UNIVERSIDADE DE BRASÍLIA
FACULDADE DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA FLORESTAL

ESCOAMENTO SUPERFICIAL E PERDA DE SOLO EM ÁREAS DEGRADADAS, RESTAURADAS E NATURAIS DOS CERRADOS, USANDO PARCELAS ABERTAS

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DISSERTAÇÃO DE MESTRADO EM CIÊNCIS FLORESTAIS

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DISSERTAÇÃO DE MESTRADO SUBMETIDA AO DEPARTAMENTO DE ENGENHARIA FLORESTAL DA UNIVERSIDADE DE BRASÍLIA COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE MESTRE.

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"Anda, quero te dizer nenhum segredo

Falo desse chão da nossa casa

Vem que 'tá na hora de arrumar

Tempo, quero viver mais duzentos anos

Quero não ferir meu semelhante

[...]

Vamos precisar de todo mundo

Um mais um é sempre mais que dois

Para melhor juntar as nossas forças

É só repartir melhor o pão"

O Sal da Terra,

Beto Guedes e Ronaldo Bastos

RESUMO

Aproximadamente 45% dos solos mundiais estão degradados em algum nível pelo uso intensivo e efeito das alterações climáticas. A erosão é uma das principais formas de degradação do solo e é fortemente influenciada pela cobertura, responsável pela qualidade das águas, o que a torna um fator fundamental na sustentabilidade ambiental. Dois métodos de quantificação de erosão e escoamento são amplamente utilizados, apesar de possuírem suas limitações. O presente estudo correlaciona os resultados de perdas de solo e água obtidos por Calhas de Gerlach e Parcelas-padrão de Enxurrada em três tipos de cobertura do solo em 3 propriedades dos municípios de Mambaí, Buritinópolis e Damianópolis, no estado de Goiás, sobre Latossolo, Neossolo Litólico e Neossolo Quartzarênico, sob pasto degradado, restaurado, e cerrado natural, na região da APA das Nascentes do Rio Vermelho (GO). Foram medidos os volumes de precipitação, concentração de sedimento, erosividade da chuva e escoamento superficial dos anos hidrológicos 2022/2023, 2023/2024 e 2024/2025. Para fins estatísticos, as propriedades são interpretadas como blocos e os manejos do solo como tratamentos. Concluiu-se que as Calhas de Gerlach foram eficientes na estimativa da enxurrada e da perda de solo, e que a restauração de pastagens contribuiu para uma significativa redução desses processos após três anos de monitoramento.

Palavras-chave: Calhas de Gerlach; erosão hídrica; restauração de pastagem; Cerrado.

ABSTRACT

Approximately 45% of the world's soils are degraded to some degree by intensive use and the effect of climate change. Erosion is one of the main forms of soil degradation and is strongly influenced by the cover, which is responsible for water quality, which makes it a fundamental factor in environmental sustainability. Two methods of quantification of erosion and runoff are widely used, although they have their limitations. The present study correlates the results of soil and water losses obtained by Gerlach troughs and Standard Runoff Plots in three types of soil cover in 3 properties in the municipalities of Mambaí, Buritinópolis and Damianópolis, in the state of Goiás, on Latosol, Litholic Neosol and Quartzarenic Neosol, under degraded and restored pasture, and natural cerrado, in the region of the APA of the Nascentes do Rio Vermelho (GO). Precipitation volumes, sediment concentration, rainfall erosivity, and surface runoff for hydrological Years 2022/2023, 2023/2024, and 2024/2025 were measured. For statistical purposes, Properties are interpreted as blocks and soil management as treatments. Gerlach troughs were efficient in estimating runoff and soil loss, and that pasture restoration contributed to a significant reduction of these processes after three years of monitoring.

Keywords: Gerlach troughs; water erosion; pasture restoration; Cerrado.

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Capítulo 1: Contextualização

A erosão é um processo de desprendimento e transporte de materiais do solo por agentes erosivos naturais ou induzidos antropicamente, que desagregam e removem partículas do solo em um ponto e depositam em outra localidade. O processo erosivo é responsável pela degradação da terra ao reduzir a fertilidade, a capacidade de armazenamento de água e a matéria orgânica, além de poluir, assorear corpos d'água (Cerdan et al., 2010) e contribui diretamente para a deterioração do solo, caracterizada pela dispersão de partículas, destruição da estrutura e alteração da densidade e porosidade do solo (Osman et al., 2014).

A erosão hídrica é um dos principais impulsionadores da degradação do solo (Lal, 2001) e é agravada pela degradação da cobertura vegetal local, que, quando permanente, é considerada o único componente natural de proteção do solo (Fonseca et al., 2023b), visto que a cobertura vegetal aumenta a interceptação de água e reduz, portanto, o efeito da energia de impacto das gotas de chuva na superfície do solo (Eduardo et al., 2013). Além disso, a presença de serrapilheira e raízes superficiais reduzem o escoamento superficial e o transporte de sedimentos (Hofmann et al., 1983). Portanto, alterações na gestão e uso do solo podem acentuar a erosão (Santos et al., 2017).

De acordo com Guerra e Jorge (2017), problemas relativos à erosão acontecem quando a perda de solo supera os níveis naturais em decorrência da ausência de práticas conservacionistas. Além disso, sabe-se que os problemas decorrentes do processo de erosão-sedimentação resultam em perda de nutrientes, influência e variação da microfauna e microflora existentes e redução do potencial produtivo, em razão, principalmente, da alteração da capacidade de retenção hídrica (Marques, 1998).

A erosão hídrica é considerada uma das mais agressivas e é causada tanto pelo impacto da queda das gotas de chuvas e pelo movimento de enxurrada ou escoamento superficial. Por isso, é um processo dependente da energia cinética e potencial e, consequentemente, de uma massa de água ou solo e da posição em relação à outra massa, a diferença de altura entre a posição original e a posição de destino (Volk, 2006).

Os tipos de erosão incluem a erosão em sulcos (rill), erosão laminar (interrill) e em voçorocas (gully). O primeiro tipo ocorre em defluência do desprendimento e transporte das partículas do solo pelo escoamento canalizado (Govers et al., 2007). Já a erosão laminar ocorre entre sulcos através do destacamento de partículas do solo por impacto das gotas de chuva e do transporte por fluxo superficial (Meyer; Wischmeier, 1969). Enquanto as voçorocas são causadas pela combinação de processos de lavagem hidráulica e movimento de massa e o

transporte de sedimentos por fluxo (Bocco, 1991).

O Sudeste e Centro-Oeste brasileiros possuem áreas de risco de erosão hídrica associadas a erosividades fortes e ao avanço da conversão de cobertura do solo (Oliveira et al., 2013). A estimativa de perda de solo média anual encontrada por Fonseca et al. (2021) para cobertura natural, pastagem e solo exposto em Cerrado brasileiro evidencia que a presença de vegetação protege o solo contra a erosão. Os solos existentes nesse bioma são considerados pouco férteis, em decorrência das características químicas e nutricionais (Fontana et al., 2006) e a alteração da vegetação feita pelo homem ocasiona a aceleração do processo de erosão hídrica (Checchia, 2005).

Na savana brasileira, foram registradas diversas ocorrências de paisagens cársticas, com mais de 11 mil cavernas, formadas por rochas carbonáticas e siliciclásticas (Fonseca, 2022). Ambientes cársticos são formados por múltiplos processos de intemperismo químico, além de serem desenvolvidos em rochas solúveis com fraturas e porosidade secundária (Ford; Williams, 2007) o que os torna altamente sensíveis, frágeis e de difícil restauração após serem submetidos a perturbações (Fonseca et al., 2023a).

De tal forma, ambientes cársticos são caracterizados por conter cavernas, depressões fechadas, afloramentos rochosos estriados, grandes nascentes e sistemas hídricos subterrâneos extensos. São também desenvolvidos, principalmente, em rochas solúveis, e ocorrem pela associação desta alta solubilidade, com fratura e porosidade secundária (Ford; Williams, 2007). O carste é encontrado em rochas solúveis (Williams, 2008) e impacta hidrologicamente cerca de 25% da população mundial (Travassos, 2019).

O bioma Cerrado, assim como ambientes cársticos brasileiros, tem sofrido crescente pressão antrópica. Os impactos são significativos na paisagem natural (Rabelo et al., 2018), resultam em pressões sobre o sistema aquífero cárstico e sistemas espeleológicos (Cadamuro, 2006) e proporcionam o aumento de erosão (Anache, 2018). Com o advento da mecanização agrícola, ao longo do século passado, os níveis de erosão e degradação do solo globalmente foram sem precedentes (Vanwalleghem, 2017).

Sabendo que a cobertura vegetal desempenha importante papel na desaceleração do processo de desagregação e transporte de partículas do solo, Fonseca et al. (2022) estimaram perda de solo para diferentes tipos de cobertura no bioma Cerrado. O valor médio anual de perda de solo obtido para cobertura natural foi de 0,1 (Mg ha^{-1}ano^{-1}), enquanto para pastagem foi de 0,2 (Mg ha^{-1}ano^{-1}) e solo exposto, 19,4 (Mg ha^{-1}ano^{-1}). Valores estes que comprovam os efeitos protetivos da presença de vegetação sobre o solo contra a erosão e são inferiores à

tolerância de perda de solo de 4 a 12 Mg ha^{-1}ano^{-1} do Cerrado brasileiro (Chaves, 2010).

Por isso, além de auxiliar na compreensão do transporte sedimentar, a compreensão da cobertura vegetal do solo estudado contribui para o conhecimento do balanço hídrico climático da área em questão. Este consiste em um método de monitoramento da umidade no solo, amplamente difundido, que calcula entrada e saída de água em camadas com raízes de plantas periodicamente (Conceição, 2010).

Compreender e mitigar a erosão e a degradação associada do solo é fundamental para a redução dos efeitos, como assoreamento de rios e reservatórios, piora da qualidade da água e redução da produtividade do solo (Benavidez, 2018). Além disso, o processo também é uma das causas do transporte de poluentes do solo para um curso d'água, da redução de biodiversidade e de padrões de inundação (Wicharuck et al., 2023).

O estudo foi desenvolvido na Área de Proteção Ambiental das Nascentes do Rio Vermelho, localizada no noroeste do estado de Goiás, na região Centro-Oeste do Brasil (Esbérard et al., 2005). A APA abriga áreas estratégicas para a recarga hídrica e para a conservação de sistemas da interconectividade da superfície com os sistemas subterrâneos (Ferreira, 2020). Para a realização do estudo, foram selecionadas três propriedades rurais, representativas das condições ambientais e de uso do solo existentes na área.

A paisagem da região é marcada por ambientes cársticos cobertos, caracterizados pela dissolução de rochas carbonáticas, o que favorece o desenvolvimento de cavernas, dolinas, fraturas e sistemas de drenagem subterrânea. O relevo varia de suavemente ondulado a ondulado, com setores localmente mais dissecados, e exerce forte influência sobre os processos hidrológicos superficiais e subsuperficiais. A conexão entre escoamento superficial, infiltração e circulação subterrânea torna o sistema altamente sensível a alterações no uso e cobertura do solo.

O uso e cobertura do solo na área de estudo são compostos predominantemente por pastagem degradada, pastagem em processo de restauração e áreas de Cerrado nativo. As áreas de pastagem degradada apresentam menor cobertura vegetal, compactação do solo e maior propensão ao escoamento superficial e à perda de solo. Já as áreas de Cerrado natural exercem papel fundamental na proteção do solo, na regulação hídrica e na manutenção da estabilidade dos sistemas cársticos.

Os solos identificados na área de estudo são Latossolo Vermelho, Neossolo Quartzarênico e Neossolo Litólico, os quais apresentam comportamentos distintos em relação aos processos hidrológicos e à dinâmica cárstica (Nogueira, 2022). O Latossolo Vermelho,

geralmente mais profundo e bem estruturado e favorece a infiltração da água. O Neossolo Quartzarênico, caracterizado por elevada fração arenosa e baixa coesão, apresenta alta permeabilidade. O Neossolo Litólico, por sua vez, é raso e ocorre sobre rocha (Embrapa, 2006).

A interação entre tipos de solo, uso do solo e feições cársticas influencia diretamente a formação, a estabilidade e a vulnerabilidade das cavernas identificadas na área, especialmente no que se refere à recarga hídrica, ao aporte de sedimentos e à qualidade da água subterrânea.

Assim, identifica-se a necessidade da utilização de métodos que quantifiquem a perda de solo e de água, conforme disposto por Bertoni e Lombardi Neto (1990), a obtenção de perda solo por erosão pode ser gerada laboratorialmente ou em campo, utilizando das condições naturais da área de estudo. O último tipo de aferição é mais realista e, portanto, mais apropriado para a coleta de dados de erosão dos solos (Guerra, 2005). Duas possíveis formas de quantificar a perda de solo são pelo uso de parcelas de enxurrada (Wischmeier; Smith, 1978) e de Calhas de Gerlach (Gerlach, 1967).

As parcelas-padrão possuem área definida, o que permite que os resultados sejam representativos, apesar de apresentar alto custo de instalação e manutenção. Este método é amplamente usado para fazer a avaliação de erosão em sulcos e obtenção do escoamento superficial tanto em áreas naturais, quanto em áreas agrícolas (Renard; Foster, 1985, Wischmeier; Smith, 1978).

Já nas Calhas de Gerlach, esta informação é ausente, característica que dificulta a utilização (Wicharuck, 2023) e obtenção de resultados precisos, mas permite A realização de avaliação de grandes regiões e para muitas áreas aleatoriamente selecionadas, no entanto, é uma técnica barata e de simples instalação (Silveira, 2017), o que a torna conveniente para o monitoramento dos processos erosivos (Antoneli, 2011). A estrutura do material de coleta visa reduzir a entrada de material resultante do efeito splash e o equipamento é posicionado em locais terminais da área de convergência, para receber a enxurrada (Nunes, Lourenço, 2019).

A qualidade da água presente em uma bacia hidrográfica depende de condições naturais e ações antrópicas, pois é influenciada pelo uso da terra nos arredores. Padrões de qualidade de água referem-se às características físicas, químicas e biológicas de um corpo d'água em relação ao uso específico ou designado pelo governo numericamente, ou por narrativa (Brooks, 2010). Os fatores naturais de uma bacia hidrográfica influenciam na qualidade de águas superficiais por esta ser afetada pelo escoamento e infiltração das chuvas, fazendo com que a proteção e composição do solo desempenhem grande influência. Já a ação antrópica é manifestada concentradamente, introduzindo compostos não presentes no solo da bacia (Von Sperling,

2007).

Com base no exposto, o objetivo geral deste estudo é:

- Analisar o escoamento superficial e a perda de solo por Calhas de Gerlach, tanto em áreas degradadas, quanto em áreas naturais e restauradas.

