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Influence of Forest-Pasture on the Erodibility of a Dystrophic Red Yellow Latosol in the Southwestern Amazon

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ABSTRACT

The objective was to evaluate the erodibility of a Dystrophic Red Yellow Latosol from the Mutum Paraná River sub-basin to understand the influence of forest conversion and different pasture temporalities on its physical structure and the potential for sediment release after surface samples undisturbed were subjected to the Inderbitzen experiment. Tests of Mechanical Resistance to penetration and physical parameters under forest and pasture conditions were carried out. A simulation of surface runoff by water spraying (Inderbitzen) was carried out to analyze the disaggregation and transportability of particles. The erodibility equation (K factor) was applied, and the Limits of Consistency were defined to measure the Plasticity Index of the soil that qualifies its erodibility. The pasture and forest samples submitted to the experiment indicated soils of low susceptibility to erosion, even under conditions of maximum slope of the area (17°) and under intense simulated flow (3 L and 6 L min⁻¹) of sprinkler, not showing large losses of sediments or intense surface degradation. There was a relation between soil physical properties and the response of the sample in the experiment. Samples with higher total porosity ($r = 0,89$) and lower apparent densities ($r = -0,88$) showed higher disaggregation. There was a significant correlation between the simulated samples that showed lower sediment losses, with a higher percentage of clay ($r = -0,65$). Samples with a higher percentage of total sand indicated higher percentages of disaggregation ($r = 0,68$). Erodibility data obtained by the K-factor equation and Plasticity Index endorsed the low soil erodibility

Keywords: Inderbitzen, Disaggregation, Atterberg, Mutum, Sprinkle.

Influência da conversão Floresta-Pastagem na Erodibilidade de um Latossolo Vermelho Amarelo Distrófico na Amazônia Sul Ocidental

RESUMO

O objetivo foi avaliar a erodibilidade de um Latossolo Vermelho Amarelo Distrófico da sub-bacia do rio Mutum-Paraná para compreender a influência da conversão da floresta em diferentes temporalidades de pastagens em sua estrutura física, potencial de desprendimento de sedimentos, após as amostras superficiais indeformadas serem submetidas ao experimento Inderbitzen. Realizou-se ensaios de Resistência Mecânica à Penetração, levantamento de parâmetros físicos sob condições de floresta e pastagem. Para analisar a desagregação e transportabilidade de partículas, realizou-se simulação de escoamento superficial por aspersão d'água – o Inderbitzen. Aplicou-se a equação de erodibilidade (fator K) e definidos os Limites de Consistência para mensurar o Índice de Plasticidade do solo que qualifica sua erodibilidade. As amostras de pastagem e floresta submetidas

ao experimento indicaram solos de baixa susceptibilidade à erosão, mesmo em condições de declive máximo da área (17°) e sob fluxo simulado intenso (3 L e 6 L min⁻¹) de aspersão, não demonstrando grandes perdas de sedimentos ou intensa degradação superficial. Observou-se correlação entre as propriedades físicas do solo e a resposta da amostra no experimento. Amostras com maior porosidade total ($r = 0,89$) e menores densidades aparentes ($r = -0,88$) apresentaram maior desagregação. Houve correlação significativa entre as amostras simuladas que apresentaram menores perdas de sedimento, com maior percentual de argila ($r = -0,65$). Amostras com maior percentual de areia total indicaram maiores percentuais de desagregações ($r = 0,68$). Dados de erodibilidade obtidos pela equação do fator K e Índice de Plasticidade, endossaram a baixa erodibilidade do solo no experimento.

Palavras-chave: Inderbitzen, Desagregação, Atterberg, Mutum, Aspersão.

Introduction

The process of water erosion is studied as a phenomenon that involves a set of variables shaping the landscape. Soil erosion by water results in the detachment, breakdown, and transport of soil particles due to physical and mechanical action. It is worth noting that the rate and amount of disaggregated and transported material during the erosive process can be influenced, in addition to natural conditions, by human interactions within the natural system (Guerra et al., 2014; Silva et al., 2007). The model of occupation in the Amazon advocates for economic development focused on the exploitation of natural resources, and the increase in cattle herding has been linked to the main causes of deforestation in this region (Moura et al., 2018).

Deforestation, in turn, has been identified as the primary cause of erosion in the last 60 years in the Amazon (Riquetti et al., 2023) and creates a cause-and-effect relationship with other types of anthropogenic interventions (Skidmore et al., 2021). Lense et al. (2020) pointed out a 12% increase in deforestation, which was associated with a 312% increase in water erosion, equivalent to about 180 million tons of soil lost per year.

Care is necessary when analyzing how human interactions and the resulting territorial dynamics cause changes in the soils of the Amazon region, a region that represents the axis of agribusiness development in the country, with special emphasis on the intensive use of soil in agricultural activities (Fearnside, 1989; Skidmore et al., 2021).

The implementation of pastoral activities, prevalent in the region, combined with the high pluviometric conditions resulting from convective rains, have indicated how susceptible the region is to exploitation and alteration of natural resources. These characteristics can intensify erosion, as rain is the conditioning agent that provides energy for the

occurrence of the erosive process in the region (Jasechko et al., 2013; Santos et al., 2020; Lense et al., 2020).

Soils constitute one of the fundamental variables in the natural and dynamic system established in the sub-watersheds. These soils are subject to changes due to the influences of human activities, derived from the historical occupation model in the Amazon region of the upper Madeira River. The basins of Mutum-Paraná and the São Francisco River are representative examples of this occupation pattern, where anthropogenic interventions play a significant role in altering and evolving the soils over time (Nunes, 2014; Watanabe et al., 2018). Soils are in continuous and integrated contact with the atmosphere and undergo various chemical, physical, and biological processes that define the arrangement of their particles with their properties and nature, inherited from this process interaction over time (Bertoni & Lombardi Netto, 1999), mainly since the implementation of pastures (Lima et al., 2023).

These intrinsic characteristics that soil develops can express its own potential for resistance to the efforts from variables involved in the erosive process, due to the physicochemical and morphological aspects characteristic of its composition, which define its degree of erodibility. This refers to the soil's capacity to undergo erosion and can be defined as the greater or lesser ease with which soil particles are detached due to a complex physicochemical interaction between its morphological properties (Denardin, 1990; Vilar; Prandi, 1993; Lal & Elliot, 1994).

Studies on soil erodibility have sought to portray this susceptible potential of soils through analysis methodologies, which range from the use of empirical equations to estimate the potential soil loss by water erosion (Neves et al., 2011; Di Raimo et al., 2019), to actual field experimentation, both under simulated rainfall on erosion plots, and during monitored periods under natural rain (Misra & Teixeira, 2001; Aquino et

al., 2012; Thomaz, 2013; Schick et al., 2014; Carvalho et al., 2022).

Data on soil properties that facilitate the estimation of the erodibility factor have also been used, based on characteristics that are quicker, simpler, and less costly to obtain, such as texture, content and type of oxides, and aggregate stability (Nunes & Cassol, 2008). In general, these models denote, on one hand, a generalization of processes regarding the use of general empirical equations; and on the other hand, rise in logistic costs and increased complexity in experiment execution. As an alternative to these models, we have the proposal of the Inderbitzen Experiment, which emerges as one of the alternatives to these models, because, by simulating the sprinkling (showering) of water over an undisturbed sample, it can support the study of erodibility through the measurement of disaggregation and sediment transport from undisturbed soil samples in the face of the dynamic impact of water and its surface runoff.

