates tend to be more susceptible to erosion, less water infiltration and greater surface sealing, exacerbating soil degradation processes.

Aquino et al. (2014), in their study on the spatial variability of anthropogenic and non-anthropogenic soils, found that anthropogenic soils have greater stability. Physical analyses, including texture, density, macro- and microporosity, total porosity and aggregate stability, revealed superior characteristics in anthropogenic soils for agronomic purposes. The application of descriptive statistics and geostatistics showed distinct behaviors between the soil types, with predominantly moderate to weak spatial variability, suggesting the influence of extrinsic factors. In this line of research, other studies have explored the spatial distribution of soil aggregates under different management practices. For example, Gomes et al. (2017) analyzed the spatial changes of aggregates as a function of different uses, Silva et al. (2016) investigated the spatial dependence of aggregate stability in "*terra preta de índio*" cultivated with cocoa. Alho et al. (2014) examined aggregates and soil organic carbon in natural field and natural forest areas. These studies contribute to the understanding of soil dynamics and its better sustainability for the maintenance and conservation of these environments.

The variability of the microbial population can also have a significant influence on the stability of soil aggregates. Melloni et al. (2008) compared the physical and chemical attributes of soil in areas of Atlantic forest, Araucaria forest, eucalyptus plantations and pasture (*Brachiaria decumbens*) in Minas Gerais. These authors observed a similar degree of flocculation in the pasture and forest areas. These results can be attributed to the high microbial population of the soil. These findings highlight the importance of microbial diversity in the stability of soil aggregates in different types of vegetation cover.

Due to the high acidity of the soils in Roraima, liming is a common practice before implementing production systems. However, this practice can alter physical and water properties, as observed by Albuquerque et al. (2003). They found that the application of limestone reduced the degree of clay flocculation from 69% to 58%, with the addition of 9 t ha^{-1}. This is due to an increase in the thickness of the diffuse electrical layer, resulting in greater dispersion of the colloids, which impacts agricultural planning by clogging the soil pores and hindering water percolation.

Therefore, the physico-hydric characterization of the Ultisol in this study seeks to evaluate in detail the properties related to aggregate stability in different ecosystems, including Natural Savannah and Natural Forest, as well as Savannah and Natural Dense Forest converted into pasture. This analysis aims to gain a deeper understanding of the dynamics of aggregate stability and its influence on ecosystem functions, taking into account the specific conditions of management and land use. With this data, it is hoped to provide robust technical support for the implementation of agricultural practices that promote sustainability, optimizing land use and minimizing adverse environmental impacts.

2. Material and Methods

This study was carried out in the state of Roraima from March 2017 to July 2018. The representative area of the natural dense forest ecosystem (NF) was determined in the municipality of Rorainópolis (vicinal 09), at UTM coordinates 0°86'071"N and 60°60'258"W. Nearby, an area of natural dense forest converted to pasture (FC) for cattle and sheep was selected at UTM coordinates 0°86'589"N and 60°59'360"W. An area of natural savannah (NS) was selected in the municipality of Bonfim on the edge of the BR-410 highway, approximately 20 km from the capital Boa Vista (coordinates 03°13'852"N and 60°26'908"W). For the converted savannah area (SC), a pasture area was selected on the Smith farm, which was approximately 4 km away from the NS (coordinates 03°15'072"N and 60°23'766" W).

The soil studied in both areas was classified as Ultisol in both Natural Forest and Natural Savannah. The relief in the Savannah was flat to undulating (5 to 10%) and in the Natural Forest, undulating to wavy (8 to 13%). The textural class of the soil in the converted and natural forest was sandy loam up to a depth of 0.20 m, from 0.20 to 0.40 m it was sandy-clay-loam. In the Savannah (Natural and Converted) the textural class is sandy-clay to a depth of 0.20 m and from 0.20 to 0.40 m it was clayey sand. These are deep, well-drained soils, with the presence of plinthite from a depth of 0.30 m only in the Natural Forest, which is not sufficient for a plinthic diagnosis. There is evidence that these soils were formed as a result of the destruction of the lateritic, which are abundant in the region. The studies carried out on soils in the Amazon region, where it was identified that deep, well-drained soils, with the presence of plinthite from a depth of 0.30 m, occur only in the Natural Dense Forest, without meeting the criteria for classification as Plinthosol. The formation of these soils is related to the destruction of lateritic concretions, which are frequent in the area studied (Cruz et al., 2014).