A partir disto, os objetivos específicos dessa pesquisa são:

- Compilar dados de perda de água e solo de parcelas padrão e de calhas de Gerlach em áreas cársticas do Cerrado de três anos hidrológicos e atingir relações hidrossedimentológicas significativas;
- Verificar a possibilidade quantificar o volume de enxurrada e perda de solo com métodos mais acessíveis do que as tradicionais parcelas de enxurrada, com parcelas abertas;
- Estimar o serviço hidrológico de restauração ambiental das parcelas experimentais entre áreas restauradas e as testemunhas (degradada e cerrado natural).

Buscando atender os objetivos desta pesquisa, as hipóteses são:

- A restauração de pastagem é capaz de reduzir a erosão, a sedimentação e a enxurrada de áreas.

- As calhas de Gerlach conseguem reproduzir os resultados de parcelas de enxurrada.

Esta dissertação conta com quatro capítulos: 1) Contextualização, 2) Artigo Científico em Língua Inglesa: manuscrito submetido à revista Catena, 3) Artigo Científico em Língua Inglesa: manuscrito publicado pela revista Sustainability, e 4) Considerações finais, em que são destacados os principais resultados e pontos relevantes da discussão realizada nos artigos, em português.

O segundo capítulo é composto por um artigo científico submetido à revista Catena, no qual são avaliados o escoamento superficial e a perda de solo em áreas degradadas, restauradas e naturais do Cerrado ao longo de dois anos hidrológicos. Além da análise dos processos hidrossedimentológicos, este capítulo apresenta a avaliação da confiabilidade das Calhas de Gerlach como método para a quantificação da perda de solo e de água em ambientes cársticos, demonstrando sua aplicabilidade e consistência nesse tipo de sistema.

O capítulo três corresponde a um artigo científico publicado na revista Sustainability, que amplia a análise temporal dos processos de perda de solo e água, considerando o período de três anos hidrológicos na mesma área de estudo do capítulo anterior. Neste capítulo, as

Calhas de Gerlach são novamente empregadas como método de monitoramento, permitindo a comparação interanual dos resultados e o aprofundamento da compreensão sobre a dinâmica hidrossedimentológica em áreas do Cerrado sob diferentes condições de uso e cobertura do solo.

Já o capítulo quatro apresenta as conclusões gerais da dissertação, integrando os principais resultados obtidos nos capítulos anteriores. Este capítulo discute os achados para a compreensão dos processos de escoamento superficial e perda de solo em ambientes cársticos do Cerrado, bem como para o uso das Calhas de Gerlach como ferramenta metodológica em estudos hidrológicos e ambientais, além de apontar limitações do estudo e perspectivas para pesquisas futuras.

Capítulo 2:

Artigo Científico submetido à revista Catena

Effect of Pasture Restoration on Runoff, Soil loss, and Sediment Enrichment in a Karst Basin of a Tropical Savannah

Abstract

Karst landscapes are fragile environments and are difficult to restore once disturbed, causing soil loss and downstream sedimentation. Because of the expansion of the agricultural frontier in the Brazilian savanna during the last 60 years, karst areas have been subjected to severe degradation, affecting the sustainability of farmers in the region. The research aimed to quantify the erosion rates occurring in degraded pastures in the Brazilian savannah and to evaluate the effectiveness of its restoration, the possible correlation of soil loss with runoff, and whether Gerlach collectors, a simple and unexpensive method to assess soil loss, could be used in the erosion assessment in karst areas. In this study, runoff and soil loss in degraded and restored pastures, and in natural savannah were assessed during two years using Gerlach plots at three sites (farms) of the Vermelho river basin, in Brazil. Runoff was reduced by 40% and erosion decreased by 50%-80% in the restored pasture treatments, compared to the degraded pasture condition. In most plots, the sediment was enriched with fines, reducing the silting potential of sinkholes and underground rivers in the Vermelho river basin. Furthermore, Gerlach collectors, which are simpler and cheaper than traditional erosion plots, emulated the latter in terms of quantitative soil erosion assessment, facilitating soil loss monitoring in tropical karst areas.

1. Introduction

Karst landscapes are fragile environments, covering 12% of all continents worldwide (Febles-González et al., 2012), and are difficult to restore once disturbed (Drew, 1999; Fonseca et al, 2023). Among the threats affecting karst landscapes are soil loss and soil degradation (Parise et al., 2009; Hu et al., 2018), due to water erosion (Jacinthe et al., 2004; Nie et al., 2015; Wacha et al., 2020; Fonseca et al., 2023), particularly on high erodible soils (Gan et al., 2002; Zhao and Hou, 2019).

In addition to those on-site impacts, affecting land-use and socioeconomic sustainability of karst areas, off-site impacts, such as downstream sedimentation, contribute to silt-up sinkholes and underground rivers (Kurecic et al., 2021; Fonseca et al., 2023). Since water

erosion is a selective process (Hashin et al., 1998; Tesfahunegn et al., 2014), fine-enriched sediments (Flanagan and Nearing, 2000) to which nutrients are preferentially adsorbed (Wang and Li, 2010) cause downstream water quality impairment (Walker et al., 1978; Nie et al., 2015; Wacha et al., 2020). However, very little information about sediment enrichment exists in tropical karst areas (Fonseca et al., 2023), requiring further investigation.

Since permanent soil cover is the only natural feature protecting against erosive processes (Zhang et al., 2016; Zhao and Hou, 2019), its removal leads to soil erosion and the loss of essential soil nutrients (Nadeu et al., 2011; Nie et al., 2015; Wacha et al., 2020). Thus, if the erosion process in karst areas is not controlled, soil and vegetation degrade together (Jiang et al., 2014), creating a vicious cycle negatively affecting both farmers and the environment (Gao and Wang, 2019).

Because of the expansion of the agricultural frontier in the Brazilian savanna during the last 60 years, karst and non-karst landscapes in the region, particularly pastureland (Cava et al., 2017), have experienced significant impacts due to accelerated soil erosion (Oliveira et al., 2015, Vanwalleghem et al., 2017; Anache et al., 2018) and off-site sedimentation (Chaves and Piau, 2008; Minella et al., 2009). The fallowing of degraded pastures in tropical savannas is often ineffective, since it cannot spontaneously restore the main soil attributes of the natural landscape (Cava et al., 2017).

On the other hand, if active pasture restoration is carried in degraded lands of tropical savannas, providing adequate soil cover and tilth, soil erosion would be reduced (Montagnini, 2008; Galdino et al., 2016), improving farmers' income (Buisson et al., 2019). However, despite sedimentological studies have been carried in restored karst watersheds in different parts of the world (Wang et al., 2004; Jiang et al., 2014; Zhang et al., 2016), limited information exists about the restoration impact of degraded karst areas in the Brazilian savannah (Fonseca et al., 2023).

The latter evaluated the hydrological effectiveness of ecologically restored pasturelands of an Entisol of a karst area of the Brazilian savannah and found that runoff and soil loss were reduced by 50% and 90%, respectively, compared to degraded, uncovered plots. However, no information exists about the soil loss of restored plots of more developed soils in karst areas of Brazil, such as Oxisols.

Previously, Fonseca et al. (2021) showed that soil loss measured in traditional runoff plots of different regions, soils, and cover-types in the Brazilian savannah was largely explained by runoff, which was inversely correlated with permanent soil cover. Since restored

pastures have a higher soil cover than degraded pastures, this additional cover could help reduce both runoff and erosion, decreasing downstream sedimentation.

However, traditional bounded runoff plots are expensive to install and to maintain (Morgan, 1989) when compared to smaller and unbounded plots, monitored with simple Gerlach collectors (Gerlach, 1967). Additionally, bounded runoff plots are unnatural erosion monitoring setups, since plot borders of bounded plots force runoff and sediment in a pre-determined direction (Mastura and Al-Toum, 2000).

Depending on the plot topographic conditions, the Gerlach plot setup allows for the sampling of both rill and interril erosion processes, since their slope lengths are about the same of traditional bound Wischmeier's plots (L = 22.1 m) (Matsura & Al-Toum, 2000). In traditional 22m-bound plots of a karst area of the Brazilian savanna, near the present experiment, Fonseca et al. (2023) observed that rills were formed 5 m from the upper plot border, indicating that Gerlach plots may represent the main erosion processes occurring on tropical karst slopes.

On the other hand, since Gerlach plots collect only episodic samples of sediment concentration and not integrative runoff and soil loss volumes, the obtention of representative data, particularly in longer slopes and small watersheds is limited, requiring the use of different monitoring devices, such as flumes and automatic sediment samplers (Burney & Edwards, 1994). Additionally, improper installation or alignment of Gerlach collectors can lead to inaccurate sampling, and clogging of its hose/bottle set may underestimate soil loss (Morgan, 1989).

The objective of this research was to evaluate the effectiveness of restored pasturelands in three different soils of a karst basin of the Brazilian savanna, utilizing unbound plots and Gerlach collectors to assess soil loss, and sediment enrichment, analyze the correlation between runoff and erosion of different land covers, and statistically compare the results with those of degraded pasture and natural savanna.

2. Materials and Methods

2.1 Hypothesis Structure

The study's hypotheses were: H1- Restored pastures will show a statistically significant reduction in annual runoff and soil loss compared to degraded pastures; H2- The generated sediment in the restored plots will be selectively enriched in fines, demonstrating the sorting mechanism related to land use; and H3 – Gerlach collectors can be effectively used in the erosion assessment of tropical karst areas.

2.2 Study Area

The study area comprised of three cattle farms in a karst zone of the Brazilian savannah (Figure 1), within the Vermelho River watershed, composed of different soils and topography. In each farm, three types of land-use/management were monitored during 2 hydrologic years, between 2022 and 2024: a) Heavily degraded pasture-DP; b) Restored pasture-RP; and c) Natural savannah vegetation-NS. The soils, slope grades, and land-use & management of the experimental sites are presented in Table 1.

Table 1. Topography (grade), soils (texture), and land-use & management of the 3 experimental sites.

Experimental Site	Topography (Slope grade)	Soil Type (Texture)	Land-Use & Management Treatments
Funil farm	Gentle (9.3%)	Red Orthox (sandy-loam)	Degraded & restored pasture, savannah
Progresso farm	Gentle (6.8%)	Psamment (sandy)	Degraded & restored pasture, savannah
Tarimba farm	Moderate (11.5%)	Orthent (silt-loam)	Degraded & restored pasture, savannah
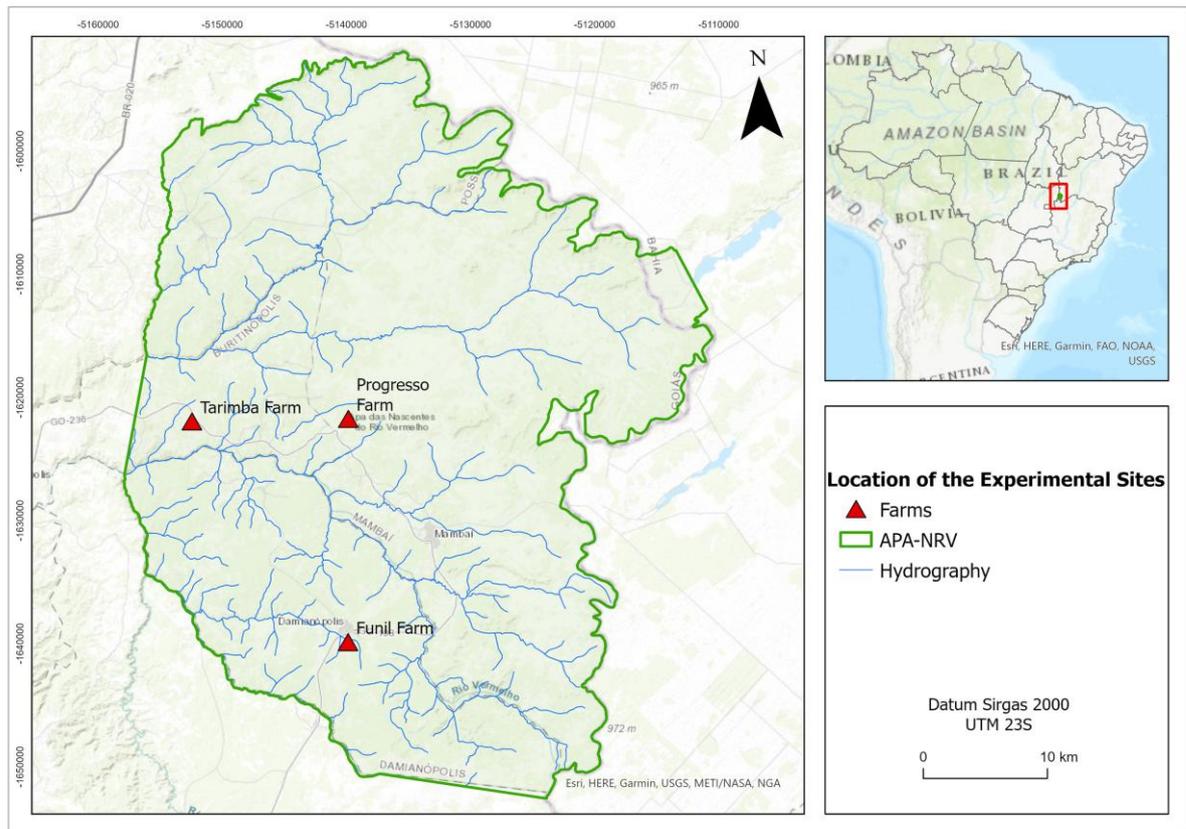
Figure 1- Cattle farms in a karst zone of the Brazilian savannah

Since each experimental site had unique landscapes and soils, each was treated as a

block, and the treatments within each block were the three land-use and management types, described in Table 1. Since the farms' soils and slope grades were dissimilar (Table 1), they were they were nested within each block (experimental site), the hypothesis being that restored pasture could significantly reduce runoff and soil loss, approaching the condition of natural savannah.

The first land-use/management treatment, Degraded pasture (DP), comprised of degraded areas where the dominant cover was the *Andropogon gayanus* grass, and were classified based on their reduced plant cover, low fertility and organic matter, and high soil compaction (Chaves et al., 2017), the latter measured with a ring penetrometer between 0-10 cm (Table 2). The degraded pasture (DP) areas of the three farms varied between 0.5 and 1.0 hectare. As a consequence of the poor cover condition of the degraded pastures in the three experimental sites, visual evidence of severe wash erosion, such as rills and erosion pedestals (Blanco-Sepulveda, 2018), was observed.

Table 2. pH, total P, K, organic matter, ground cover & penetration resistance of the degraded pastures (DP) of the three experimental sites.

Site	pH	P (ppm)	K (ppm)	O.M. (%)	Soil Cover (%)	Penet. Rest. (Mpa)
Funil farm	6.1	1.6	0.32	0.02	15%	3.33
Progresso farm	7.0	1.7	0.03	0.05	17%	0.78
Tarimba farm	6.4	1.5	0.03	0.03	12%	1.95

Natural Savannah (NS) areas comprised of natural wood & grass remnants (0.2 – 2.0 ha) located in the three experimental farms, and were classified as open savannah, where small trees (3-5 m) covered about 50% of the area, with the remaining vegetation formed by natural bushes and grasses (0.1-0.3 m) (Silva Jr. and Sarmento, 2009). Within each block (farm), the natural savannah, degraded & restored pasture areas had the same soils and similar slope lengths and grades (Table 1), allowing the plots to be taken as independent treatments. All plots were fenced, to avoid cattle intrusion.