During the experiment, the sample is positioned on a surface that coincides with a plane of variable inclination, which allows simulating the degree of slope, while receiving a controlled water flow. Erodibility, in this case, is measured in terms of soil loss rates and percentages, according to the simulated conditions (Inderbitzen, 1961; Bastos et al., 2000; Vieira et al., 2019).

The Inderbitzen test has demonstrated its capacity to represent the erodible potentials of the studied soils through comparative analysis of the erodibility of soils from the saprolitic horizon and pedological horizon B (Moreira & Polivanov, 2018), including when associated with the study of aggregate stability and monitoring plots of sheet erosion under natural rains and the differentiation between types of predominant erosion in erosive features (Santos et al., 2002; Vieira et al., 2019) and the assessment of the erodibility of a typical dystrophic sandy Neosol litolic (Thoma et al., 2022).

Although the experiment involves results that account for the quantitative loss of sediments per test, the qualitative and comparative nature of the simulated conditions will prevail in the data analysis (Thoma et al., 2020). And, as a disaggregation test, the Inderbitzen proves satisfactory in the qualitative analysis of erodibility. In Pinheiro et al., (2022), the Inderbitzen test showed the highest correlation with soil behavior in the field.

The conversion of forest into pasture promotes significant changes in the soil from a physical, chemical, and biological standpoint (Desjardins et al., 2004; Stewart et al., 2020). The effect of modifications over time can be observed in physical properties of the soils of research interest, usually associated with the decrease in soil aggregate stability and the average diameter of aggregates with years after deforestation (Shao-Shan, 2008).

Among the most notable consequences of these transformations are the alteration in penetration resistance and soil shear characteristics, fundamental factors for understanding erosive processes and the hydrological dynamics of landscapes modified by human action. In Martinez & Zinck (2004), there is evidence of an increase in soil density and resistance to penetration, in opposition to a decrease in porosity and infiltration rate over the time of forest conversion. It is also important to note that these physical soil properties are often used as indicators of its compaction, affecting root development capacity, soil aeration, water infiltration, and consequently, permeability and erodibility of soils (Silva et al., 2020; Matos & Bassaco, 2023).

Compaction in pastures indicates that there was an expulsion of air and water from the soil's porous spaces causing a decrease in internal pore spaces after being subjected to an external pressure from agricultural machinery traffic or animal trampling; this is reflected in soil penetration resistance (Szymczak et al., 2014; Matos & Bassaco, 2023).

The mechanical resistance to penetration demonstrates the reorganization of soil aggregates resulting from the forces acting on it, in the case of pastures associated with cattle trampling. It is directly influenced by density and porosity and can vary according to soil use and vegetation cover (Augusto et al., 2022). The decrease in water content increases soil resistance causing a greater mechanical impediment to penetration, and the greater the resistance to penetration, the more compacted the soil (Collares et al., 2008).

Compacted soil presents an increase in density and porosity that directly affects water infiltration and percolation in the soil profile, therefore it is associated with the study of erodibility (Couto et al., 2021). This occurs in the short term due to both exposure of the surface to rainwater and temperature fluctuations, as well as animal trampling (Cerqueira et al., 2017; Shao-

Shan, 2008). This compaction can vary depending on the time the surface is exposed, so the longer the exposure time, the greater the compaction. In this case, compaction is the factor that expresses the modification of the physical properties of the soil caused by the transformation of the forest into pasture and can affect the erodibility responses of soils (Pandur et al., 2022).

Soil shearing is related to the soil's capacity to resist deformations or ruptures under the action of tangential forces, being a crucial parameter to understand the stability of erosion in pasture areas. It is associated with the capacity of soil particles to bind to water molecules and offer internal resistance to the forces imposed on the rupture of soil particles, and therefore has a direct relationship with the moisture factor (Couto et al., 2021). Higher moisture content in the soil implies greater soil compaction and the formation of deeper grooves when a load is imposed on the soil structure. As moisture content increases, the cohesion between soil particles decreases and the soils reach maximum vulnerability; more compacted soils present greater resistance to shearing and, therefore, lower erodibility (Bazarov et al., 2020; Couto et al., 2021; Pandur et al., 2022).

Changes in the physical properties of soil, such as resistance to penetration and shearing, in pasture areas, have direct implications for the sustainability of ecosystems and agricultural production. Management strategies that promote adequate vegetal cover, controlled trampling practices, and pasture rotation are essential to mitigate soil compaction and preserve its structure and functionality (Vogel & Fey, 2016).

Therefore, the research aimed to evaluate the erodibility of a Dystrophic Red-Yellow Latosol (LVAD) to understand changes in its physical structure promoted by the influence of forest conversion into pastures. The study of LVAD erodibility was associated with the potential for sediment detachment, after undisturbed surface samples were subjected to the Inderbitzen experiment and their responses correlated with basic physical soil properties, such as Bulk Density, Total Porosity, and Mechanical Resistance to Penetration. We highlight the fact that it is widely discussed that forest areas, possessing vegetal cover that attenuates the impact of water on the soil, are less erodible (Korkanc et al., 2008; Hassane et al., 2023), up to 70% less than the detachments observed in pastures (Parhizkar et al., 2020), but it is also necessary

to consider that forest soils have a more porous and less dense structure compared to already deforested areas or pastures, and this basic element of the physical structure of soils can confer low resistance to shearing (Bazarov et al., 2020), which implies greater detachment of particles when the recently deforested soil is exposed to weather conditions.

Over time after the removal of vegetal cover, the tendency is, initially, the depletion of surface soil particle detachments, and subsequent changes in physical parameters such as bulk density and total porosity, increase in resistance to shearing and mechanical penetration, justified by the increase in friction of the forces imposed on the particles composing the soil (Holthusen et al., 2020). In this sense, after these changes, the soil begins to have a physical structure more resistant to the disaggregating forces imposed than forest soil.

Our hypothesis suggests that forest soils, recently converted to pasture, present low resistance to contact with rainwater and tend to mobilize a greater amount of particulate in the occurrence of erosive processes. This fact, in the short term, can trigger nutrient losses and erosive processes that did not exist in these areas.

The greater susceptibility of forest soil samples compared to pasture soils is due to the modification of their physical properties that affect resistance to shearing and the depletion of sediments already transported by surface runoff, although we recognize that, in the location of these soils, vegetation plays an essential role in reducing the potential for erosion and improving soil stability through rooting, which increases the cohesion between soil particles (Menezes et al., 2020).

This research is relevant as it endorses the problem of vegetation removal for pasture implementation and because most studies on the conversion of the Amazon Forest have focused on hydrochemistry, greenhouse gas emissions, and carbon depletion. Conversely, there are not enough studies on changes in soil properties in the Amazon, with emphasis on soil erodibility (Thomaz et al., 2020). Additionally, erodibility tests performed on undisturbed samples are rare it is important to understand soil erodibility considering its architecture or totality (Fernández-Raga et al., 2017; Thomaz & Pereira, 2017).