Currently, Roraima's climatological database is small, with a history of studies linked to precipitation (Araújo et al., 2001; Silva et al., 2015; Barni et al., 2020), evapotranspiration (Araújo et al., 2007) and climate (Barni et al., 2020). Depending on the region of the state, according to the Köppen classification, there is the “Rainy Tropical” climate type (A) and the sub-types (Am), Savannah Areas (Aw) and Natural Dense Forest Areas (Af) (Araújo et al., 2024). SC was an area that had been cleared of *Brachiaria brizantha* five years ago by plowing and harrowing.

The NS area was classified as “savana park” according to the Brazilian environmental laws, with a predominance of “Caimbés” (*Curatela americana*). The NF was classified as Dense Ombrophilous Natural Dense Forest, and a non-anthropized area was selected. The FC was cleared approximately 25 years ago by fire and mechanized deforestation. This area has been occupied by *Brachiaria brizantha* and *Brachiaria humidicola* for 16 years to raise cattle and sheep and was installed by plowing and harrowing to plant the pasture.

The experimental design was randomized blocks (DBC) in a subdivided plot scheme, based on similar studies such as Silva (2005). This study consisted of 4 treatments: T1 = Natural Forest (NF); T2 = Natural Savannah (NS); T3 = Natural Forest Converted to Pasture (FC) and T4 = Savannah Converted to Pasture (SC), and five blocks (five mini trenches) within the delimited area, and 3 sampling depths (0.00 - 0.10 m; 0.10 - 0.20 m and 0.20 - 0.40 m (Table 1). The samples for physical and water analysis were obtained from five mini trenches 0.40 m deep distributed over the area of each treatment (1 ha^{-1}).

Table 1: Plots (main treatments), subplots (secondary treatments) and variables analyzed in the study

Treatments	**Depths**		
	0.00 – 0.10 m	**0.10 – 0.20 m**	**0.20 – 0.40 m**
Natural Forest (NF)	--- Variables ----		
Forest Converted do pasture (FC)	Aggregate Classes, Geometric Mean Diameter (GMD), Weighted Mean Diameter (WMD), Dispersed Clay (DC %), Clay Flocculation Degree (FD %), Clay Flocculation Degree (FD %), Sensitivity Index (SI), Organic Matter (OM)		
Natural Savana (NS)			
Savannah Converted to pasture (SC)			

In each mini trench, undeformed samples were collected, so each treatment had 15 samples. These samples were sent to the Soil Physics Laboratory at the Federal University of Viçosa (UFV) for further physical and water analysis, in accordance with Embrapa's methodology (1997). The data collected was organized in an electronic spreadsheet for evaluation using the F Test, with the aim of examining the effect of plots (areas), sub-plots (depths) and the interaction between area and depth on the averages. After identifying a significant effect using the F Test, the means were compared using the Tukey test, with a significance level of 5%, using the R program.

3. Results and Discussion

In the 4 to 2 mm aggregate class, the highest percentages of aggregates retained on the sieve were observed in the NF and FC treatments (59.22% and 57.55%, respectively), while the lowest percentage was recorded in SC (39.31%), with NS showing an intermediate value at a depth of 0.00 to 0.10 m (as shown in Table 2). This pattern was repeated at all depths, although there was no statistical difference between 0.10 and 0.20 m. There were no statistically significant differences between the treatments within the 2 to 1 mm class at the 0.00 to 0.10 m depth.