The Restored Pasture (RP) plots (0.5-1.0 ha) were installed in previous degraded pastureland, neighboring the degraded pasture (DP) areas. The sequence of pasture restoration involved the following operations, carried during the dry season previous to the first monitoring year: i) ploughing with disc plow (30 cm); ii) soil sampling (0-20 cm); iii) liming and fertilizing based on the soil chemical & physical condition; iv) pre-emergence & post-emergence herbicide spraying; v) planting with Massai grass (*Panicum maximum v. Massai*); and vi) ant control with solid ant baits. Replanting was performed in patches without adequate cover, when

necessary.

Based on the soil fertility samples, the soils were limed with 2,000 kg ha^{-1} of dolomitic limestone to reduce aluminum toxicity and increase soil pH. The fertilization consisted of 1,000 kg ha^{-1} of powder urea, 250 kg ha^{-1} of superphosphate, and 25 kg ha^{-1} of micronutrients, all incorporated in the top 20 cm of the soil by disc-ploughing. After one year of planting, when the Massai grass cover was suitable for grazing, bovine cattle was allowed to graze in all restored plots of the three sites. The first runoff and sediment sampling year immediately followed the recently restored plots, whose vegetative cover was consolidated by the end of the first rainy season.

Figure 2 shows the degraded pasture (DP), restored pasture (RP), and natural savannah (NS) condition in all 3 farms, during the second year of the study, indicating the significant improvement in soil cover between DP and RP.

Figure 2- Degraded pasture (DP), restored pasture (RP), and natural savannah (NS) condition in all 3 farms

2.3 Runoff Plot Assembly

In each treatment plot (natural savannah, degraded & restored pasture) within each block/farm, two Gerlach collectors (N=2 replicates) were installed to collect the upstream runoff and sediment, since the plot conditions were small (< 1 ha) and homogeneous. One collector was set in the left upslope portion of the plot and the other in the right downslope portion, to guarantee site representativeness. Since Gerlach collectors seldom consider the contributing drainage area, a detailed topographic survey of the immediate upstream area of each collector was carried, to obtain the collectors' drainage areas and slope characteristics (Figure 3). The runoff plots' contributing areas are presented in Table 3. The mean plot length

was 8.5m, with a standard deviation of 0.15 m.
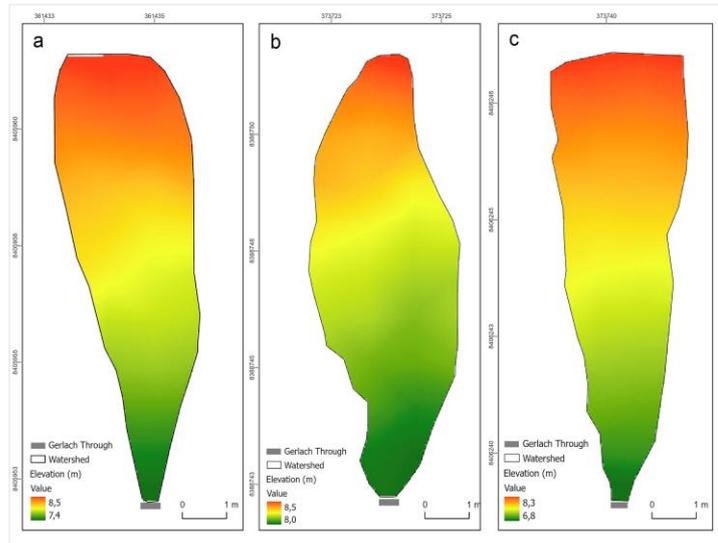
Figure 3 - Runoff plots' contributing áreas

Table 3. Runoff plot drainage areas (m²) in each experimental site/treatment.

Site	Degraded Pasture		Restored Pasture		Natural Savannah		
	Rep. 1	Rep. 2	Rep. 1	Rep. 2	Rep. 1	Rep. 2	
Funil farm	17.0	20.7	18.4	21.2	21.0	19.0	
Progresso farm	12.7	22.3	15.1	21.6	20.0	22.0	
Tarimba farm	28.5	22.7	20.9	20.8	20.0	16.0	

In the lower end of each plot, a metallic Gerlach collector (Gerlach, 1967) was installed flush with the soil surface, so that runoff and sediment were adequately collected. In the lower portion of the collector, a 1-L *Nalgene*® bottle was attached with a plastic hose to an orifice in the collector's lower end (Figure 4). In each experimental site, a rain gage was installed, and readings of precipitation volume were taken whenever the runoff & sediment samples were collected.
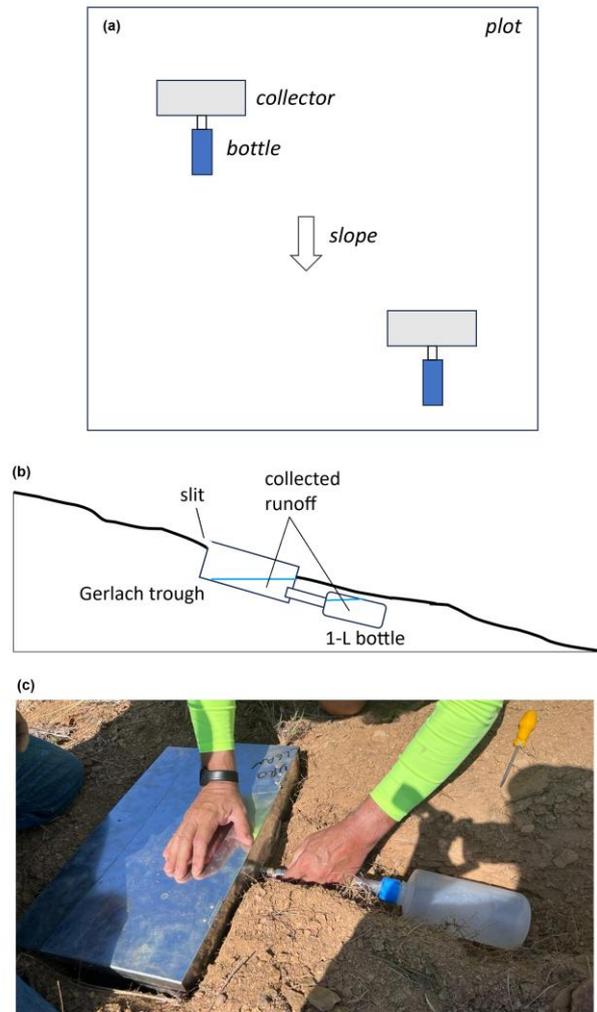
Figure 4 - Gerlach trough

2.4 Rainfall Erosivity

Rainfall erosivity was calculated on a monthly and yearly basis, using a Fournier-type equation, developed for Central Brazil by Silva (2004):

$$R \ = \ 12.59 \ \sum_{i=1}^{12} \left(\frac{M_i^2}{P}\right)^{0.60} \qquad (1)$$

Where: R (MJ mm ha^{-1} hr^{-1}) = site annual rainfall erosivity; M_i (mm) = site monthly precipitation; and P (mm) site annual precipitation.

2.5 Runoff Sampling and Laboratory Analyses

The 1-L Gerlach bottles were collected from the plots whenever a significant

precipitation volume (P >10 mm) occurred (Cardoso et al., 2022; Fonseca et al., 2023), i.e., a rainfall event capable of generating runoff and soil loss in the plots. Precipitation volume was read from the rain gages whenever runoff bottles were collected. The runoff and sediment collected in the Gerlach bottles were transferred to lab beakers in the laboratory and weighed. The sediment was decanted with a 0.04 g L^{-1} alum solution, and after the samples were oven-dried for 24h@100ºC and weighed, the corresponding runoff volume and sediment concentration were obtained.

2.6 Runoff Volume and Soil Loss

Since the Gerlach bottles collected only a 1-L sample of the generated plot runoff and sediment in each significant rainfall event, a hydrological calculation was necessary to assess the total runoff and sediment volumes generated in it. In the case of runoff, the NRCS (2021) equation was used to obtain total runoff generated in each event.

The initial curve numbers-CN of the plots were obtained from the NRCS (2021) table using the plots' soils and land-use/management combinations. Condition II of antecedent soil moisture was assumed for the entire monitoring period, since this is the most common condition of the Brazilian savannah (Chaves et al., 2012). The CN of each soil/cover combination obtained from tables were later calibrated with observed CN values from four 22.1 m-long bounded runoff plots, located at the Tarimba farm, with similar land covers, were used (Fonseca et al., 2023).

In the case of the other two experimental sites (Progresso and Funil farms), where traditional runoff plots and observed CN values were not available, the initial CN values from the NRCS (2021) tables were adjusted following the calibration process obtained from the Tarimba farm, where the Gerlach and traditional 22.1 m plots were available. The assumption was that the proximity, climatic and hydrologic conditions of the two farms would allow the same CN adjustment.

Soil loss in each significant rainfall event in the Gerlach plots was obtained by the product of sediment concentration of the 1-L sample bottles (g L^{-1}) and the runoff plot runoff volume, calculated from equations 2-3, namely:

$$SL = F_c * C_s * R / 100$$

(2)

<u>where</u>: SL (Mg ha^{-1}) = soil loss in each event in the Gerlach plot; F$_C$ (dimensionless) =

correction factor between the event soil loss of the 22.1 m-long (observed) plots and the Gerlach plots; C_S (g/L) = sediment concentration in the 1-L sampling bottle of the Gerlach plot; R (L) = Gerlach plot total runoff.

The correction factor F_C was obtained by dividing the observed 22.1 m bounded plot soil loss of the Tarimba farm by the corresponding Gerlach plot soil loss (equation 2). If $0.9 < F_C < 1.1$, F_C was taken as unity, assuming that the observed deviation was due to experimental error.

2.7 Natural Soil & Sediment Texture, and Sediment Enrichment

The texture of the natural soil, obtained from randomly collected samples (0-10 cm) from all experimental plots, and the texture of sediment samples of the Gerlach bottles, from all treatments/sites (N=4), were obtained with the *Better-sizer ST®* granulometer, to assess the sediment enrichment-ER in the runoff (Wacha et al., 2020):

$$SSA = SA_{sand} \cdot f_{sand} + SA_{silt} \cdot f_{silt} + SA_{clay} \cdot f_{clay}$$

(3)

$$ER = SSA_{sed} / SSA_{soil}$$ (4)

<u>where</u>: SSA = specific surface area of soil or sediment ($m^2\,g^{-1}$); SA_i = the reference value of specific area of soil *or* sediment fraction ($m^2\,g^{-1}$); f_{sand}, f_{silt}, and f_{clay} = the fractions of sand, silt, and clay in soil *or* sediment, respectively; and ER (adimensional) = enrichment ratio of sediment. An ER>1 indicates enrichment of fines in the sediment, while ER< 1 indicates depletion of fines (Flanagan and Nearing, 2000; Wacha et al., 2020).

2.8 Runoff & Soil Loss Monitoring

The runoff and soil loss monitoring was carried during two consecutive hydrologic years (2022/23 and 2023/24), since precipitation in the Brazilian savannah is concentrated in the summer months (Nov-May) (Fonseca et al., 2021). The 2-yr monitoring period was important to assess not only the inter-annual climatic variability but also the effect of time in the pasture restoration process.

2.9 Statistical Analysis

To assess the effect of pasture restoration on runoff, soil erosion, and sediment enrichment, and compare it with the degraded pasture and natural savannah treatments, the Tukey multiple-range test ($\alpha= 0.05$), which reduces Type I error and provides more information than simple p-values (Dunnett, 1980), was used. The experimental sites (farms) were taken as blocks, and the means of the two hydrologic years were used to increase data robustness. Additionally, box-plots were used to show the degree of dispersion and the presence of outliers

in the experimental data (Williamson et al., 1989).

Since soil loss in erosion plots was found by Fonseca et al. (2021) to be a non-linear function of runoff in non-karst tropical landscapes, where soil cover was a key controlling factor, the relationship obtained those authors was fitted to the runoff and soil loss data of the three experimental sites. If a good fit was obtained, the runoff and erosion processes in karst areas of the Vermelho river basin could be (at least partially) explained by those of non-karst data, which are more abundant in the literature, facilitating the establishment of soil conservation policies in the region. Additionally, a Spearman correlation test with the corresponding p-value was carried between runoff and soil loss data, to assess the relationship between the two variables.

3. Results

3.1 Rainfall and Erosivity

The monthly and annual rainfall volumes and rainfall erosivities of the three experimental sites are presented in Tables 4 and 5, for the 2022/23 and 2023/24 hydrologic years, respectively. These tables indicate that rainfall volumes and erosivities were very similar in both years and varied very little among farms, avoiding the need of normalization of runoff and soil loss by rainfall volume and erosivity, respectively (Fonseca et al., 2021).

Table 4. Monthly and annual rainfall volumes (P) and rainfall erosivities (R) of the three experimental sites, during the 2022/23 hydrologic year.

Month/year	Funil farm		Progresso farm		Tarimba farm	
	P (mm)	R (MJ mm ha^{-1} hr$^{-1)}$	P (mm)	R (MJ mm ha^{-1} hr$^{-1)}$	P (mm)	R (MJ mm ha^{-1} hr$^{-1)}$
aug/22	0.0	0.0	0.0	0.0	0.0	0.0
sep/22	0.0	0.0	0.0	0.0	0.0	0.0
oct/22	0.0	0.0	0.0	0.0	0.0	0.0
nov/22	291.2	1995.0	170.5	1091.1	181.7	1178.4
dec/22	293.7	2102.5	335.9	2471.7	160.9	1017.6
jan/23	196.1	1291.6	189.3	1237.4	169.4	1082.3
fev/23	30.9	139.0	39.2	185.4	305.0	2199.8
mar/23	121.0	721.5	119.4	709.7	90.1	539.5
apr/23	172.6	1107.1	241.3	1658.4	183.4	1191.6
may/23	0.0	0.0	0.0	0.0	0.0	0.0
jun/23	0.0	0.0	0.0	0.0	0.0	0.0
jul/23	0.0	0.0	0.0	0.0	0.0	0.0

| Total | 1100.5 | 7356.6 | 1095.5 | 7353.7 | 1090.5 | 7209.2 |

Table 5. Monthly and annual rainfall volumes (P) and rainfall erosivities (R) of the three experimental farms, during the 2023/24 hydrologic year.