Materials and Methods

The study was carried out in pastures with different conversion time (4, 7, and 12 years) and forest areas, settled in a Dystrophic Red Yellow Latosol that composes the Mutum-Paraná River sub-basin, located northwest of the state of Rondônia, between the cities of Porto Velho and Nova Mamoré,

upstream from the capital Porto Velho. The basin's mouth is in the Madeira River, and the sector of the basin studied in this research constitutes a headwater area located upstream of the main hydrographic system. With approximately 330.62 km², the basin contains about 45% of its total area within the Karipuna Indigenous Reserve. Figure 1 indicates the location.

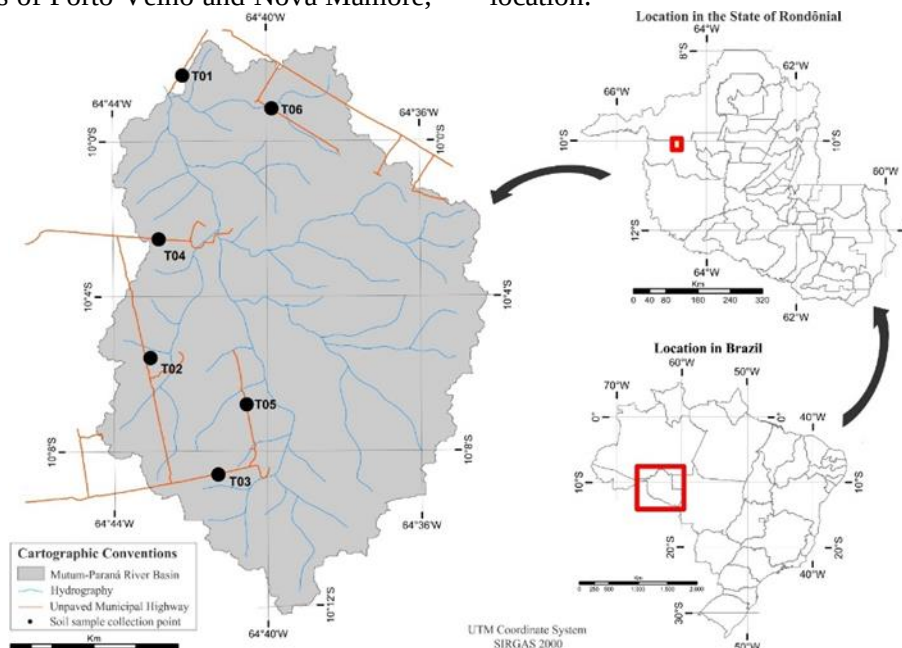


Figure 1. Study area location map and data collection points. Source: Organized by the authors based on Brasil (2018; 2021) and Rondônia (2021).

A collection sequence was designed based on the definition of a 20m transect (with three repetitions in the sample collection) to obtain physical parameters of the soil and samples for simulation in the Inderbitzen experiment, using temporality of pastures, areas of recent deforestation, and forest areas as a criterion for defining the established points. The description of the transects carried out at the established points can be seen in Table 1. It was noticed that the data obtained referring to total porosity showed higher variability when compared to the averages for the apparent density represented by the standard deviation variable as shown in table 1.

In the field, the following activities and measurements were carried out:

1) Tests of Soil Mechanical Resistance to Penetration (SMRP) via Impact Penetrometer model IAA/PLANALSUCAR (Stolf, 1991) with prospecting

up to 40cm in depth in 5 repetitions for each established 20m transect;

2) Collection of undisturbed samples in volumetric rings for analysis of bulk density, total porosity, and gravimetric moisture, in the 0-20 and 20-40 cm layers, following the technical procedures of Teixeira et al. (2017), with three repetitions;

3) Collection of undisturbed surface samples in metallic ring squares, with an approximate volume of 1,176cm³, to carry out the Inderbitzen test (Freire, 2001; Higashi et al., 2011), with three repetitions;

4) Collection of samples to perform the Liquidity Limit and Plasticity Limit tests with the repetitions provided, respectively, in NBR 06459/1984 and NBR 07180/1984, with three repetitions;

5) Collection of samples to obtain the particle size and organic matter composition necessary to apply the K Factor Equation, according to Denardin (1990),

in the layers of 0-20 and 20-40 cm in depth in the six transects, with three repetitions.

Table 1. Description of the established points for the description of Red Yellow Latosol.

Established points	Apparent density (g cm ⁻³)	Total Porosity (%) ¹	Soil texture	General description
Pasture (P1)	1.59 ± 0.11	39.6 ± 4.2	Sandy loam	Seven years of use interlarded with trees and shrubs, prominent presence of rocky outcrops.
Pasture (P02)	1.53 ± 0.08	41.8 ± 3.1	Sandy clay franc	Twelve years of use; smooth wavy relief in the area and presence of laterites.
Pasture (P06)	1.52 ± 0.07	42 ± 2.9	Sandy clay	Four years of use; intensive use in the last three years with bovine trampling without handling techniques.
Forest (F03)	1.37 ± 0.03	48.04 ± 1.3	Sandy clay franc	Open Ombrophilous Forest with pioneer vegetation and selective logging without management.
Forest (F04)	1.39 ± 0.03	47.2 ± 1.3	Clayey	
Recent Deforestation (D05)	1.42 ± 0.03	46 ± 2.2	Sandy clay franc	Seven years of use interlarded with trees and shrubs, prominent presence of rocky outcrops.

Source: Organized by authors based on field data.

¹ The bulk density and total porosity values refer to the average of the 3 replicates in the first layer of soil (0-20 cm).

The erodible potential of the Dystrophic Red Yellow Latosol under different pasture temporalities can be estimated by analyzing the data of physical soil parameters, combined with the sediment loss responses obtained through the Modified Inderbitzen

experiment (direct method), through the erodibility equations applied (indirect method), and the definition of the Consistency Limits (indirect method), as shown in Figure 2.

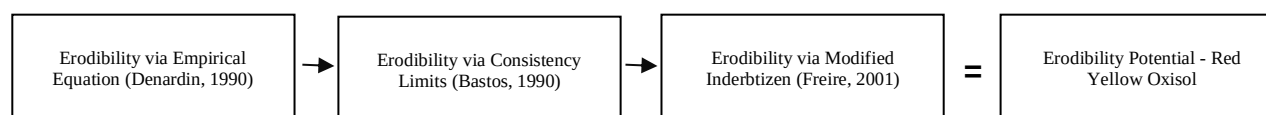


Figure 2. Erodibility Measurement Scheme for Dystrophic Red Yellow Latosol. Source: Organized by the authors.

The Inderbitzen device and test was adapted from the experiment by Freire (2001). It is based on other studies that were important for the evolution of the experiment to overcome some problems of its original conception, mainly regarding its execution with the sample below the sprinkler, in an attempt to reproduce particle detachment processes through the splash effect, as recorded in Almeida et al. (2015), Bastos et al., (2001), Fácio (1991), Higashi et al. (2011), Lemos et al. (2007), Moreira & Polivanov (2018), Santos et al. (2002), Silva & Melo (2016), and Thoma et al. (2020).