However, in the 1 to 0.5 mm class, the highest percentage of aggregates was observed for SC (9.87%), with no statistically significant difference from NS (5.88%) and FC (5.71%). NF (3.69%) was significantly lower than SC, but did not differ from FC. At the other depths, the lowest values were found in the FC, maintaining the same pattern. In the 0.5 to 0.25 mm class, the highest percentage of aggregates was found in SC (12.32%), which differed significantly from the other treatments in the 0.00 to 0.10 m depth. The conversion from NF to FC did not affect the size of the aggregates, following the same response pattern observed at the other depths.

Table 2: Results of the comparison between means (Tukey at 5%) of aggregate classes according to the Areas

Aggregate Class (mm)	Areas	Depths (m)		
		0.00 – 0.10 m	**0.10 – 0.20 m**	**0.20 – 0.40 m**
4 - 2	NF	59.22 A	55.60 A	51.37 A
	FC	57.55 A	55.87 A	57.76 A
	NS	49.55 AB	47.40 A	40.96 AB
	SC	39.31 B	36.60 A	31.34 B
2 - 1	NF	21.87 A	22.75 A	24.92 A
	FC	20.57 A	21.52 A	19.60 A
	NS	21.66 A	25.23 A	22.33 A
	SC	20.36 A	21.90 A	20.85 A
1 – 0.5	NF	3.69 B	6.46 AB	8.31 AB
	FC	5.71 AB	6.20 B	7.68 B
	NS	5.88 AB	7.88 AB	9.04 AB
	SC	9.87 A	12.12 A	13.23 A
0.5 - 0.25	NF	3.80 B	3.93 B	5.69 B
	FC	4.31 B	4.94 B	5.04 B
	NS	7.08 B	7.20 B	9.40 AB
	SC	12.32 A	14.0 A	15.02 A
0.25 – 0.106	NF	1.56 C	1.56 B	2.46 B
	FC	2.42 BC	2.36 B	2.42 B
	NS	4.69 B	4.44 B	6.08 AB
	SC	7.91 A	8.07 A	9.20 A
< 0.106	NF	9.83 A	9.68 A	7.22 A
	FC	9.42 A	9.09 A	7.47 A
	NS	11.12 A	7.84 A	12.17 A
	SC	10.22 A	7.30 A	10.33 A

Capital letters for comparison between treatments at each depth. NF: Natural Forest; FC: Forest Converted to Pasture; NS: Natural Savannah; SC: Savannah Converted to Pasture.

The highest percentage of retained aggregates in the 0.25 to 0.106 mm class was observed in SC (7.91%), which differed statistically from NF (1.56%), FC (2.42%) and NS (4.69%) in the 0.00 to 0.10 m depth. At a depth of 0.10 to 0.20 m, the highest percentage was also observed in SC, which differed statistically from the other treatments. At the depth of 0.20 to 0.40 m, there was no difference between SC and NS, despite the higher value in the former. There was no difference between NF and FC at these two depths. In the class smaller than 0.106 mm, there was no statistically significant difference between the treatments at any depth. In all aggregate classes, the percentage retained was slightly higher at the shallow depth of 0.00 to 0.10 m, due to the higher organic matter content at the surface. It was also not possible to detect any statistical difference in the percentage of aggregates between a Natural Forest (in a transition area) and a pasture on Ultisol in the state of Roraima. Thus, the results show that more than 90% of the aggregates in these two areas were retained in the 2 to 4 mm mesh. This can be taken as an indication that most of the aggregates are large and stable. However, in the 1 to 2 mm class, the percentage of aggregates retained in this work was higher than the results obtained in this research, with 2.04% for the Natural Dense Forest and 2.0% for the pasture in the 0.00 to 0.10 m depth.