Month/year	Funil farm		Progresso farm		Tarimba farm	
	P (mm)	(MJ mm ha^{-1} hr^{-1})	**P** (mm)	(MJ mm ha^{-1} hr^{-1})	**P** (mm)	(MJ mm ha^{-1} hr^{-1})
aug/23	0.0	0.0	0.0	0.0	19.3	77.1
sep/23	22.7	53.6	47.1	226.9	0.0	0.0
oct/23	33.1	148.2	26.1	111.3	90.4	497.6
nov/23	111.3	639.7	80.3	431.6	64.0	328.3
dec/23	213.5	1403.7	118.8	692.4	139.8	842.4
jan/24	193.2	1244.1	216.8	1429.6	168.9	1058.3
fev/24	289.2	2023.8	288.2	2014.8	306.9	2171.4
mar/24	154.3	948.8	156.8	966.9	161.3	986.0
apr/24	122.6	718.7	197.4	1276.8	183.1	1166.4
may/24	0.0	0.0	0.0	0.0	0.0	0.0
jun/24	0.0	0.0	0.0	0.0	0.0	0.0
jul/24	0.0	0.0	0.0	0.0	0.0	0.0
Total	1140.0	7180.6	1131.5	7150.3	1133.5	7127.5

3.2 Runoff

Figure 5 shows the box plots of the mean annual runoff volume assessed in the different treatment plots (means of N= 2 replicates, 2 years) of the Funil, Progresso, and Tarimba farms, and Table 6 shows the results of the Tukey multiple-range test.
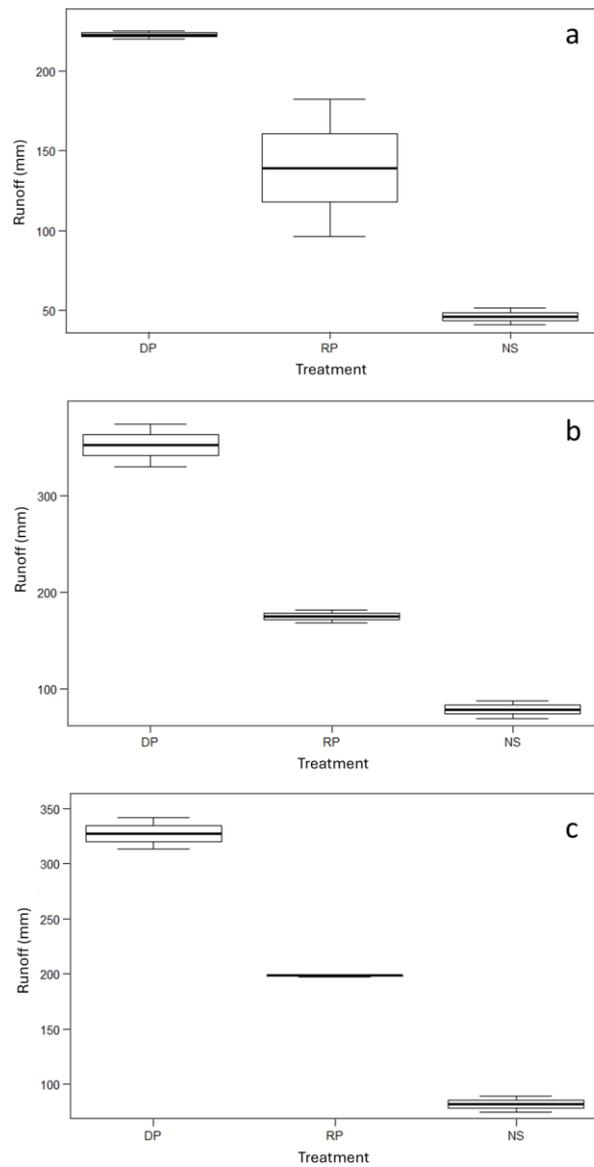
Figure 5 - Mean annual runoff volume collected

Table 6. Tukey multiple-range test for mean annual runoff in the three experimental sites and corresponding treatments (α=0.05).

Site	Treatment	Runoff (mm yr^{-1})
	Degraded pasture	222.8 *a*
Funil	Restored pasture	139.2 *ab*
	Natural savanna	46.1 *b*
	Degraded pasture	352.4 *a*
Progresso	Restored pasture	175.1 *b*
	Natural savanna	78.9 *c*
Tarimba	Degraded pasture	327.6 *a*

	Restored pasture	198.4 *b*
	Natural savanna	81.7 *c*

3.3 Soil Loss

Figure 6 shows the box plots of soil loss collected in the different treatment plots (means of N= 2 replicates, 2 years) for the Funil, Progresso, and Tarimba sites. Since the correction factor (F_C) of equation 4 was 0.95, it was taken as unity. Table 7 shows the results of the Tukey multiple-range test form mean annual soil loss in the three experimental sites.
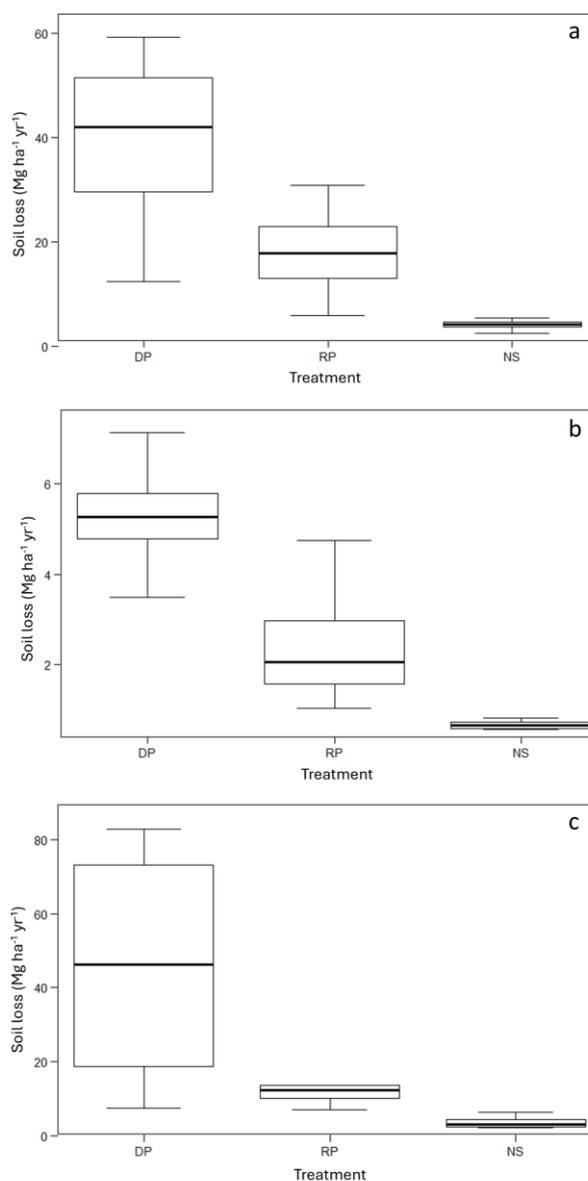
Figure 6 - Box plots of soil loss collected in the different treatment plots

Table 7. Tukey multiple-range test for mean annual soil loss in the three experimental sites and corresponding treatments (a=0.05).

Site	Treatment	Soil Loss (Mg ha^{-1} yr^{-1})
Funil	Degraded pasture	38.9 *a*
	Restored pasture	18.1 *ab*
	Natural savanna	4.1 *b*
Progresso	Degraded pasture	5.3 *a*
	Restored pasture	2.5 *b*
	Natural savanna	0.7 *b*
Tarimba	Degraded pasture	45.7 *a*
	Restored pasture	11.4 *ab*
	Natural savanna	3.8 *b*

3.4 Sediment Enrichment

The sediment enrichment ratios of the three treatments in the Funil, Progresso, and Tarimba farms for the two hydrologic years (N=4, means of 2 years) are presented in Figure 7. Table 8 shows the results of the Tukey multiple-range test for the sediment enrichment ratio.
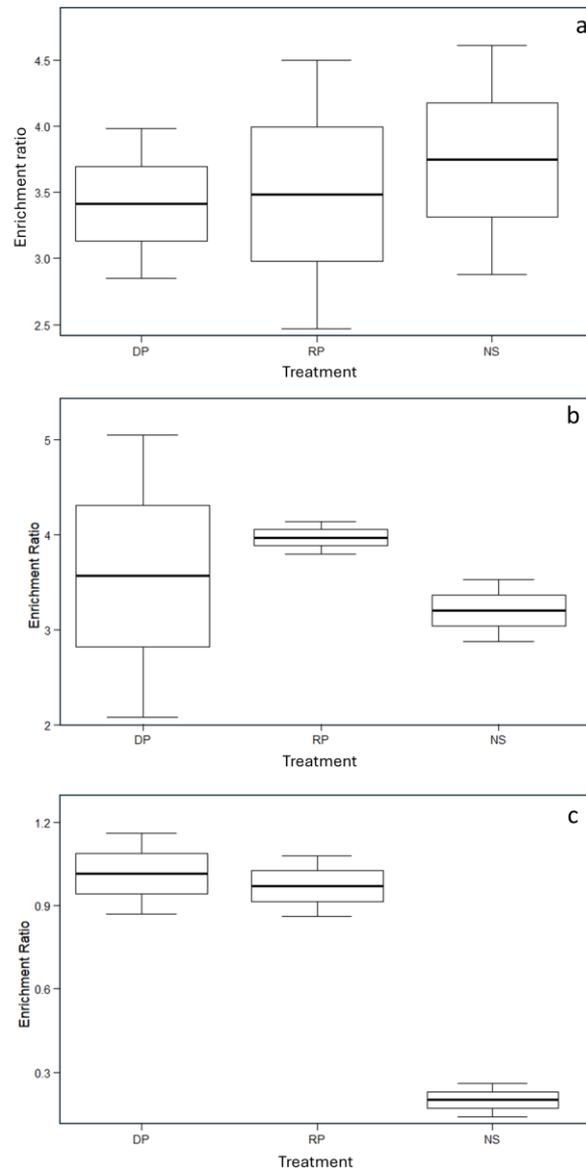
Figure 7 - Sediment enrichment ratios of the three treatments in the Funil, Progresso, and Tarimba farms for three two hydrologic Years

Table 8. Tukey multiple-range test for sediment enrichment ratio in the three experimental sites and corresponding treatments (a=0.05).

Site	Treatment	Sediment Enrichment Ratio
	Degraded pasture	3.8 *a*
Funil	Restored pasture	3.5 *a*
	Natural savanna	3.4 *a*

Progresso	Degraded pasture	4.0 *a*
	Restored pasture	3.6 *a*
	Natural savanna	3.2 *a*
Tarimba	Degraded pasture	1.0 a
	Restored pasture	1.0 a
	Natural savanna	0.2 b

3.5 Relationship between Runoff and Soil Loss

Figure 8 presents the relationship between mean annual runoff and annual soil loss of the experimental plots, in the two hydrologic years, and Figure 9 shows the experimental data (solid points) plotted against the scatter-plot of other 50 runoff and soil loss data of non-karst areas of the Brazilian savanna, compiled by Fonseca et al. (2021) (hollow points). Triangles in the Figure represent plots without permanent cover (NP) and circles represent plots with permanent (P) cover.
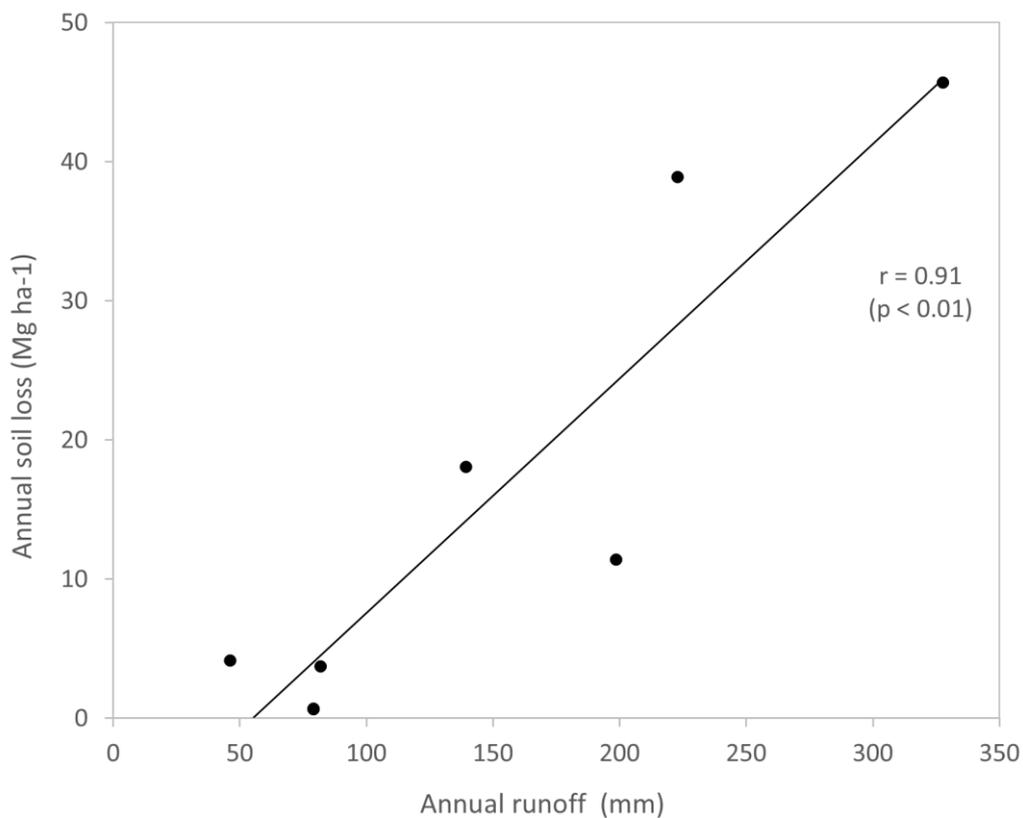
Figure 8- relationship between mean annual runoff and annual soil loss of the experimental plots, in the two hydrologic years
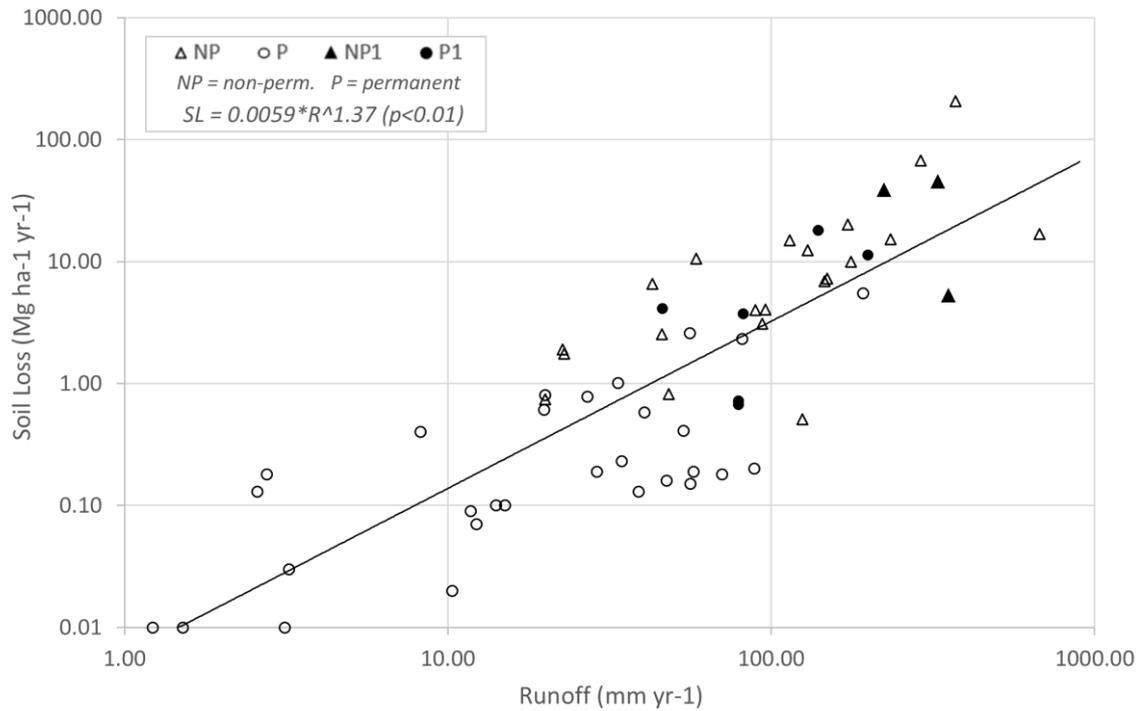
Figure 9 - fitted equation of the data

The Spearman-r between the plots' runoff and soil loss was 0.91 (p<0.01), indicating a high correlation between the two variables. The fitted equation of the data of Figure 9, encompassing both karst and non-karst areas of the Brazilian savannah, was $SL = 0.0059\ Q^{1.37}$ (p <0.01).