The Inderbitzen experiment features a PVC tubular frame with a variable-tilt grated ramp. The water sprinkler line with perforated pipes proposed by Freire (2001), who presented the Modified Inderbitzen, was modified by Higashi (2006), who proposed installing a sprinkler at the same distance of 20 cm from the sample, improving the test conditions since its dimensions coincide with the dimensions of the specimen. For regulation and maintenance of the water flow, the tubular structure of the equipment was connected to a water tank exclusively installed to

supply the constant flow in the test with a capacity of 20 L (Figure 3).

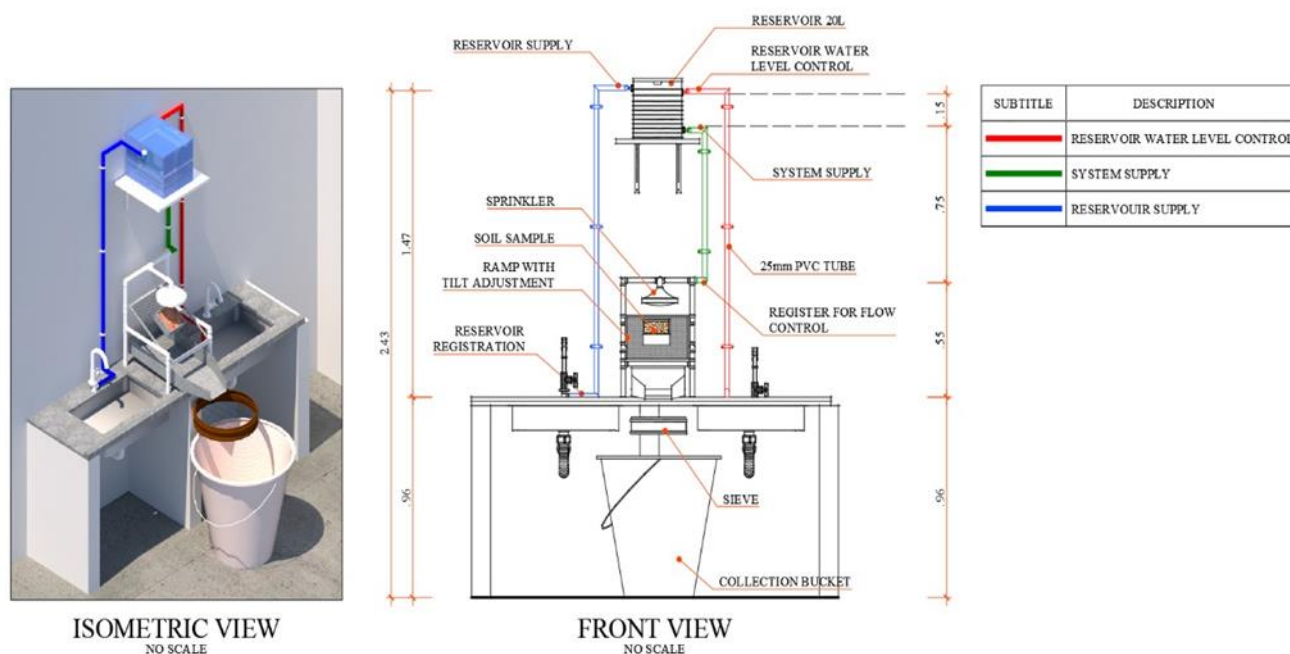


Figure 3. Representative scheme of Inderbitzen assembled with water tank supply. Source: Organized by the authors based on Freire (2001) and Higashi et al. (2011).

Fixed test execution parameters were defined, and the undisturbed soil sample collected was subjected to continuous spraying with flows of 3 and 6 L min⁻¹, sufficient to generate flow over it and enable the observation of its disaggregation potential in response to spraying (Lemos et al., 2007; Vieira et al., 2019), on a slope with a 17° slope, corresponding to the maximum slope of the terrain found in the sub-basin. The disaggregated particles were collected and quantified in sieves with a 0.075mm mesh at predetermined periods of 1, 5, 10, and 30 minutes, which gives the amount of disaggregated sediment loss of the undisturbed sample in relation to the time.

Soil erodibility was expressed as a percentage of eroded mass from the equation proposed by Higashi (2006) and Higashi et al. (2011), given by the ratio between the weight of the total eroded material, including the weight of passing material retained in each sieve after drying, and the total dry weight of the sample (Equation 1).

$$E = (P_{tes} - P_t) * 100 \quad (1)$$

Where:

E = Erodibility of the soil in %;

P_{tes} = total weight of "dry" eroded soil in grams;

P_t = total weight of the dry sample after testing in grams.

The erodibility factor (K) expressed in Mg ha h ha⁻¹ MJ⁻¹ mm⁻¹ was obtained using the mathematical model proposed by Denardin (1990), according to Equation 2.

$$K = 7,48 * 10^{-6} * M + 4,48059 * 10^{-3} * P - 6,31175 * 10^{-2} * DMP + 1,03957 * 10^{-2} * R \quad (2)$$

Where:

M = is given in % of (fine sand + silt) x [(fine sand + silt) + coarse sand];

P = is the estimated permeability value by analyzing in an integrated way the entire soil profile data, up to the top of the C horizon, whose values range from 1 = very low to 6 = fast;

R = is given in %, refers to the content of [coarse sand x (organic matter content/100); and

DMP = refers to the weighted average diameter of soil particles in millimeters, as indicated in Equation 3.

$$DMP = [(0,65 * coarse\ sand) + (0,15 * fine\ sand) + (0,0117 * silt) + (0,00024 * clay)] / 100 \quad (3)$$

The values referring to the percentages of sand fractions (coarse, fine, and medium), clay, and Organic Matter were obtained by sending the samples to a specialized laboratory (Agroanalysis-MT), whose analyzes follow the pattern established in Cantarella et al. (2001). As no hydraulic conductivity tests were performed, values described for the SOTRO (Soils and Lands of Rondônia) units were adopted to establish the permeability values, where soil profiles were mapped and detailed in the Rondônia (2001) database.

The Liquidity Limit of the soil was obtained from a test directed by NBR 06459/1984 and the Plasticity Limit prescribed by NBR 07180/1984. For the analysis of the erodibility proposed here, the Plasticity Index (PI) was considered, which is given by the difference between the Liquidity Limit presented and the Plasticity Limit, so that the higher the value of the IP, the more plastic the soil presents and less erodible it will be (Pinto, 2006).

The collected data were processed using Excel 2016 and Sigma Plot 12.0 software for analysis and interpretation. The statistical analysis included the application of ANOVA and normality tests, as well as the t-test. These analyses enabled the identification of sample groups belonging to the same environment and the differences found among them. Furthermore, correlations between variables were examined. The

primary objective was to observe measures of central tendency and data variability, aiming to find typical values that represented the physical properties in the analyzed transects. This was achieved through the average of the data measurements obtained from field-collected information, and also through simple linear correlation graphs (Ferreira, 2009). The statistical analysis of these data provided important insights to understand the relationship between the variables and identify significant patterns or trends between soil losses and physical properties the soil exhibited after forest conversion to pasture.

Results and discussion

Inderbitzen Experiment and Soil Loss

The samples simulated in the experiment showed disaggregation responses in a superficial and subsurface way when water infiltrates the sample. There was a higher loss of sediment during the first 5 minutes of the test, characterizing the “trend curve” of sediment loss in the initial minutes, also verified in works such as Fácio (1991), Higashi et al. (2011), Moreira & Polivanov (2018) and Silva et al. (2022). Therefore, it can represent the applicability of the experiment, even in different conditions of flows or slope gradients (Figure 4).