Thus, the results showed that the size of the aggregates decreased with increasing depth, probably due to the decrease in organic matter content, which is an efficient cementing agent and contributes to the formation of aggregates. The formation of stable aggregates at depths where organic matter is scarce is due to the action of other aggregating and cementing agents such as iron and aluminum oxides and the action of microorganisms associated with deeper root systems. This may explain the close aggregate percentage values found between Savannah and Natural Dense Forest, since the organic matter content in the latter is much higher.

The establishment of pastures in the Amazon has led to divergent opinions in scientific circles. From the point of view of this physical attribute, the conversion from NF to FC did not significantly affect the size of the aggregates at any of the depths, so there was no detrimental effect on soil aggregation with the installation of pasture. The same did not occur in the savannah area due to the history of the area involving mechanized planting in a more recent period. Agricultural practices involving soil disturbance, such as conventional cultivation, can lead to the destruction and fragmentation of soil structure, reducing aggregates into smaller classes and compromising total porosity, as well as other properties related to aeration and water dynamics in the soil. This observation is corroborated by several recent studies.

For example, the fragmentation of soil aggregates and the reduction in porosity due to tilling are evidenced in a study by Harmon et al. (2020), which shows how conventional soil management, especially the use of plows, destroys soil structure and decreases water infiltration, resulting in lower water availability for plants and increased surface runoff.

In addition, soil compaction resulting from these practices decreases porosity, negatively affecting aeration and water retention capacity, which impairs root growth and microbial activity. Bastida et al. (2019) point out that the intensification of agriculture and the frequent use of heavy machinery to turn the soil increase the density of the soil, further reducing its porosity and affecting the physical properties necessary for good soil health. In addition, tilling exposes MOS to greater aeration, which can result in its more intense oxidation.

Several researchers highlight the beneficial effect of grasses on the formation of soil aggregates, due to the greater incorporation of organic matter, which plays an effective role as a cementing agent and modifies the bonds between soil particles (Campos et al., 1995; Silva and Mielniczuk, 1998). This partly explains the equality in the percentage of aggregates between the NF and FC. Another important factor is the 25 years since the pasture was established, which may have been enough to stabilize the soil structure. For the native savannah areas, these researchers observed the presence of larger and more stable aggregates, which required greater kinetic energy to disintegrate compared to corn-green manure rotation systems, in which the grasses demonstrated a greater aggregating capacity than the legumes.

The practice of liming may have influenced the lower quantity of aggregates found in the Converted Savannah. Albuquerque et al. (2003) observed a reduction in the degree of clay flocculation after liming. According to this study, this change was attributed to alterations in the surface of the soil particles, which resulted in a reduction in the forces of attraction between the colloids, making dispersion in aqueous media easier. This dispersion of colloids can negatively affect the flow of solution and air in the soil, reducing the diameter and volume of pores and, consequently, decreasing the rate of water infiltration.

This dynamic also explains why the Natural Savannah showed similar values for the percentage of aggregates in the 4 to 2 mm class to the Natural Dense Forest, since $Al3^+$ and H^+ are the main flocculating agents in acidic soils (Morelli and Ferreira, 1987), since the soils are acidic and have a high concentration of exchangeable aluminum, even though the Savannah does not have the same amount of organic matter.

The dynamics of the formation of stable aggregates in the soil involves many factors that interact in a complex and different way in Savannah and Forest environments converted into productive areas. Thus, he found a higher aggregate stability index (wet WMD/dry WMD) in no-till systems compared to conventional planting systems, both with 12 years of implantation in a dystrophic Ultisol. Even in the face of the possible momentary negative impact on the soil's physical attributes during initial tillage, partial recovery can later occur when the soil is left untilled, a process that may have occurred in the areas studied. The GMD and WMD (Tables 3 and 4) of the aggregates are indicative of the stability of the soil structure.