4. Discussion

4.1 Precipitation and Rainfall Erosivity

The results of Tables 4 and 5 indicate that there was little spatial (inter-block) and temporal (inter-annual) variability in rainfall volume and erosivity, which are important drivers of runoff and soil loss, respectively. The relative proximity of the farms (blocks) and the hydrologic years in a sequence explain the reduced variability observed (Chaves, 2010), allowing a direct comparison of inter-year runoff and soil loss between and within treatments, and their corresponding means. Fonseca et al. (2023) found a similar behavior in other karst experimental sites of the Brazilian savannah.

4.2 Runoff

In all farms, runoff from the restored pasture (RP) plots was significantly reduced (42%) when compared to the degraded pasture (DP) plots. Except for the Funil farm, the means of the two other farms were statistically different. In the restored pasture condition (RP) of all sites, yearly runoff volume was situated midway between degraded pasture (DP) and natural savannah (NS), indicating that a significant hydrologic service was promoted by the pasture restoration after two years, nearing that of the natural savanna (NS). In previous studies at the Tarimba farm,

using traditional 22.1 m bounded plots, a decrease of 50% in annual runoff was observed after 3 years of ecologic restoration of a degraded savannah (Fonseca et al., 2023). Although indirectly assessed, runoff reduction in the restored pastures resulted from improved soil cover (Fonseca et al., 2021), as indicated in Figure 2, and improved soil tilth (Chaves et al., 2017), resulting from soil tillage. Runoff reductions were observed in all sites, as reported by Fonseca et al. (2021) for non-karst areas of the Brazilian savannah. Furthermore, treating sites as blocks avoided spurious comparison and bias (Wilding and Drees, 1983), due to inherent site variability.

4.3 Soil Loss

Soil loss was reduced in the restored pasture (RP) condition, compared to degraded pasture (DP), in all three farms. Reductions varied between 50% and 80%, depending on the farm/block analyzed. The statistically similar soil loss means in DP and RP of the Funil and Tarimba sites resulted from a large dispersion in the data (Figure 6). Similar reductions in soil loss were found at the Tarimba site in an earlier study, using native grasses/bushes in bounded 22.1 m plots (Fonseca et al., 2023).

Similarly to the runoff data, soil loss in the restored pasture (RP) plots were situated midway between degraded pasture (DP) and natural savannah (NS), indicating that pasture restoration was almost as effective as natural savannah regarding erosion abatement. The increase in grass cover and the improvement in soil tilth in the restored pasture (RP) plots explain the observed erosion reduction (Figure 2), due to reduced splash and runoff processes (Figure 5). The latter reduces rill erosion (Fonseca et al., 2021) and the former decreases sheet erosion (Nearing et al., 1989).

Another key finding in the study was that soil loss in the Gerlach collectors of the Tarimba farm was very similar to that of the 22.1 m-long bounded plots, given by a correction factor (F_c) of 0.95. This indicates that, if adequately installed and calibrated, Gerlach plots could effectively emulate the more expensive and labor-intensive bounded runoff plots (Morgan, 1989), facilitating erosion research, particularly in developing countries.

4.4 Runoff and Soil Loss Relationship

The high correlation obtained between mean annual soil loss and runoff (r = 0.91, p<0.01) indicates that the former is strongly influenced by the latter. Since runoff is easier and less expensive to obtain, it could serve as a proxy for the estimation of soil loss in tropical karst areas (Fonseca et al., 2021). Additionally, Figure 9 indicates that soil loss and runoff of karst

areas of the Brazilian savanna fits well the data of non-karst areas, and that covered plots provide significant reductions in both variables, when compared with uncovered areas.

4.5 Sediment Enrichment

Figure 6 indicates that, except for the Tarimba site, the sediment was enriched in fines (ER > 1), due to the sediment sorting process proportioned by ground cover during erosive events (Wacha et al., 2020). This sediment sorting process, restraining larger particles, would reduce the silting potential of downstream sinkholes and underground rivers in the Vermelho river basin (Fonseca et al., 2023). On the other hand, finer sediments, not sorted at the Tarimba farm (ER ≤ 1) because of its intrinsic pedologic characteristics (Entisol), tend to adsorb and transport more nutrients than coarse sediments, leading to a potential eutrophication of downstream lentic waters (Chardon and Schoumans, 2007).

4.6 Reduction Mechanisms and Hydrological Implications

Although not directly measured in the experiment, the agents responsible for runoff and soil loss reduction were improved soil tilth and infiltration, and increased soil cover, previously recognized by Fonseca et al. (2023) in a nearby experiment. Because runoff is reduced in the restored plots, and because soil loss is positively correlated with runoff, a reduction in the latter decreased the former (Fonseca et al., 2021).

The hydrologic implications of restored pastures of karst areas of the Brazilian savanna are two-fold: i) The runoff reduction would increase groundwater recharge, and ii) The soil loss decrease would reduce sediment yield, which causes the silting of sinkholes and underground rivers. Both contribute to the long-term sustainability of the karst landscape.

4.7 Gerlach Collector Validity

The experimental data indicate that Gerlach plots, although simple and non-integrative monitoring devices, are useful in the assessment of soil loss in tropical karst areas. The unbound nature of its setting, allowing unconstrained runoff (Morgan, 1989), not only allowed for the detection of significant differences between degraded and restored plots, but the results compared well with those of traditional and integrative bound plots of a similar landscape (Fonseca et al., 2023).

Furthermore, the high correlation between runoff, obtained from the NRCS (2021) equation and soil loss (r = 0.91), as well as the good fit of the experimental data to the runoff and soil loss relationship of non-karst areas of the Brazilian savanna (Fonseca et al., 2021),

indicate that the present results are meaningful. Provided that appropriate precautions are taken, Gerlach plots are a simple and cost-effective means of assessing soil loss in tropical karst landscapes, providing elements for the establishment of sound conservation policies.

5. Conclusions

- The main conclusions of the present study were:
- In all three experimental sites, runoff in the restored plots was reduced by 40%, compared to the degraded plots, after the first year of restoration;
- Soil loss in the restored was reduced between 50% and 80% when compared to the degraded plots, and neared that observed in the natural savannah plots;
- Runoff and soil loss in the restored pasture plots were situated in the midway between degraded pasture and natural savannah, indicating that an important hydrologic service was accomplished after two years;
- In two of the three experimental sites, an enrichment in fines in the sediment was observed, which could reduce the silting of downstream sinkholes and underground rivers;
- Gerlach plots proved to be a suitable method of runoff & soil loss assessment in the studied area;
- Runoff and soil loss were highly correlated, and were adequately fitted to the data of non-karst areas of the Brazilian savannah;
- Although the results fill an important gap in the estimation of runoff and soil loss of natural, degraded, and restored areas of karst savannas of Brazil, they are preliminary and require further validation.

6. Recommendations

The significant reductions observed in runoff and soil loss in a karst area of the Brazilian savannah, resulting from restored pastures, nearing those of natural savanna conditions after two years, indicate that karst landscapes could be hydrologically improved with simple restoration practices. These results can lead to the establishment of effective soil and water conservation policies, including incentive payment mechanisms based on environmental performance. Since simple and inexpensive Gerlach collectors proved to be efficient in the erosion assessment of restoration programs, their use is recommended, particularly in developing countries.

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TITLE PAGE

Title: Effect of Pasture Restoration on Runoff, Soil loss, and Sediment Enrichment in a Karst Basin of a Tropical Savannah

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Article

Pasture Restoration Reduces Runoff and Soil Loss in Karst Landscapes of the Brazilian Cerrado

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Abstract

Water erosion is a major driver of soil degradation in the Brazilian Cerrado, intensified by the conversion of natural vegetation into agricultural land. The excessive runoff and sediment generated in poorly-covered karst slopes impacts the hydrologic cycle of the biome's sinkholes and underground rivers. This study evaluated the effectiveness of pasture restoration in reducing runoff and soil loss in three experimental farms situated in a vulnerable karst area of Central Brazil. Runoff and soil loss were monitored during three hydrologic years in plots of degraded pasture (DP), restored pasture (RP), and natural savannah (NS), using unbound Gerlach settings. The experiment was carried in three farms of the Vermelho river basin, which were treated as blocks. Results indicate that pasture restoration reduced runoff by 50% and soil loss by 55–95% when compared to degraded pasture conditions, below on-site erosion tolerance thresholds. Runoff and soil loss in restored pasture (RP) plots fell between DP and NS, though in some cases soil loss in RP reached levels comparable to natural savannah. Normalized soil loss was highly correlated with runoff ($R^2 = 0.94$), allowing the latter to be used as a proxy of the former. The increased groundwater recharge and reduced sediment yield resulting from pasture restoration improve on- and off-site resilience in vulnerable karst landscapes, and could be utilized as a sustainable soil conservation policy.

Keywords: pasture restoration; erosion & runoff, ecosystem services.

1. Introduction

Water erosion is a primary driver of soil degradation which is aggravated by the removal of natural vegetation, resulting in decreased land productivity [1,2]. Permanent vegetation is considered the only natural component of soil protection [3], stabilizing the soil through its canopy and root system, enhancing infiltration, reducing surface runoff [4] and retaining soil moisture [5].

In addition to other on-site impacts, such as soil degradation and declining agricultural productivity [6], soil erosion also generates off-site effects, such as downstream silting and eutrophication [7], nutrient enrichment of sediments [8,9] and the consequent deterioration of downstream water quality [10–12, 13].

The Brazilian Cerrado, in Central Brazil, has been increasingly subjected to anthropogenic pressures, with profound impacts on its natural landscape [13], including stressed aquifer systems [14] and excessive soil erosion [15]. More than 50 million hectares of the Cerrado biome are now at high risk by water erosion, a process intensified by a combination of high rainfall erosivity, high soil erodibility, and the conversion of natural vegetation into agricultural land [16], culminating in permanent soil degradation [17]. It was shown that soil loss is positively correlated to and even predicted by surface runoff. However, maintaining permanent soil cover, such as natural vegetation and well-managed pastures, is critical for minimizing runoff generation and reducing soil erosion [18].

Within the Brazilian Cerrado, there are highly vulnerable karst areas, such as the Vermelho river basin, where poorly structured sandy soils, lying over fractured limestones, are severely affected by soil erosion, leading to the silting of sinkholes and subterranean rivers [3].

Pasturelands, which dominate the majority of the Brazilian Cerrado landscapes, have been severely degraded in the last 50 years, largely due to erosion and inadequate soil management [19,20]. Natural restoration of these areas has proven insufficient, as it fails to restore key soil properties and ecosystems functions [19].

In contrast, active reclamation strategies, such as pasture restoration and the establishment of adequate vegetation cover, have significantly reduced erosion and improved ecosystem services [21,22], while enhancing the well-being of rural communities [23]. However, effective pasture restoration requires adaptive management, including regulated stocking rates to allow for regrowth and the creation of appropriate soil cover, and cattle fencing during critical germination and seedling periods [24]. Additionally, effective restoration is achieved when on- and off-site soil loss in the landscape is reduced below the accepted tolerance values, i.e., below 10 Mg ha^{-1}yr^{-1} and 1.0 Mg ha^{-1}yr^{-1}, respectively [18].

In a pioneer study carried in a karst area of the Brazilian Cerrado, it was found that active pasture restoration with grasses and shrubs reduced runoff by 50% and soil loss by 80%, with respect to fallow, uncovered areas [3]. However, the research looked at one soil type only, and could not be generalized to different landscapes.

To assess runoff and soil erosion under different land-uses, several methods have been used, including standard (bound) runoff plots [3] and erosion pins [25], which are complex and time consuming [26]. Simpler devices, such as unbound Gerlach troughs [26,27] are more practical and inexpensive to install and to operate, although non-cumulative runoff collection is a challenge [24]. Additionally, traditional bounded runoff plots are unnatural erosion monitoring setups, since plot borders of bounded plots force runoff and sediment in a pre-determined direction, affecting the natural flow path [28].

Considering the existing data and knowledge gaps about the theme, the objective of this research was to assess the effectiveness of pasture restoration in different soils, land-use, and landscape settings of a karst landscape of the Brazilian Cerrado, and to evaluate the ecosystem services

provided with respect to runoff and erosion abatement, using unbound Gerlach plots, and to evaluate the relationship between them.

2. Materials and Methods

2.1. Study area

The study area consisted of three cattle farms located at the Vermelho basin, in Central Brazil, situated 20-30 km apart (Figure 1).
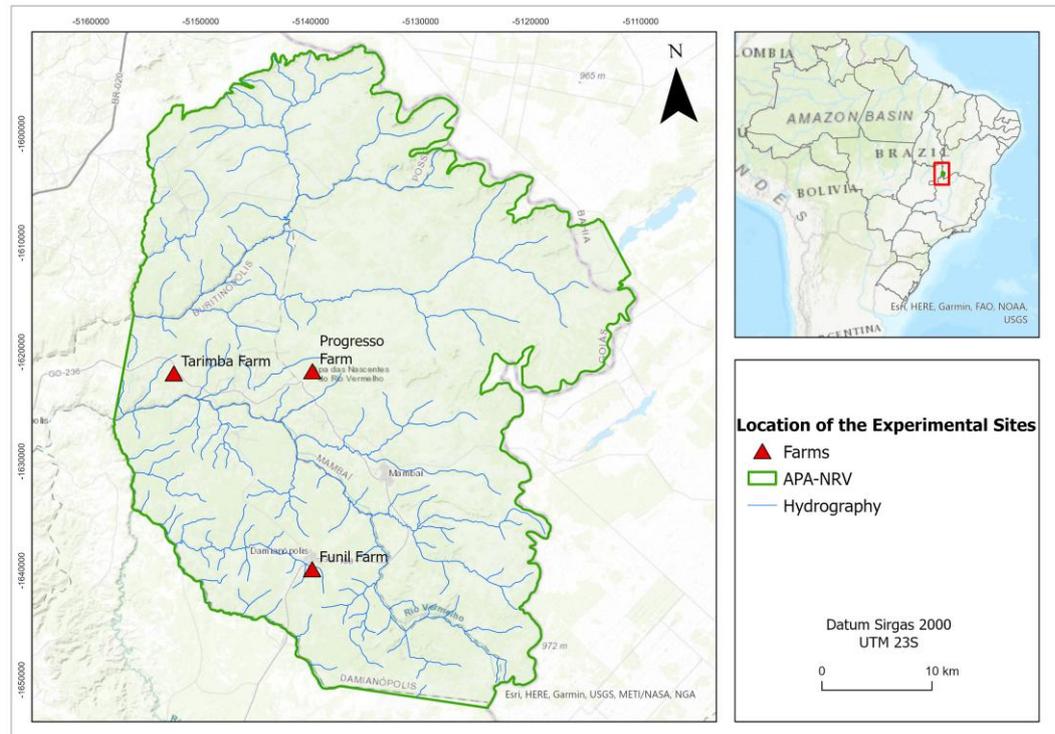
Figure 1 10. Vermelho River Basin, in Central Brazil, showing the three experimental sites.