The percentages of soil loss per sample up to 5 minutes yielded an average of 66,2% of the total sediments disaggregated during the 30 minutes experiment, while the sediments disaggregated in the interval between 10 and 30 minutes correspond to an average of only 12% of the eroded total — it is associated with the issue of sample saturation in the initial minutes.

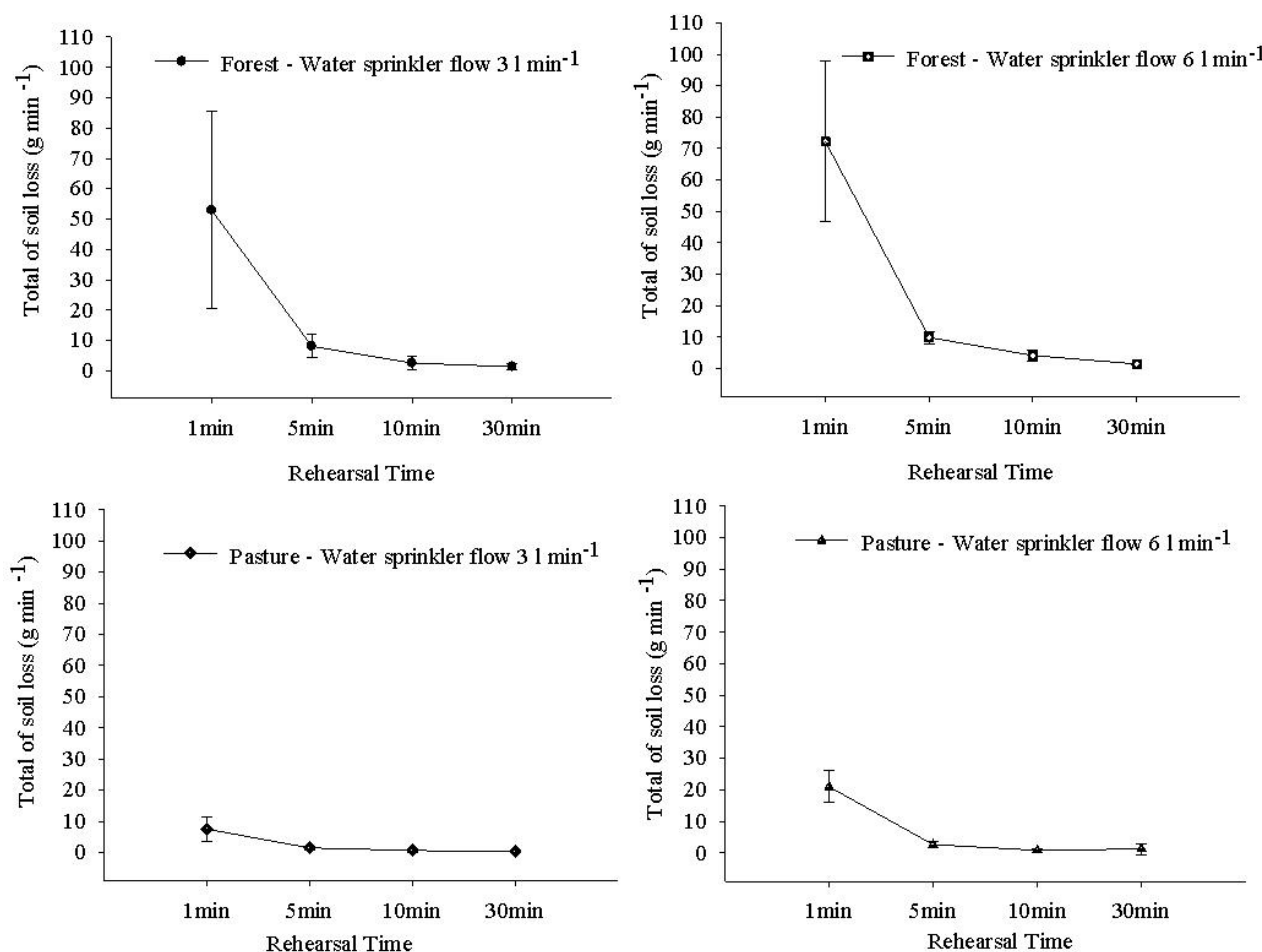


Figure 4. Plot of sediment loss velocity and test time in minutes. Source: Organized by the authors.

The transects P01, P02, and P06 configure pasture environments with different temporalities and intensities of use, which occur from the density of cattle by area and the time of continuous use of pasture (Junior et al., 2013; Miguel et al., 2009). Considering the hydroerosive dynamics during the test, it was observed that the time interval with the greatest soil loss, regardless of the environment, was between 1min and 5min. There is high variability in sample responses as we note the high standard deviation among the means for the first 5 minutes of the test, (the initial minutes) as the test time progresses (interval of 10min and 30min), the soil losses and the variabilities among the means decrease. After 10min of experimental time, the disaggregations among the samples were similar and did not show statistically significant variations between forest and pasture environments, represented by the means of $1.96 \pm 1.7 \text{ g min}^{-1}$ and $0.47 \pm 0.2 \text{ g min}^{-1}$

($p \text{ value} > 0.05$), respectively. Comparing the tested flows of 3 L min^{-1} and 6 L min^{-1} , it was verified that there were no significant differences between the means obtained in the experiment. In the flow of 3 L min^{-1} , the average detachment was $64.9 \pm 29 \text{ g min}^{-1}$ and in the flow of 6 L min^{-1} , $87.7 \pm 23 \text{ g min}^{-1}$ ($p \text{ value} = 0.489$), for the forest environment, for example. For the pasture environment, the means between flows differed significantly ($p = 0.01$); in the flow of 3 L min^{-1} , the average soil loss was $9.9 \pm 4.6 \text{ g min}^{-1}$, and with the flow of 6 L min^{-1} , it was $25.8 \pm 5 \text{ g min}^{-1}$.

Compared to forest soil samples, these differences are reflected not only in soil loss but also in other soil characteristics that can represent its erodibility, such as consistency limits, sample size, total porosity, soil density, and penetration resistance modified according to the soil formation time. Exposure to acting external factors, both natural and

anthropogenic (Dexter, 1991; Misra & Teixeira, 2001; Thomaz & Antoneli, 2020).

Answers of the Inderbitzen Experiment in Forest Soils

Total loss percentages indicated that the greatest soil losses occurred in forest soil samples, and those that disintegrated the least belonged to pasture environments. The means between Forest were statistically distinct (p value = 0.002 and F value = 18.9 when critical F = 5.9) and the greatest soil loss was attributed to the forest environment (Figure 5.b).

The data representation through the box plot shows asymmetry in distribution and data dispersion, allowing the reiteration of these central tendencies and variations observed in the analysis described above, mainly through the difference between the third and first quartile, which provides a measure of data dispersion in the central range. It is highlighted that no atypical or outlier values were found within the analyzed dataset. We notice that the responses in forest samples showed greater data variability compared to pasture samples (Figure 5.a).