At the depth of 0.20 to 0.40 m, the highest WMD and GMD were found in the NF, following the same trend observed so far, which indicates better physical-hydric conditions for the soil under this environment. Although not significant, a slight decrease in GMD and WMD can be observed in the SC area. The highest SOM (Soil Organic Matter) levels under NF correlate with greater aggregate stability, given its fundamental role in clay flocculation and aggregate cementation. In the SC area, both indices reflect the effect of mechanization on aggregate destruction. This destruction could be more severe if it were not for the incorporation of plant residues into the soil, a practice described in some studies as beneficial for promoting the incorporation of organic matter and improving soil structure.

Silva et al. (2008) contrasted the effect of various crops (cassava, maize, millet, Mucuna aterrima, and sorghum) with native vegetation in sandy-textured Ultisol under “cerrado”, identifying a significant decrease in WMD after one year of planting.

Table 3: Average Geometric Mean Diameter values (mm), ranked by Tukey's test (5%) according to treatments and depth.

	Depths (m)		
Treatments	**0.00 – 0.10**	**0.10 – 0.20**	**0.20 – 0.40**
Natural Forest (NF)	1.45 A	1.42 A	1.41 AB
Forest Converted do pasture (FC)	1.41 A	1.39 A	1.47 A
Natural Savana (NS)	1.19 A	1.26 A	0.96 AB
Savannah Converted to pasture (SC)	0.94 A	0.99 A	0.84 B

Capital letters for comparison between treatments at each depth.

Table 4: Average Weighted Mean Diameter values (mm), ranked by Tukey's test (5%) according to treatments and depth.

	Depths (m)		
Treatments	**00.0 – 0.10**	**0.10 – 0.20**	**0.20 – 0.40**
Natural Forest (NF)	2.15 A	2.08 A	2.00 AB
Forest Converted do pasture (FC)	2.10 A	2.07 A	2.11 A
Natural Savana (NS)	1.89 A	1.90 A	1.68 AB
Savannah Converted to pasture (SC)	1.62 A	1.58 A	1.43 B

Capital letters for comparison between treatments at each depth.

However, those authors found that 15 months later, soil structure was restored, with WMD in cultivated areas equaling that of native vegetation (with an average WMD value of 7 mm). This result can be explained by the high root density, the supply of organic matter, and the uniform distribution of exudates in the soil, all of which stimulate microbial activity. The values found by these authors were higher than those observed in this study, where the average value was 2 mm for NF and 1.68 mm for NS.

It is important to note that an aggregate with a high weighted mean diameter (WMD) does not always have a significant distribution of pores within it, which influences the structural quality of the soil (Bertol et al., 2004). The presence of more abundant roots under grass pastures seems to influence the formation of macroaggregates. Salton et al. (2008) observed similar results when evaluating soil aggregation and aggregate stability in various soil management systems. They found that soils with pastures, including permanent ones with *Brachiaria sp*., exhibited larger and more stable aggregates, significantly influenced by clay and carbon contents in the soil. The Sensitivity Index (SI) was obtained by the ratio of WMD in the converted area/WMD in the natural area (as shown in Table 5). This index is used to assess whether there has been soil degradation after the conversion from a natural environment to an agricultural one. An SI greater than 1 indicates an increase in aggregate stability, while a lower value indicates a reduction. In this sense, when comparing NF with FC, it is observed that only at the depth of 0.00 - 0.10 m was the SI less than 1. At the 0.20 to 0.40 m layer, the SI was greater than 1, indicating a slight improvement in aggregate stability.

Therefore, the conversion of NF into pasture does not seem to have caused drastic physical-hydric changes to the point of being classified as a degrading practice.

Table 5: Sensitivity Index for the comparison between converted area and natural area

	Depths		
Treatments	**0.00 – 0.10 m**	**0.10 – 0.20 m**	**0.20 – 0.40 m**
Natural Forest (NF)	1.00	1.00	1.00
Forest Converted do pasture (FC)	0.98	1.00	1.06
Natural Savana (NS)	1.00	1.00	1.00
Savannah Converted to pasture (SC)	0.88	0.85	0.86

Even after 16 years of establishment, the pasture in the NF appears to have maintained soil quality, as evidenced by other analyzed attributes. It was also observed that the clay content in the NF areas was high, both in NS and SC. However, a statistical difference was only observed at the depth of 0.20 to 0.40 m, where it was found that NF had the lowest clay content (as shown in Table 6).