The experimental sites had different soils, but similar topographies, land-use and management practices (Table 1), spanning the typical landscape variability of the Vermelho river basin.

Table 1: Topography, soils, and land-uses of the three experimental sites.

Site	Topography (slope grade)	Soil Type	Land Uses
Funil farm	Gentle (9.3%)	Red Orthox (sandy-loam)	Pasture & savannah
Progresso farm	Gentle (6.8%)	Psamment (sand)	Pasture & savannah
Tarimba farm	Moderate (11.5%)	Orthent (silt-loam)	Pasture & savannah

relatively homogeneous subsets before assigning treatments [29].

Degraded pasture (DP) was characterized by reduced grass cover (0-20% ground cover), planted with *Brachiaria* sp. and *Andropogon* sp., high soil compaction [30], assessed by a ring penetrometer, low infiltrability (Table 2), and low fertility and organic matter. The plot areas of degraded pasture (DP) in the three sites were between 0.5 and 1.0 hectare.

Table 2: Penetration resistance and final infiltration rate of the degraded pastures (DP) in the three experimental sites.

Experimental Site	Penetration Resistance, 0-10 cm (MPa)	Infiltration Rate (cm min^{-1})
Funil farm	3.33	0.28
Progresso farm	0.78	0.91
Tarimba farm	1.95	0.80

Adjacent to the degraded pasture (DP) plots, restored pasture (RP) plots were established on formerly degraded pastureland, with areas varying between 0.5 to 1.0 ha. Pasture restoration was implemented during the dry season preceding the first monitoring year and included disc ploughing (25 cm), liming (2.0 Mg ha^{-1} of dolomitic limestone) and fertilization (240 kg of 4-14-8 NPK granular fertilizer), herbicide (2 L ha^{-1} of glyphosate), planting of Massai grass (*Panicum maximum* v. Massai), and control of leafcutter ants (10 kg ha^{-1} of sufuramid). One year after planting, the Massai grass cover was suitable for grazing, and cattle was allowed to graze in the three restored plots.

The Natural Savannah (NS) plots comprised of small remnants of original vegetation cover (0.2 to 2.0 ha), within each experimental farm. These sites contained small trees (3 to 5 m) covering approximately 50% of the area, surrounded by shrubs and natural grasses [31].

Within each block (farm), the NS, DP and RP treatments were installed in the same soil type and had similar slope gradients (Table 1), allowing the plots to be taken as independent treatments (Figure 2). All plots were fenced to prevent cattle intrusion.

Figure 2. Soil covers under different treatments in the three experimental sites. From top to bottom: Funil farm, Progresso farm, Tarimba farm. DP = degraded pasture; RP = restored pasture; NS = natural savannah.

2.2 Runoff Plots

Within each treatment plot, two Gerlach troughs were installed, one on the upper slope area and the other on the lower slope, to collect the upstream runoff and sediment. To avoid the interference of vegetative cover, a planialtimetric survey of the plot areas was carried with a RTK surveying equipment, using pins installed in a 0.5 x 0.5 mesh, to determine the exact plot drainage area and slope grade (Figure 3). The drainage areas of the runoff plots of the three farms are presented in Table 3.
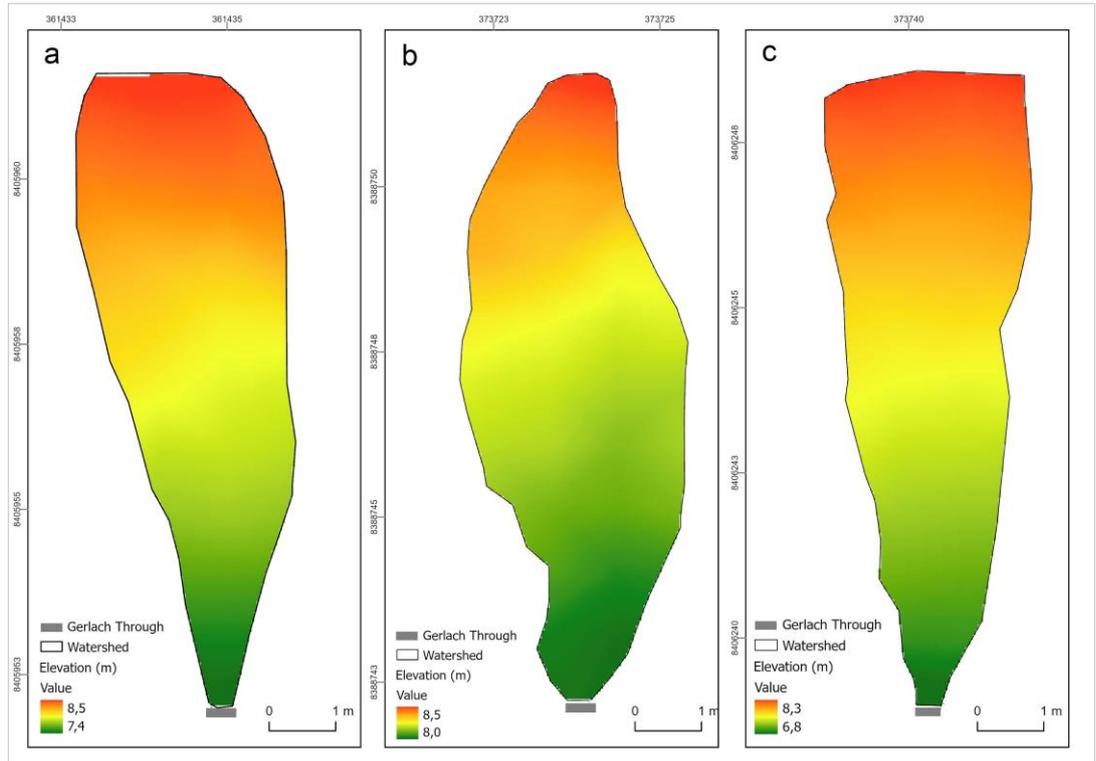
Figure 3: Examples of drainage areas and elevation of selected Gerlach plots: (a) Funil farm; (b) Progresso farm; and (c) Tarimba farm, showing the Gerlach troughs in the plot outlets.

Table 3: Runoff plot drainage areas (m²) in each experimental site/treatment.

Site	Degraded Pasture		Restored Pasture		Restored Pasture	
	a	b	a	b	a	b
	------------------------------- (m²) ---					
Funil farm	17.0	20.7	18.4	21.2	21.0	19.0
Progresso farm	12.7	22.3	15.1	21.6	20.0	22.0
Tarimba farm	28.5	22.7	20.9	20.8	20.0	16.0

At the lower end of each runoff plot, a metallic Gerlach trough [24] was installed flush with the soil surface to ensure proper collection of runoff and sediment. A 1-L *Nalgene®* bottle was connected to the trough's downstream outlet by a plastic hose to collect the runoff samples (Figure 4).
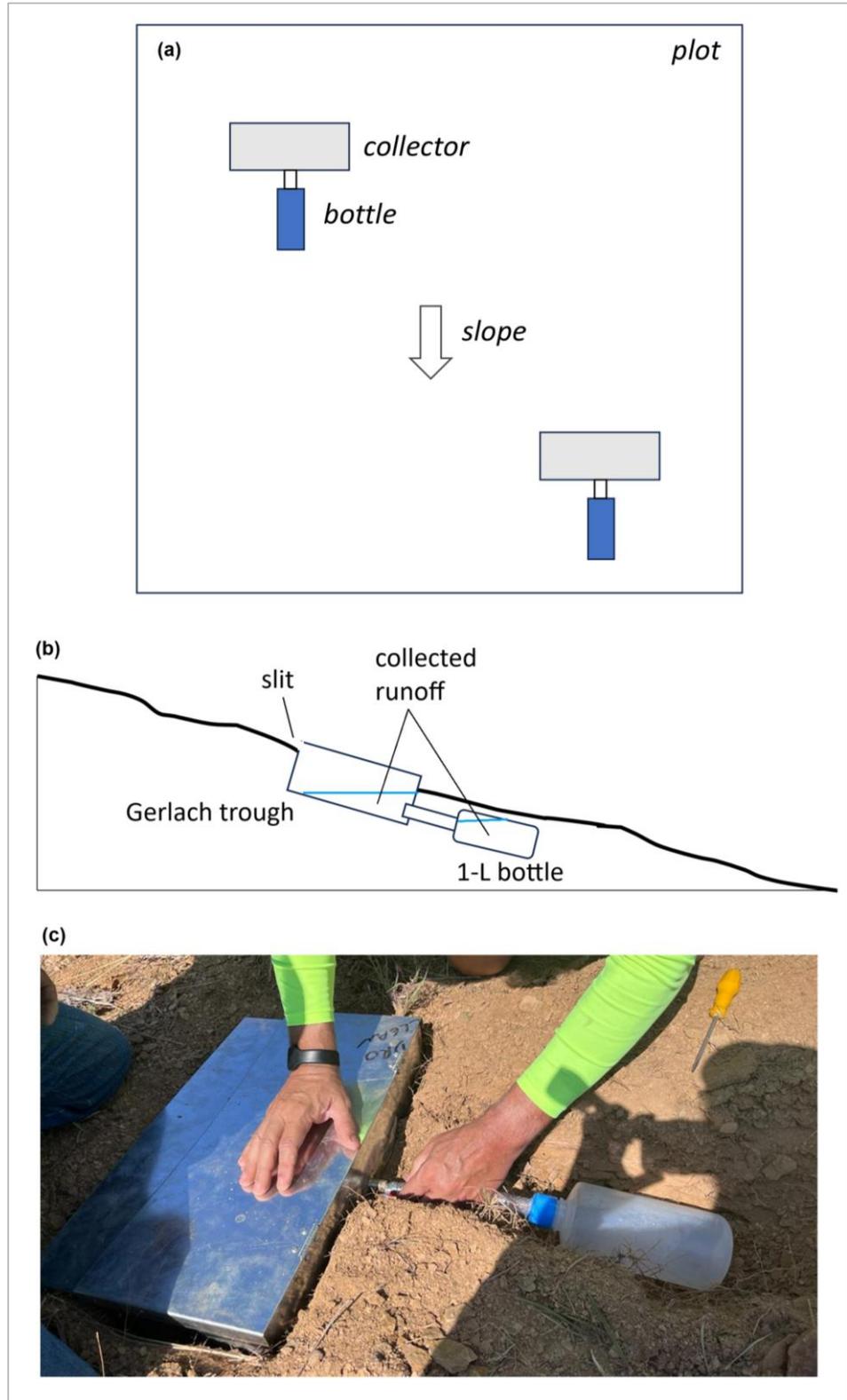
Figure 4: Layout and arrangement of the Gerlach troughs: a) Top view; b) Slope cross-section; c) Trough and bottle detail.

2.3 Rainfall Erosivity

At each experimental site, a WMO-type stainless steel rain gauge (ϕ = 0.15 m) was installed, and precipitation volumes were recorded on a daily basis, concurrently with the runoff and sediment sampling. The

rain gauge had a minimum resolution of 0.2 mm, and was placed at a safe distance from building or trees, to avoid rainfall interception.

Rainfall erosivity in each farm was calculated, on a monthly and yearly basis, using a Fournier-type equation [32] developed for Central Brazil:

$$R = 12.59 \sum_{i=1}^{12} \left(\frac{M_i^2}{P}\right)^{0.60}$$

(1)

Where: R (MJ mm ha-1 hr-1) = site annual rainfall erosivity; M_i (mm) = monthly precipitation; and P (mm) = annual precipitation.

2.4 Runoff Sampling and Laboratory Analyses

The 1-L runoff bottles were collected whenever rainfall exceeded 10 mm, since this is the threshold for runoff generation [31], which was confirmed empirically in a previous study in a nearby experiment [3]. In the laboratory, the contents of the Gerlach bottles were transferred to beakers, decanted with alum, oven-dried at 100º C for 48h (Figure 5), and weighed to determine runoff volume and sediment concentration

Figure 5. Oven-drying of runoff samples in the laboratory.

2.5 Runoff Volume and Soil Loss

Because the Gerlach bottles collected only 1-L samples of the generated runoff and sediment during each significant rainfall event, hydrological calculations were required to estimate the total runoff and the subsequent sediment yield from the plots. The NRCS equation [33] was used to obtain total runoff in each event:

$$Q = (P - 0.2 S)^2 / (P + 0.8 S)$$

(2)

and

$$S = (25,400 / CN) - 254$$

(3)

Where:
Q = surface runoff volume (mm), P = precipitation volume (mm), S =

abstraction factor (dimensionless), CN = NRCS curve-number (dimensionless). CN values for the experimental sites were derived from observed and calibrated data collected at 22.1 m-long bounded runoff plots of a previous research, conducted at the Tarimba farm [3].

Soil loss in each significant rainfall event (P > 10 mm) was calculated as the product of sediment concentration obtained from the 1-L samples and the runoff volume estimated from Equations 2-3, namely:

$$SL = F_c \, C_s \, Q \, / \, 100 \tag{4}$$

Where: Where: SL (Mg ha^{-1}) = soil loss in each event in the Gerlach plot; F_c (dimensionless) = correction factor for the 22.1 m-long (observed) runoff plots of the Tarimba farm; C_s (g/L) = sediment concentration in the 1-L sampling bottle; Q (L) = Gerlach plot runoff.

The correction factor F_c was obtained by dividing the observed 22.1 m bounded plot soil loss of the Tarimba farm from a previous study [3] by the corresponding Gerlach plot soil loss (equation 4), assuming that, due to plot set-up and sediment collection conditions, a difference could arise [34]. The same correction factor was used in the other two farms, since no corresponding bounded plots existed. However, due to the proximity of the three experimental areas and their similar climate and landscape characteristics, this assumption was hydrologically acceptable [35].