The physical structure of Forest soils with higher porosity ($49.3 \pm 1.6\%$) and lower density ($1.34 \pm 0.05 \text{g/cm}^3$) influenced the low penetration

resistance values found in comparison to pasture areas (Augusto et al., 2022). This structure suggests low shear resistance to forest soils, making them more susceptible to sediment detachment via direct sprinkling operation on the sample (Bazarov et al., 2020; Couto et al., 2021). More compacted soils exhibit higher shear resistance and therefore, lower erodibility (Couto et al., 2021; Pandur et al., 2022).

The physical structure identified in the samples is a common trend in forest soils (Wilpert, 2022), therefore, the statement that forest soils exhibited greater soil loss than pastures should be analyzed with caution, as the experiment simulates conditions of direct water sprinkling on an undeformed sample and does not consider the fundamental element in the exchange of matter and energy in forest environments, which is phytostasis (Moreira, 2009; Tricart, 1977). In the environment where these soils covered by Ombrophilous Forests occur, these physical properties express optimal conditions for water infiltration and permeability in the profile not favorable to the formation of intense erosive processes, a fact that tends to condition vertical movements of pedogenetic origin in relation to the active morphodynamics in the system (Tricart, 1977).

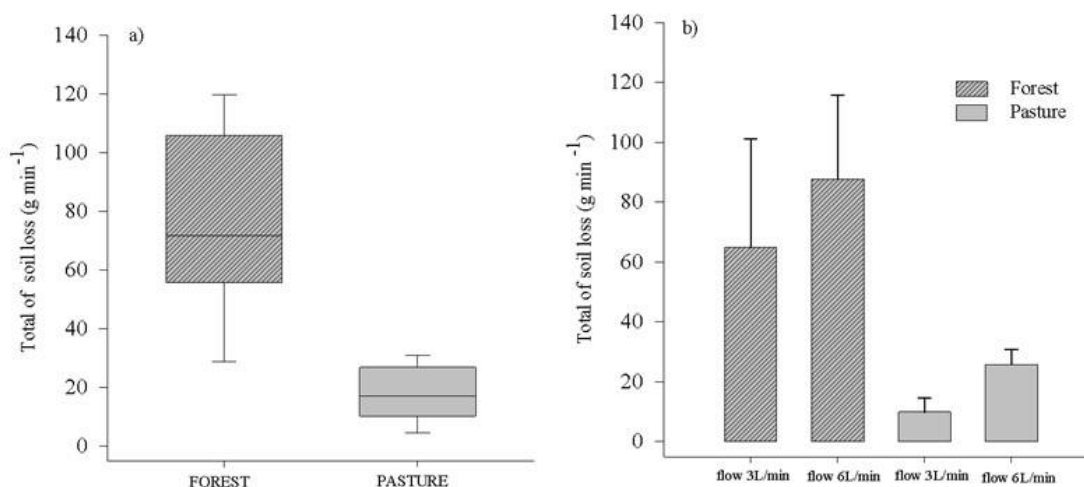


Figure 5. Total of soil loss in the Inderbitzen experiment in forest pasture environments. Source: Organized by the authors.

The experiment reveals susceptibilities related to the structure of the soil sample subjected to direct water spraying and, in this sense, the higher susceptibility to disaggregation of forest samples (F03,

F04, and D05) expresses a question of Shear Adhesion (SA) for the force acting on the water spray during the test. Soil shear is defined as a rupture caused by relative displacements between soil particles. SA is

given by the resistance that the soil structure presents to rupture due to the friction between the particles and the cohesion of the soil on the surface (Rocha et al., 2002; Silva et al., 2004; Reichert et al., 2016; Couto et al., 2021).

Soils in natural environments covered by native forest usually have a low SA (Iori et al., 2012), which provides these soils with higher susceptibility to erosion in the short term, after the forest conversion. Therefore, in this case, SA is associated with the particles' detachment from the soil that occurs when the shear stresses overcome this shear strength. Shear strength is associated with the soil particles' capacity to bond to water molecules and provide internal resistance to the forces imposed on the soil particles' rupture. Soils more susceptible to erosion possess the lowest shear resistance values (Misra & Teixeira, 2001; Silva et al., 2004; Bastos, et al., 2008; Couto et al., 2021). The removal of forest cover in these areas conditions the soil to the sediment loss in the short term and endorses the issue of the forest conversion into pastures in the Amazon environment. It is understood not only from the low SA that the soils from forest environments present, but also the susceptibility to sediment disaggregation that the experiment demonstrated, including in a situation of recent deforestation where the soil, despite its post-fire condition, retains physical characteristics from the moment before the removal of vegetation (see Figure 5). In the short, the conversion of the forest to other uses can trigger loss of nutrients and erosive processes

that did not exist in these areas (Fearnside & Barbosa, 1998; Korkanc et al., 2008; Misra & Teixeira, 2001; Guerra et al., 2014; Thomaz et al., 2020).

Experimental responses to the physical characteristics of soils to the presence of Clay-Minerals

From the data obtained, it can be inferred that there is a relationship between the time of soil exposure after the vegetation cover removal with the losses presented in the experiment and that the disaggregations presented can be related to the physical characteristics of the samples.

The physical properties of the soil samples directly interfered in their disaggregation. The dispersion of physical parameter data with the sediment losses of the simulated samples, for example, demonstrates a good correlation between the sediment loss percentage data with the bulk density and the total porosity obtained in the samples (see Figure 6). This assertion suggests that the structure of the sample interfered with the resistance to disaggregation and transport of sediments in the Inderbitzen test, so that, in the first case (see Figure 6a), there was a negative correlation, because the higher the disaggregation percentages, the lower the densities apparent presented. And in the second case, a positive correlation because the higher the percentage values of soil porosity, the higher the loss of the sample in the experiment (see Figure 6b).

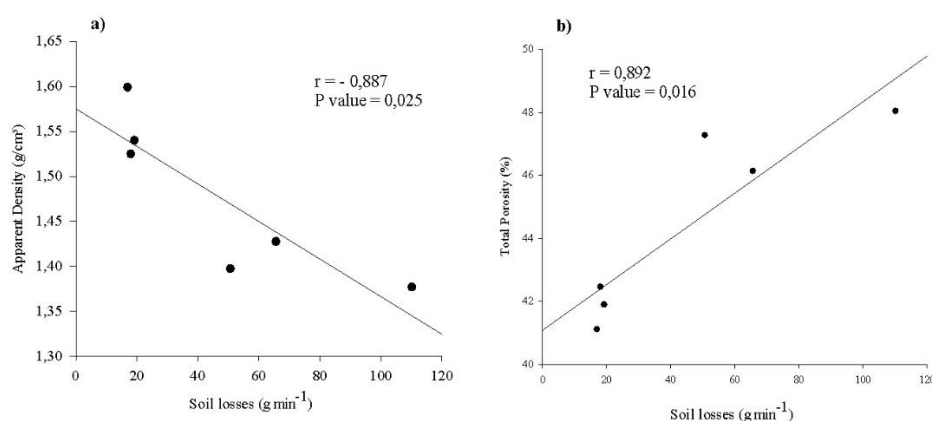


Figure 6. a) Negative correlation between soil bulk density and soil losses presented in the Inderbitzen experiment ($r = -0,887$); b) Positive correlation between soil porosity and soil losses presented in the Inderbitzen experiment ($r = 0,892$).Source: Organized by the authors.