No significant statistical difference was detected in the Flocculation Degree between NF and FC at any depth. However, the values were closer at the 0.00 to 0.10 m depth, which may indicate the beneficial effect of pasture on this parameter. Between NS and SC, no significant statistical differences were observed during the evaluation period.

In relation to the Natural Savannah (NS) and Converted Savannah (SC) areas, it was found that the Sensitivity Index (SI) was below 1 at all depths in the SC. Unlike other analyzed attributes, the SI in the SC indicated a reduction in aggregate stability with the introduction of pasture. This can be partially attributed to the lower clay content in the Ultisol under Natural

Savannah compared to the Ultisol under Natural Forest. In this context, according to Silva and Mielniczuk (1998), high clay content, organic matter, and the predominance of variable charge minerals generally characterize soils that are more resilient to physical changes resulting from management practices.

Table 6: Average Values of Flocculation Degree (%), Ordered by the Tukey Test (5%) According to Treatments and Depth

	Depths (m)		
Treatments	**0.00 – 0.10**	**0.10 – 0.20**	**0.20 – 0.40**
Natural Forest (NF)	73.05 Aa	72.85 Aa	60.21 Bb
Forest Converted do pasture (FC)	76.92 Aa	68.61 Ab	66.84 ABb
Natural Savana (NS)	87.56 Aa	77.94 Ab	83.01 Aab
Savannah Converted to pasture (SC)	88.58 Aa	77.52 Ab	79.30 Ab

Uppercase letters for comparison among treatments at each depth. Lowercase letters for comparison of depths within each treatment.

The Clay Dispersed in Water (CDW) showed an inverse response, as this attribute is negatively correlated with the Flocculation Degree (FD); that is, the more dispersed the clay, the lower the degree of flocculation (Table 7). Clay dispersion versus its degree of flocculation are key factors in soil aggregate formation and stabilization. The highest percentages of CDW were observed in the NF areas at all depths, with no statistical differences between NF and FC. Similarly, the savannah areas did not differ from each other; however, the percentage of CDW increased with depth, which also occurred in the Natural Dense Forest areas. This also explains the lower FD found at greater depths.

The higher percentages of clay content, observed in both savannah and Natural Dense Forest areas, can be explained by the higher levels of soil organic matter (SOM) found in the upper layers. SOM has a positive relationship with clay content and is one of the primary flocculating agents, as described by Filho (2008). This difference in soil structural stability due to organic matter has been demonstrated, highlighting the influence of the type of organic material and, especially, humic substances on the colloidal stability of clay suspensions. The increased flocculation of particles is associated with electrostatic modifications resulting from organic compounds (Albuquerque et al., 2003).

In savannah areas, the Flocculation Degree (FD) might be related to the activity of Al^{3+} and H^{+} ions, which are also significant flocculating agents. Soil liming can correlate positively or negatively with FD. In the former case, liming can increase plant biomass production (both in variety and quantity), which in turn boosts microbial populations, intensifying biomass decomposition and contributing to increased FD in clay. Another change resulting from limestone use that influences soil physical attributes is the reduction in Al^{3+} and H^{+} activity in the soil solution, which are the primary flocculating agents in acidic soils (Morelli and Ferreira, 1987). In this situation, the precipitation of Al hydroxide polymers can be observed due to the increased soil pH.

Another effect of limestone use that likely impacts soil physical attributes is the decrease in Al^{3+} and H^{+} activity in the soil solution, which are key flocculating agents in acidic soils (Morelli and Ferreira, 1987). Consequently, the precipitation of Al hydroxide polymers can occur due to increased soil pH.