To allow direct comparison of the runoff and soil loss between the three experimental sites [18], surface runoff and soil loss were normalized by the precipitation volume and rainfall erosivity, respectively:

$$Q_n = \frac{Q}{P} \tag{5}$$

$$SL_n = \frac{SL}{R} \tag{6}$$

Where: Q_n = Normalized runoff Q (mm) = runoff volume; P (mm) = rainfall volume; SL_n= Normalized soil loss (Mg MJ^{-1} mm^{-1} h); SL (Mg ha^{-1}) = soil loss; and R (MJ mm ha^{-1} hr^{-1}).

To assess the relationship between soil loss and runoff of permanent (NS & RP) and non-permanent (DP) soil covers, normalized means of annual runoff (Q_n) and normalized annual soil loss (SL_n) were plotted in a log-log plot, and the corresponding adjusted function and p-value were obtained [18], comparing with soil loss tolerance thresholds.

Runoff and soil loss were monitored during three consecutive hydrologic years (2022/23, 2023/24, 2024/25), coinciding with the rainy season in the Brazilian Cerrado, which extends from November to May [18]. This 3-year monitoring period enabled the evaluation of restoration progress over time and accounted for intrinsic inter-annual climatic variability.

2.6 Statistical Analyses

The treatment means and their significance were calculated using

ANOVA and the Tukey-HSD multiple comparison test [36], at the 0.05 significance level. Previously, the plot data was tested for normality using the Kolmogorov-Smirnov test, with the R-Studio® package.

3. Results

3.1. Precipitation and Erosivity

The monthly and annual precipitation volumes, with corresponding rainfall erosivities, are presented in Table 4, for the three hydrologic years.

Table 4: Monthly and annual rainfall volumes (P) and rainfall erosivities (R) of the three experimental farms, during the 2022/23, 2023/24, 2024/25 hydrologic year.

Month/year	Funil farm		Progresso farm		Tarimba farm	
	P (mm)	R (MJ mm ha^{-1} hr^{-1})	P (mm)	R (MJ mm ha^{-1} hr^{-1})	P (mm)	R (MJ mm ha^{-1} hr^{-1})
Aug/22	0.0	0.0	0.0	0.0	0.0	0.0
Sep/22	0.0	0.0	0.0	0.0	0.0	0.0
Oct/22	0.0	0.0	0.0	0.0	0.0	0.0
Nov/22	252.7	155.9	150.0	84.2	242.2	116.8
Dec/22	264.0	164.3	295.5	190.6	214.5	100.8
Jan/23	176.2	100.9	166.5	95.4	225.7	107.2
Feb/23	27.7	10.9	34.5	14.3	406.4	218.0
Mar/23	108.7	56.4	105.0	54.7	126.7	53.5
Apr/23	155.1	86.5	212.2	127.9	244.5	118.1
May/23	0.0	0.0	0.0	0.0	0.0	0.0
Jun/23	0.0	0.0	0.0	0.0	0.0	0.0
Jul/23	0.0	0.0	0.0	0.0	0.0	0.0
Total	984.5	7236.5	963.61	7140.9	1460.0	8994.0
Aug/23	0.0	0.0	0.0	0.0	19.3	77.1
Sep/23	12.6	4.1	49.7	19.5	0.0	0.0
Oct/23	29.2	11.5	27.5	9.6	98.4	43.6
Nov/23	98.3	49.5	84.6	37.1	69.7	28.8
Dec/23	188.5	108.5	125.2	59.6	152.2	73.9
Jan/24	170.6	96.2	228.5	123.0	183.9	92.8
Feb/24	255.3	156.4	303.7	173.3	333.8	190.5
Mar/24	136.3	73.3	165.2	83.2	173.5	86.5
Apr/24	108.2	55.6	208.0	109.8	199.4	102.3
May/24	0.0	0.0	0.0	0.0	0.0	0.0
Jun/24	0.0	0.0	0.0	0.0	0.0	0.0
Jul/24	0.0	0.0	0.0	0.0	0.0	0.0
Total	999.0	6988.5	1192.5	7743.1	1231.9	7871.4
Aug/24	0.0	0.0	0.0	0.0	0.0	0.0
Sep/24	0.0	0.0	0.0	0.0	0.0	0.0
Oct/24	283.6	161.0	156.1	99.3	261.6	124.1
Nov/24	231.0	125.7	276.6	132.2	293.1	142.3
Dec/24	167.8	85.5	481.1	257.6	271.5	129.8
Jan/25	204.8	108.7	206.3	92.8	286.5	138.5
Feb/25	105.2	48.7	122.6	49.5	129.7	53.2
Mar/25	56.8	23.2	181.4	79.4	164.5	70.9

Apr/25	125.7	60.3	126.4	51.4	105.9	41.7
May/25	0.0	0.0	0.0	0.0	0.0	0.0
Jun/25	0.0	0.0	0.0	0.0	27.1	8.1
Jul/25	0.0	0.0	0.0	0.0	0.0	0.0
Total	**1174.9**	**7719.6**	**1550.5**	**9181.7**	**1540.0**	**8920.8**

3.2. Runoff

The calibrated runoff curve-numbers (CN) of eqs. (2) and (3) of the three sites are presented in Figure 6.
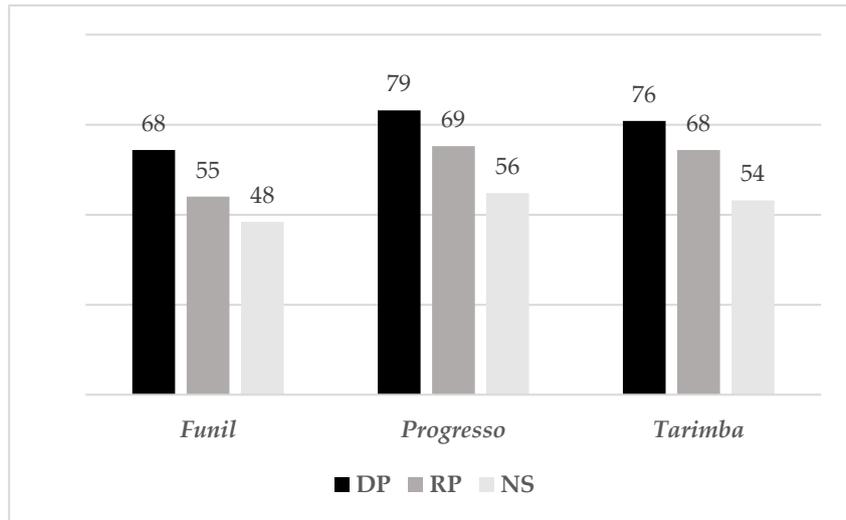

Figure 6. Calibrated runoff curve-numbers (CN) of the experimental sites and plots. DP = degraded pasture; RP = restored pasture; NS = natural savannah.

Table 5 presents the mean annual normalized runoff (mean of two replicates) for the Funil, Progresso, and Tarimba farms, for the three consecutive years. At the Funil Farm, normalized runoff differed significantly among all treatments, with degraded pasture (DP) showing the highest mean. At the Progresso Farm, restored pasture (RP) and natural savannah (NS) were statistically similar, both exhibiting significantly lower runoff than DP. At the Tarimba Farm, RP did not differ significantly from either DP or NS, indicating an intermediate response.

Table 5. Mean normalized runoff (Q/P) across treatments and farms (N=2). Different letters within the same farm indicate significant differences in Tukey's HSD test (p < 0.05).

Site	Treatment	Normalized Runoff
Funil farm	DP	0.207 *a*
	RP	0.116 *b*
	NS	0.046 *c*
Progresso farm	DP	0.283 *a*
	RP	0.133 *b*
	NS	0.061 *b*
Tarimba farm	DP	0.242 *a*
	RP	0.134 *ab*
	NS	0.055 *b*

The box-plots of normalized mean annual runoff are presented in Figure 7. In all cases, NS exhibited the lowest values with minimal variability, while DP consistently showed the highest runoff. RP, in turn, occupied an intermediate position between the other treatments.
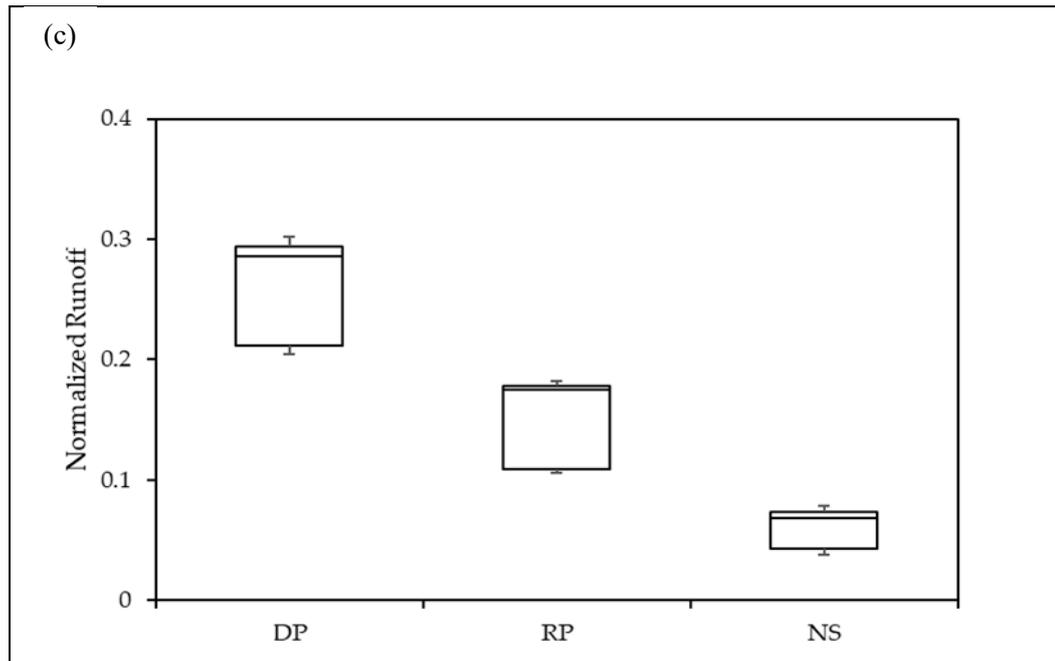
(c)
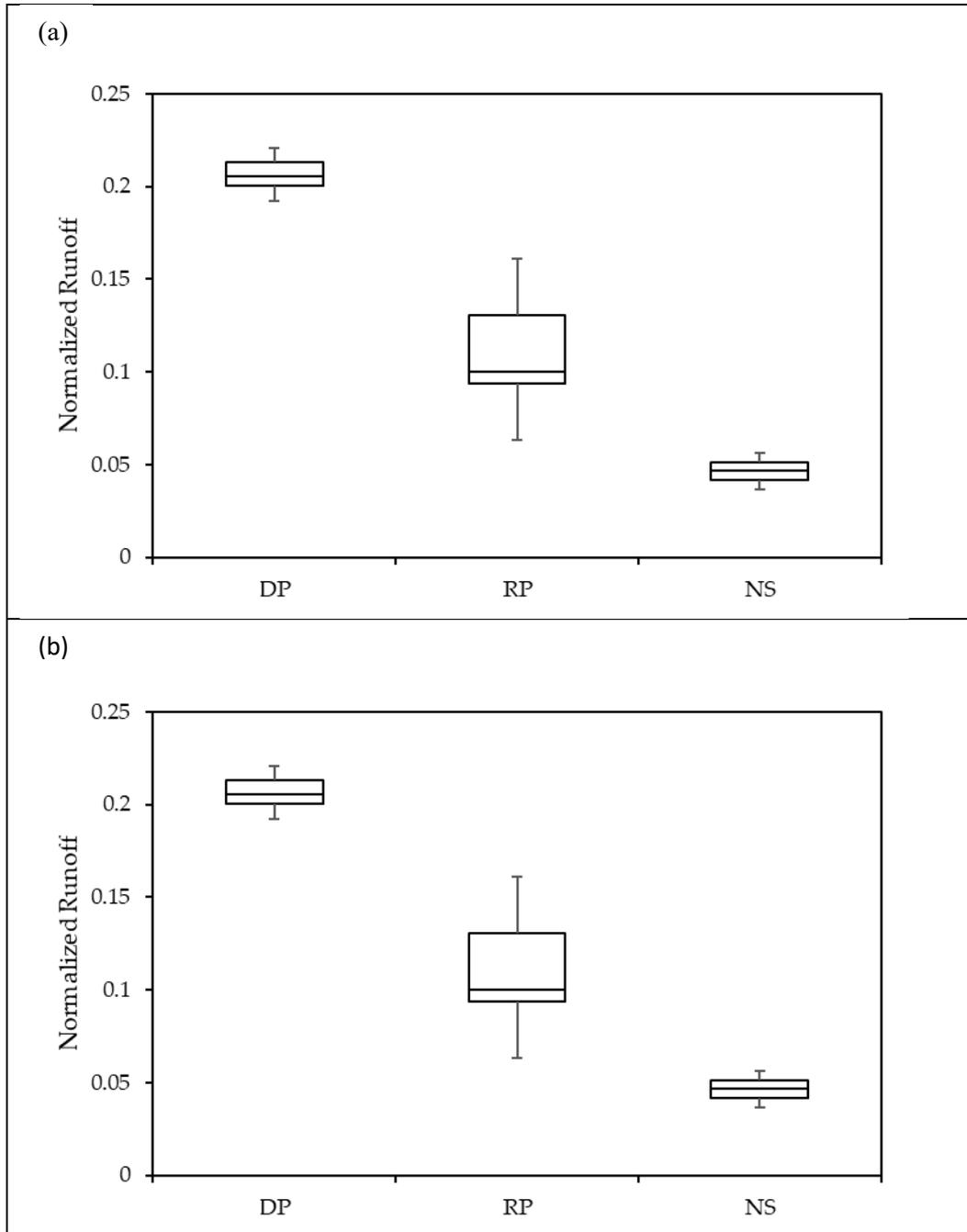
Figure 7: Box-plots of normalized runoff for the Funil farm (a), Progresso farm (b) and Tarimba farm (c). DP = degraded pasture; RP = restored pasture; NS = natural savannah.

3.3. Soil Loss

Table 6 indicates that, overall, soil loss under RP and NS were statistically similar, both showing lower values than DP. In the Progresso Farm, RP showed an intermediate position, not differing significantly from either DP or NS.

Table 6. Mean normalized soil loss for the three sites. Different letters within the same farm indicate significant differences in Tukey's HSD test (p < 0.05).