The time of soil exposure, after the vegetation cover removal and in use for pasture, reflected changes in the physical structure of the samples regarding the parameters considered (apparent density, total porosity, and SMRP). Other physical aspects of the soil, in general, change after removal from the forest to implement the pasture, such as aggregate diameter morphology, soil thickness, and hydraulic conductivity, which can vary depending on the species of pasture, for example (Thomaz et al., 2020).

In this sense, it was expected that the P06 samples would suffer higher losses because only four

years of soil exposure would not have changed the soil structure as much as in other pastures, and, consequently, the soil shear strength would be lower. These higher expected losses for P06 did not occur because, despite being recent, it was the pasture identified with the most intensive use among all samples. The intense bovine trampling in the area may have rapidly affects the soil compaction, which reached homogeneous average values of $5,6 \pm 1,2$ MPa up to 40cm of soil, including the highest SMRP observed among all transects (Table 2).

Table 2. Physical Properties of Soils and Total Sediment Loss per simulated sample.

Sample / simulated flow	Penetration Resistance (Mpa)	Soil Losses (g min ⁻¹)
P01 3 L min ⁻¹	1.0	12.1
P01 6 L min ⁻¹	1.2	21.9
P02 3 L min ⁻¹	3.3	13.1
P02 6 L min ⁻¹	2.6	25.4
F03 3 L min ⁻¹	0.56	101.4
F03 6 L min ⁻¹	0.56	119
F04 3 L min ⁻¹	1.5	28.7
F04 6 L min ⁻¹	1.6	76.7
D05 3 L min ⁻¹	0.7	64.6
D05 6 L min ⁻¹	0.5	66.7
P06 3 L min ⁻¹	5.1	4.6
P06 6 L min ⁻¹	4.4	31.6

Source: Organized by the authors.

The presence of clay material was correlated with the losses presented in the samples. There was a significant negative correlation ($r = - 0.656$): the samples with a higher percentage of clay were those with the least losses, as well as a positive correlation between the total sand percentage in the samples and the higher percentages of disaggregation and material

losses that the samples showed (Figure 7). This fact corroborates studies that showed more accelerated erosive processes in soils with a small amount of clay and a higher percentage of sands (Macedo et al., 2021; Hassane et al., 2022). The soil aggregates are bound by the action of mineral compounds such as clays, iron and aluminum oxyhydroxides (Holthusen et al., 2020).

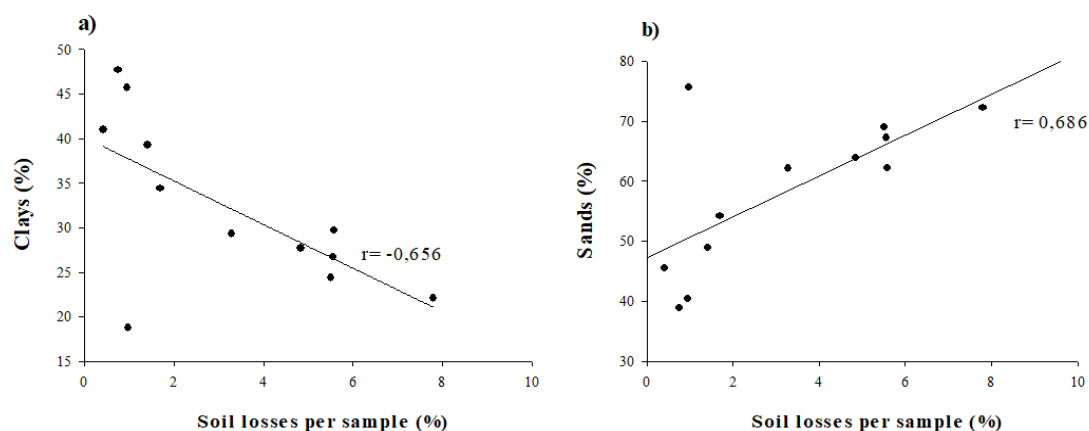


Figure 7. a) Negative correlation between the percentage of clay in the samples and soil loss presented during the Inderbitzen experiment ($r = -0,656$); b) Positive correlation between the percentage of sand in the samples and soil loss presented during the Inderbitzen experiment ($r = 0,686$).

Source: Organized by the authors.

Thus, it is understood that the movement and transport of soil particles can be related to the size of the constituent particles. Those with smaller diameters end up not being easily disaggregated due to greater cohesion between the particles, despite having a higher possibility of being transported in terms of

disaggregation. As the test simulates impact disaggregation (Soares et al., 2018), the sand fraction has a higher tendency to disaggregate (Bastos et al., 2001; Nacinovic et al., 2014; Reichert et al., 2016) (Table 3).

Table 3. Relation of the disaggregation percentage by simulated sample, Granulometric Composition, and Organic Matter

Samples	Granulometric Composition (%)					Gradient Textural	Organic Matter (%)
	Af*	Am*	Ag*	Silt	Clay		
P01 3 L min ⁻¹	24.7	27.9	23	5.6	18.8	Loam Sandy	2.13
P01 6 L min ⁻¹	24.7	18.6	5.6	11.7	39.3	Clay Sandy	2.87
P02 3 L min ⁻¹	27	14.9	3.6	13.4	41.0	Clay Sandy	2.95
P02 6 L min ⁻¹	32	15.1	7.11	11.6	34.4	Sandy Clay Loam	1.87
F03 3 L min ⁻¹	36.1	24.7	8.18	6.6	24.4	Sandy Clay Loam	2.74
F03 6 L min ⁻¹	34.9	29.9	7.39	056	22.1	Sandy Clay Loam	3.2
F04 3 L min ⁻¹	7.7	11.9	42.5	8.4	29.3	Sandy Clay Loam	3.3
F04 6 L min ⁻¹	11.4	14.7	36.1	8.0	29.7	Sandy Clay Loam	2.87
D05 3 L min ⁻¹	11.3	14.1	38.5	8.3	27.7	Sandy Clay Loam	2.56
D05 6 L min ⁻¹	20.7	22.3	24.2	6.0	26.7	Sandy Clay Loam	3.58
P06 3 L min ⁻¹	14.1	13.5	11.3	13.3	47.7	Clayey	3.12
P06 6 L min ⁻¹	12.9	14.4	13.2	13.6	45.7	Clayey	3.12

Source: Organized by the authors. * Af: Fine sand (<0.106 mm); Am: Medium sand (<0.106-0.5mm); e Ag: Coars sand (>0.5 mm)

Although it is recognized that organic matter plays an essential role in the structuring of soils and the stability of their aggregates (Tisdal & Oades, 1982), for the responses from the Inderbitzen experiment, no

correlations were identified. This fact may be linked to the issue that, in tropical soils, the stability of soil aggregates that result in the detachment of particles may be more related to the presence of Fe and Al

oxides than in relation to organic matter (Braida et al., 2011; Inda Junior et al., 2007).