The stability of aggregates between natural and converted environments observed in this study indicates that the conversion did not impair the physical-hydraulic quality of the Ultisol in Roraima. Most attributes showed contrasting results when comparing forest with Savannah, likely due to the combination of soil formation factors, particularly the parent material and vegetation. The Ultisol under savannah in this study originates from pre-weathered sediments of the Boa Vista Formation, while in the forest area there is evidence that it originated from the weathering of lateritic concretions, a material rich in iron. Therefore, more studies should be conducted, addressing a greater variety of both forest and savannah physiognomies, as well as additional pasture areas in different soil classes, to understand the pedology of these two ecosystems and develop alternatives for sustainable regional development.

Based on the results, average values of 93% and 90% were observed for the Transition Natural Dense Forest and pasture, respectively, at a depth of 0 to 10 cm. The high FD was associated with elevated SOM levels at this depth, with values of 1.85% and 2.13% for Natural Dense Forest and pasture, respectively. However, these SOM values were lower than those observed in this study (Table 7).

Table 7: Average Values of Dispersed Clay (%), Ordered by the Tukey Test (5%) According to Treatments and Depth

	Depths (m)		
Treatments	**0.00 – 0.10**	**0.10 – 0.20**	**0.20 – 0.40**
Natural Forest (NF)	6.80 Ab	8.00 ABb	13.00 Aa
Forest Converted do pasture (FC)	6.20 Ac	11.60 Ab	15.40 Aa
Natural Savana (NS)	1.20 Ab	3.80 Ba	4.60 Ba
Savannah Converted to pasture (SC)	1.40 Ab	4.20 Ba	3.80 Ba

Uppercase letters for comparison among treatments at each depth. Lowercase letters for comparison of depths within each treatment.

Soil organic matter (SOM) content was statistically higher in Natural Dense Forest areas, especially in Natural Forest (4.20%), which differed statistically from Converted Natural Dense Forest (2.53%) only at the 0.00 to 0.10 m depth due to the high coefficient of variation. No statistically significant differences were found between savannah areas at any of the evaluated depths, although a trend toward higher values in Converted Savannah was observed (Table 8).

The action of microorganisms decomposing plant residues on the surface results in the production of organic binders and an increase in fungal populations. These fungi, in turn, enhance aggregate stability by enveloping soil particles with their hyphae and by producing, along with other microorganisms, metabolites that act as cementing agents, particularly on the soil surface due to their direct contact with plant residues. The NF area was the only region that showed a statistically significant difference in SOM levels at all three depths. However, all areas exhibited a trend of decreasing SOM levels with increasing depth.

The accumulation of SOM significantly impacts nearly all chemical and physical-hydraulic attributes, culminating in increased aggregation, porosity, water retention, and reduced bulk density and penetration resistance. Therefore, based on the results obtained here, it can be affirmed that the interaction between SOM and soil physical and chemical characteristics is valid.

It is emphasized that the most effective systems for rehabilitating degraded areas are those that maintain or increase SOM levels, such as well-managed pastures. Soil management and conservation in the Amazon region involve guidelines that directly or indirectly address SOM accumulation in both agricultural systems and degraded areas intended for recovery. This is due to the high rates of SOM mineralization, given the elevated temperature and microbial activity in the soil (Cerri, 2003), which ensure nutrient recycling responsible for the ecological balance of the Amazon. When converting natural forest to pasture, the SOM input decreases due to the removal of a large variety of trees, which partly explains the differences in physical-hydraulic attributes between NF and FC in this study.

Over time, SOM stocks are consumed by microorganisms, leading to soil fertility loss and the onset of soil degradation, which hampers agricultural production. SOM levels in savannah areas reflect the differences in vegetation cover and its incorporation into the soil. Contrary to what was observed in the NF area, the savannah area with the highest SOM content was the SC at all depths. This response likely resulted from the biomass produced by crops planted in direct planting systems, combined with pastures that are known to incorporate high amounts of SOM into the soil. In this sense, savannah areas were less sensitive to conversion, slightly improving SOM content in the soil.