Site	Treatment	Normalized Soil Loss (Mg hr^{-1} MJ mm)
Funil farm	DP	0.0060 *a*
	RP	0.0020 *b*
	NS	0.0005 *b*
Progresso farm	DP	$6.05*10^{-4}$ *a*
	RP	$2.80*10^{-4}$ *ab*
	NS	$6.61*10^{-4}$ *b*
Tarimba farm	DP	0.0070 *a*
	RP	0.0010 *b*
	NS	0.0004 *b*

The box-plots of normalized soil loss are presented in Figure 8 for the three sites. In all cases, NS exhibited the lowest values with minimal variability, while DP consistently showed the highest soil loss. RP, on the other hand, occupied an intermediate position
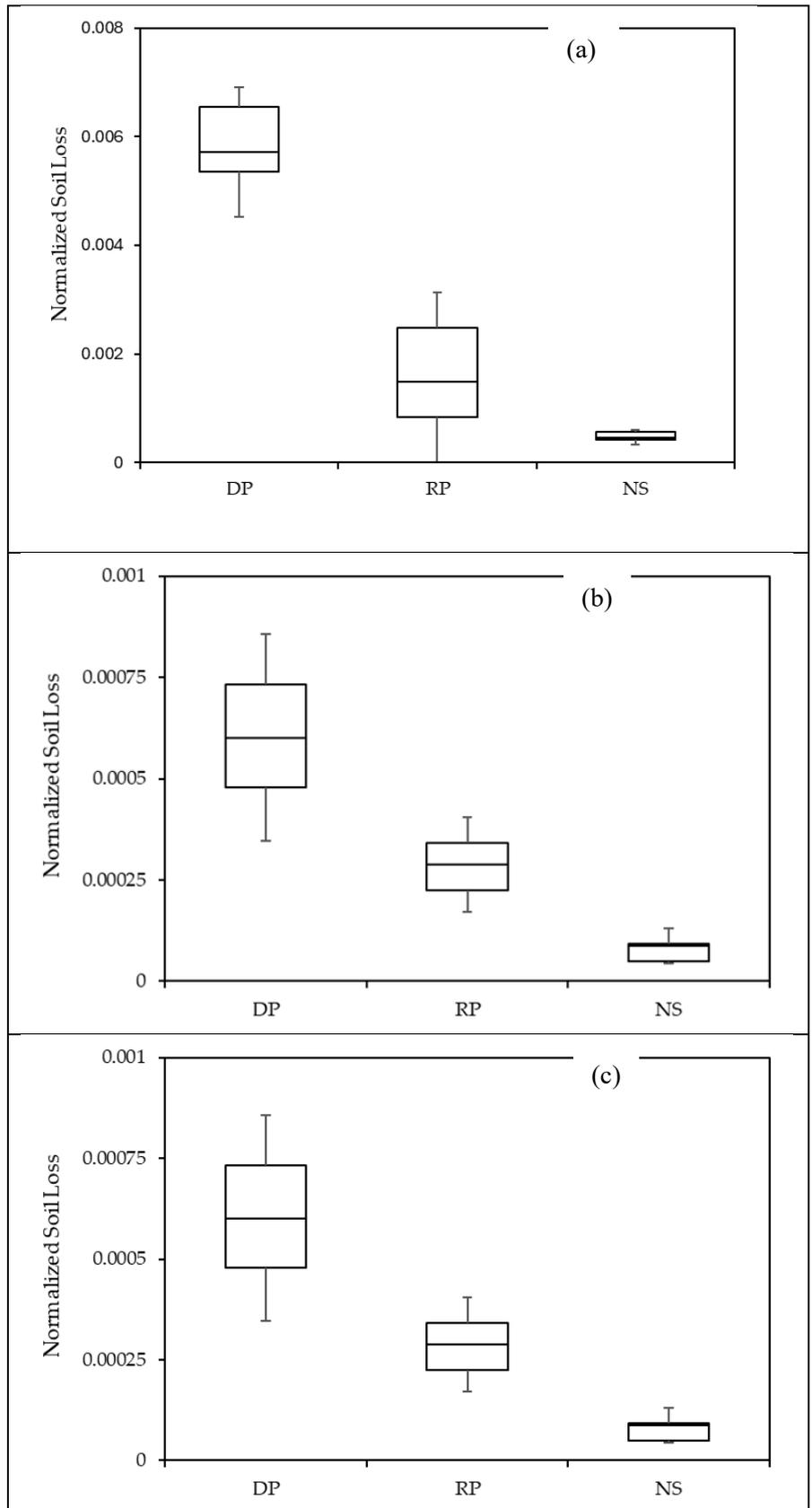
Figure 8: Distribution of Normalized soil for Funil farm (a), Progresso farm (b) and Tarimba farm (c). DP = degraded pasture; RP = restored pasture; NS = natural savannah.

3.4. Relationship between Runoff and Soil Loss and On- and Off-site Tolerance

The relationship between normalized annual runoff and annual soil loss is presented in Figure 9. In this Figure, a good fit ($R^2 = 0.94$, p < 0.01) was obtained for a power function, similar to that of non-karst landscapes of the Brazilian savannah [18].

Additionally, the soil loss of all permanently covered plots (NS & RP) fell below the on-site soil loss tolerance, as opposed to the degraded pasture plots (non-covered plots).
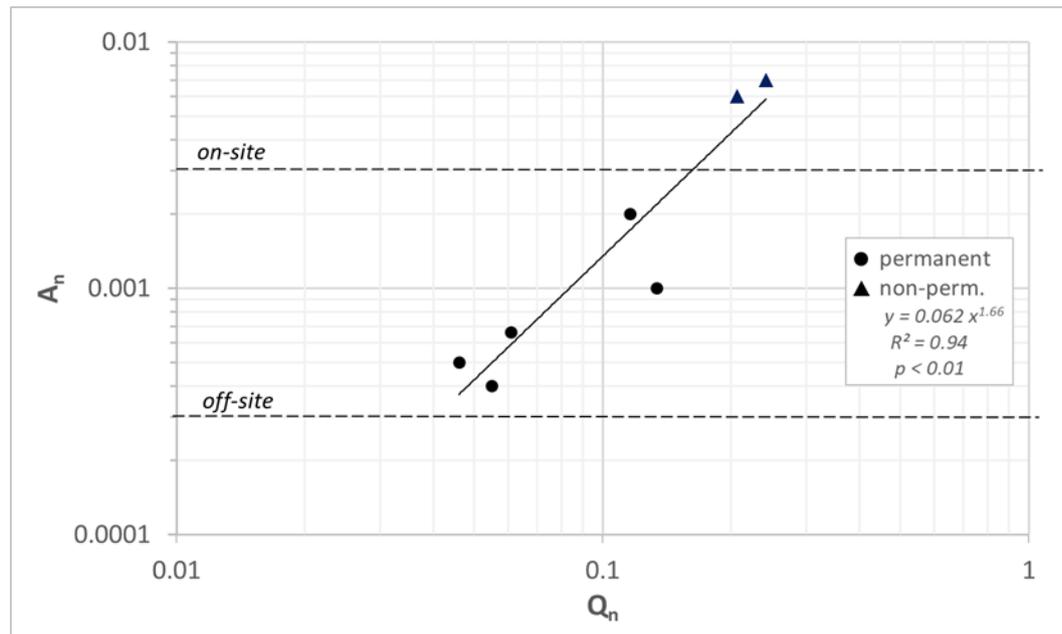
Figure 9. Relationship between normalized runoff (Qn) and soil loss (SLn) for permanent and nonpermanent treatment covers, showing the on- and off-site tolerance thresholds (dotted lines).

4. Discussion

4.1. Precipitation and Rainfall Erosivity

The results of Table 4 indicate that there was spatial (inter-block) and temporal (inter-annual) variability in rainfall volume and erosivity, which are key drivers of runoff and soil loss, respectively, as reported previously [18]. The relationship between rainfall and erosivity has also been widely documented, with several studies reporting strong correlations between them [37]. Since these sources of variability were minimized through the normalization of runoff and soil loss, respectively (eqs. 5-6), they allowed for the unbiased comparison of runoff and soil loss means between treatments and years.

4.2. Runoff

According to Figure 6, CN decreased from degraded pasture (DP) to natural savannah (NS), with restored pasture in between. The differences arise from the diverse soil infiltrability in the three farms, which affect CN [32].

In all sites, runoff from the restored pasture (RP) plots was reduced by at least 50% compared with degraded pasture (DP). The runoff in RP at all experimental sites was situated between DP and NS. This finding indicates that, within a short period, the hydrological behavior of restored pasture approached that of natural savannah. Previous research [38] showed that pasture restoration is indeed an interesting conservation practice since it reduces the runoff, improving water quality in the process.

As shown in Figure 7, normalized runoff was similar in the three farms, ranging from 0.05 to 0.3, despite the pedological variation among them, with the observed differences associated with the land-use treatments. As indicated in Figure 7, reduced runoff was associated with improved soil cover [18], which enhances water infiltration and mitigates soil compaction [24]. Additionally, the tillage, fertilization, and improved rooting of restored pastures may have contributed to increase infiltration and reduce runoff [3]. Runoff reduction was more pronounced during the first hydrologic year because of the rapid soil cover in RP, and equilibrated in the subsequent years, as expected.

4.3. Soil Loss

Soil loss in RP was significantly lower than in DP, with reductions ranging from 55% to 95%, depending on the site analyzed. Comparable reductions were also reported in a nearby restored savannah site established with native grasses and shrubs in bounded 22.1 m plots [39]. Soil loss in the RP plots fell between those of DP and NS in all sites. These findings suggest that pasture restoration can be nearly as effective as, and in some cases comparable to, natural savannah in reducing soil erosion, only a few years after restoration.

The observed reductions could be attributed to increased ground cover and improved soil structure in RP, which together mitigate the erosion processes. Enhanced soil tilth reduces rill erosion [18] while improved grass cover diminishes sheet erosion by decreasing raindrop impact and runoff [37]. These findings underscore the long-term importance of restoration measures for soil conservation [18] and sustainable land management.

4.4. Practical Implications of the Study

The significant reductions in runoff and soil loss after 3 years of restoration indicate that degraded pastures, which dominate both karst and non-karst areas of the Brazilian Cerrado, are hydrologically effective, and could be implemented as part of a financial compensation policy based on hydrologic the services provided.

Because of the high correlation between soil loss and runoff (Figure 9), the latter could be used as a proxy to the former, which is more difficult to obtain. Furthermore, soil loss in the permanently covered plots (NS & RP) were below the on-site soil loss tolerance threshold, indicating that restored pasture is effective in increasing landscape stability and sustainability of karst areas [3].

Finally, the simple and inexpensive Gerlach troughs were effective in assessing runoff and soil loss, being suitable for developing countries with little research infrastructure, and able to provide robust data for the establishment of sound soil conservation policies.

4.5. Methodological Limitations

The main methodological limitation of the experiment was the non-integrative runoff sampling of the Gerlach troughs, since only episodic sediment concentration samples were obtained, as opposed to the cumulative sampling of traditional runoff plots [27]. This was solved by the indirect obtention of storm runoff volume, via the NRCS method. However, the high correlation found between normalized runoff and soil loss (Figure 9) indicates that the indirect method was appropriate.

Also, the correction factor (Fc) of equation 4, obtained for one of the farms, was assumed to be the same for the two other, despite the local landscape differences. However, considering the proximity of the three experimental sites, and the fact that Fc was very close to 1.0, these evidences reinforce the validity of the assumption [40].

5. Conclusions

Pasture restoration reduced runoff by over 50% and soil loss between 55 and 95%, reaching levels comparable to natural savannah, during a period of three hydrologic years, indicating that pasture restoration and permanent soil cover is an effective hydrologic measure, generating significant hydrologic services both on- and off-site, particularly in vulnerable karst areas. The good fit between normalized runoff and soil loss allows for the utilization of the former as a proxy of the later. Additionally, simple and inexpensive Gerlach troughs proved to be useful in the assessment of soil loss of natural, degraded, and restored karst areas, and suitable in the assessment of active restoration services in developing countries.

Abbreviations

The following abbreviations are used in this manuscript:

DP   Degraded Pasture
RP   Restored Pasture
NS   Natural Savannah

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Capítulo 4: Conclusões

Os resultados dessa dissertação mostram que a maneira como a terra é usada e manejada influencia diretamente na quantidade de água disponível e a conservação do solo. Isso porque a estrutura da paisagem, o tipo de cobertura do solo e o estado de manejo são determinantes para os processos hidrossedimentológicos. Ao longo do período de monitoramento, foi possível observar que pastagens degradadas perdem mais água e solo, enquanto pastagens restauradas e áreas de Cerrado natural conseguem reter melhor a água da chuva e proteger o solo contra a erosão. Isso evidencia que a cobertura vegetal desempenha um papel central na estabilidade da paisagem e na manutenção dos recursos hídricos.

Em regiões onde a disponibilidade de água é limitada, como no Cerrado, existe um processo de retroalimentação: quando o solo perde vegetação, aumenta o escoamento superficial e diminui a infiltração, reduzindo a água disponível para plantas, animais e a longo prazo. Por outro lado, quando a vegetação é recuperada, o solo passa a reter mais água, favorecendo o crescimento das plantas e contribuindo para a recarga dos sistemas subterrâneos, inclusive das cavernas associadas ao carste. Além de permitir e facilitar a manutenção da vida dos animais.

Um resultado importante do estudo foi a confirmação, no Capítulo Dois, de que as Calhas de Gerlach são um método confiável e acessível para medir a perda de água e solo em campo. A comparação realizada demonstrou que esse método produz resultados equivalentes aos obtidos com parcelas-padrão de enxurrada, tradicionalmente utilizadas em pesquisas científicas. Na prática, isso significa que as calhas podem ser utilizadas diretamente em propriedades rurais, projetos de restauração e programas de monitoramento ambiental, permitindo acompanhar, de forma simples e de baixo custo, se as práticas adotadas estão realmente reduzindo a erosão e melhorando a infiltração da água.

Os dados também mostram que a restauração de pastagens gera benefícios ambientais expressivos, com reduções de até 95% na perda de solo e superiores a 50% no escoamento superficial, aproximando essas áreas das condições encontradas no Cerrado natural. Esses ganhos são ambientais e econômicos. Pastagens com solo protegido e maior disponibilidade de água tendem a ser mais produtivas, resilientes a períodos de seca e capazes de sustentar o gado por mais tempo, reduzindo custos com recuperação emergencial da área e aumentando a estabilidade da produção pecuária.

Assim, os resultados desta dissertação demonstram que conservar o solo e a água não significa reduzir a produção, mas sim torná-la mais eficiente e sustentável. A adoção de práticas conservacionistas aliadas ao uso de métodos simples de monitoramento, como as Calhas de Gerlach, permite transformar resultados científicos em decisões práticas de manejo, beneficiando produtores rurais, recursos hídricos e ecossistemas cársticos. Dessa forma, o estudo contribui para ampliar a base de conhecimento necessária à gestão sustentável do território, conciliando produção agropecuária, conservação ambiental e segurança hídrica no Cerrado.

Com base nos conhecimentos produzidos, fica evidente a importância deste estudo para compreender melhor como a água e o solo se comportam em áreas cársticas do Cerrado. Ainda assim, é importante destacar que os resultados obtidos podem ser aplicados a outras áreas apenas quando estas apresentarem características ambientais e formas de uso do solo semelhantes à área estudada, desde que sejam feitas as adaptações necessárias. Assim, os achados apresentados devem ser entendidos como um primeiro passo, reforçando a necessidade de novas pesquisas que ampliem esse conhecimento e aprofundem a compreensão dos processos analisados.

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