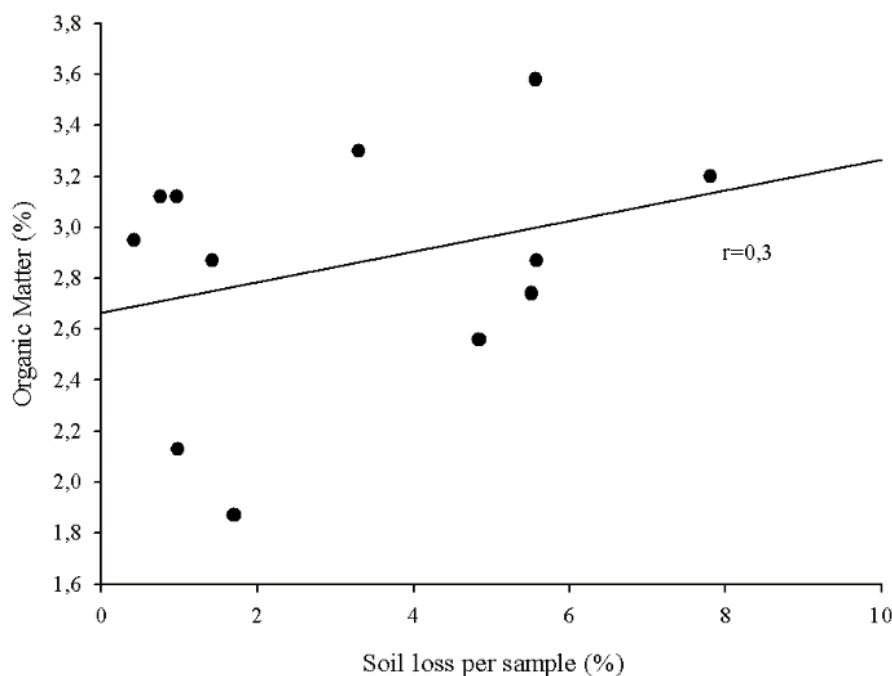


Figure 8. Correlation between soil organic matter content and soil loss along the Inderbitzen experiment. Source: Organized by the authors.

Potential Erodibility of the Dystrophic Red Yellow Latosol

Overall, the Inderbitzen experiment resulted in low soil loss percentage, when compared to the results obtained by other tests, carried out even with flows of lower intensities in a slope without direct showering, indicating low erodibility soils (Higashi et al., 2011; Moreira & Polivanov, 2018; Santos et al., 2002). In some cases, when a high rate of sediment loss was observed, the tested soils were characterized as residual soils (i.e., saprolite) with numerous problems related to erosion and mass movements (Lemos et al., 2007; Vieira et al., 2019).

The analysis of the low erodibility of the Dystrophic Red Yellow Latosol, observed through the Inderbitzen experiment, is corroborated by the results of other indirect methods applied: the Plasticity Index (Pinto, 2006) and Denardin (1990) K factor equation. In addition, it is possible to infer that the soils do not present high erodibility since no indicators of erosion processes, even initial, were seen at the sampling sites.

The results obtained through the application of the K factor equation showed soils that were also poorly erodible. The P02 sample was classified as Low erodibility, even though it was the highest index calculated for the collected samples ($0,0202 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$). The other samples referring to P01, F03, F04, D05, and P06, were classified as having Very Low erodibility (Bertoni & Lombardi Neto, 1999). The low erodibility of the Latosol is corroborated by the high Plasticity Indices (see Table 4), where even the percentage of 6,8% of the P01 sample (lowest value found for PI) did not represent high erodibility soils in relation to the Plasticity parameter (Pinto, 2006).

The values obtained for the K factor are within the erodibility range of latosols proposed by Bertoni and Lombardi Neto (1999) between $0,013$ and $0,020 \text{ Mg ha h ha}^{-1} \text{ MJ}^{-1} \text{ mm}^{-1}$ (see Table 4) and were also close to the values obtained by Ranzani (1980), Silva et al. (2000) and Silva et al. (2016). The latosol studied in Duarte et al. (2020) was classified as having moderate erodibility, while Spodosols and Gleysols

had high and very high erodibility, respectively. And Miguel et al. (2021) found values of 0.05 to 0.06 t h

MJ⁻¹ mm⁻¹ to neosols a soil with greater erodibility, for example.

Table 4. Result of Plasticity Indices of the samples, with the detachment by the experiment and the values referring to the Erodibility Equation

Sample / temporality	Granulometric Composition (%)			Inderbitzen Experiment Disaggregation (g/cm ²)	Plasticity Index (%)	K factor Erodibility Equation (Mg ha h ha ⁻¹ MJ ⁻¹ mm ⁻¹)
	Sand	Silt	Clay			
P01 Pasture 07 years	82.3	3.2	14.5	0.370	6.8	0.0166
P02 Pasture 12 years	64	8.3	27.7	0.345	9.8	0.0202
F03 Forest	72	6.5	21.5	1.746	10.1	0.0199
F04 Forest	44	12.2	43.8	1.285	14.2	0.0175
D05 Recent deforestation	57.3	11.1	31.6	1.485	11.3	0.0161
P06 Pasture 04 years	49	11	39.7	0.273	16.5	0.0180

Source: Organized by the authors.

The class of soils that presented the B-latossolic horizon as a diagnostic horizon is characterized by its advanced stage of weathering, evidenced by the concentration of sesquioxides (usually iron and aluminum oxides), 1:1 clay, and by the complete alteration of primary minerals less resistant to weathering (Brasil, 2007; Guerra & Botelho, 1998). Then, some authors claim that the presence of abundant iron and aluminum oxides and hydroxides in tropical soils increases the stability of their aggregates (Albuquerque et al., 2000; Bronick & Lal, 2005), much higher than that verified in non-oxidic soils with a predominance of organic matter (Inda Junior et al., 2007; Six & Jastrow, 2002), which contributes to reducing the erodibility of these types of soils, as verified in this study on the erodibility of a Red Yellow Dystrophic Latosol.

Conclusions

The trials conducted with the Modified Inderbitzen Experiment showed results that demonstrate the experiment's potential use, both in terms of low cost for model construction and for observation and analysis of the samples' disintegration. This indicates it can be used in the study of soil disaggregation potential, suggesting their erodibility.

Considering the experiments conducted, the results showed that the studied soil exhibited, in the context of total soil losses, little disaggregation. Therefore, the Dystrophic Red Yellow Latosol showed low erodibility by the potential for sediment loss. This

result was confirmed after applying the erodibility equation, which showed data within the Low and Very Low Erodibility Class, ratified by the soil plasticity indexes.

Regarding the physical structure of the soil, the most significant disaggregations were observed in forest soils. However, although they represented low resistance to the shear forces imposed by direct sprinkling, this did not necessarily mean that these soils could suffer intense erosion in areas covered by forests. It's also highlighted that converting the forest into pasture may, in the short term, trigger previously non-existent erosive processes. The forest acts as a phytostasis mechanism whose soil structural conditions are maintained by the force of the vegetative cover that attenuates the impact of water on soil with little resistance to shear stresses.

The results indicated that the experiment was sensitive to the change in the particle disaggregation potential of the different soil samples analyzed in the Inderbitzen experiment, as a factor of forest conversion into pasture that reconfigured the physical structure of the Dystrophic Red Yellow Latosol.

Although the experiment demonstrated its viability for data collection in the Amazon, application and repetition in environments with different slopes and pedological covers are necessary to observe the slope effect on soil erosion of these environments that indicated, in this research, potential for sediment production in the short term after the conversion of the forest into pasture.

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