Table 8: Average Values of Soil Organic Matter (%), Ordered by the Tukey Test (5%) According to Treatments and Depth

	Depths (m)		
Treatments	**0.00 – 0.10**	**0.10 – 0.20**	**0.20 – 0.40**
Natural Forest (NF)	4.20 Aa	2.66 Ab	1.45 Ac
Forest Converted do pasture (FC)	2.53 Ba	1.86 Ab	1.37 ABb
Natural Savana (NS)	0.94 Ca	0.68 Ba	0.34 Ba
Savannah Converted to pasture (SC)	1.02 Ca	0.71 Bab	0.66 ABb

Uppercase letters for comparison among treatments at each depth. Lowercase letters for comparison of depths within each treatment.

This explains the low variation between Natural Savannah and Savannah Converted to Pasture and the high variation between NF and FC in Penetration Resistance, Soil Bulk Density, Gravimetric Moisture, Total Porosity, Available Water Capacity, and Aggregate Stability values, all of which are significantly dependent on SOM levels in the soil. Studies conducted in the Amazon region have revealed a trend of increasing carbon (C) proportion derived from pastures over time. This is due to the C enrichment from C4 photosynthetic cycle grasses. Consequently, the remaining C stocks from the Natural Dense Forest decrease while the C stocks from pastures increase, as observed in studies conducted in different locations such as Rondônia (Neill et al., 1996), Manaus (Desjardins et al., 2004), Pará (Desjardins et al., 1994), and Acre (Salimon et al., 2007).

The SOM levels observed in the pasture areas studied may have mitigated more significant changes in soil physical-hydraulic attributes. Flores et al. (2007) similarly found no significant differences in soil porosity or bulk density with intense cattle grazing, attributing this phenomenon to the plant residues deposited on the soil (5.4 Mg ha^{-1}) from past crops managed in direct planting systems, which reduce the effect of animal trampling on surface soil compaction. This may explain the greater range found in soil bulk density and porosity between NF and FC, as there was no well-managed planting system in the Forest Converted to Pasture as was the case in the Converted Savannah.

4. Conclusions

The research demonstrated that the conversion of natural ecosystems into pasture areas, particularly in Natural Forest and Natural Savannah environments, did not result in significant loss in soil aggregate stability. Despite agricultural intensification, the data suggest that, with proper management, it is possible to preserve the physical structure of the soil. It was observed that, at greater depths where there is a higher organic matter content, aggregates are more stable, indicating that practices which conserve this organic matter are crucial for maintaining soil structural quality.

Furthermore, the establishment of pastures in Savannah areas showed a reduction in aggregate stability, possibly due to recent intensive mechanization and soil disturbance. This underscores the need for management policies that balance agricultural productivity with soil conservation, considering the specifics of each ecosystem. Thus, the study contributes to understanding how different agricultural practices can influence soil physical properties, providing important guidelines for the sustainable management of these areas in the Amazon.

Authors' Contribution

Since the conception of the idea and most of the execution of the practical field and laboratory work was carried out by Diego Lima de Souza Cruz (currently assistent professor at UFRR) and his advisor, Prof. Dr. José Frutuoso do Vale Júnior, from the Graduate Program in Agronomy at UFRR (POSAGRO/UFRR), who also contributed writing and the submission process of the article. Collection of field/laboratory data and statistical analysis and interpretation were carried out by Prof. Dr. Leandro Camargo Neves and Prof. Dr. Ozimar Lima Coutinho, as well as writing the methodolgy and discussion of the article. Jéssica Milanez Tosin Lima and Laís de Brito Carvalho were responsible for updating the bibliographic references and controlling the journal's submission/correction process.

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