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Land use transformations in the Brazilian Savanna: A decade of soil erosion and runoff measurements

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ABSTRACT

Changes in land cover and land use (LULC) are one of the main drivers of erosion and runoff. How ever, most research has relied on short-term observations and only focused on one or two land cover types. We investigated the long-term trade-off between common agricultural land covers (sugarcane, pasture, and soybean), runoff, and soil loss rates. We compared these to native forest (wooded Cerrado) and bare soil. The field observations were done in 100 m^2 experimental plots in Brazil maintained during the past 10 years. The paper provides three main contributions: (1) long-term runoff and soil loss rates of plots under different LULCs, (2) comparison of runoff, soil loss, and pedological characteristics between plots constructed 10 years apart, and (3) analysis of the trade-off between different LULCs. When ranking land covers based on runoff and soil loss rates, there is a shift in ranking positions, making it difficult to determine which one is more environmentally harmful. However, it is evident that whatever agricultural practice is used, there is a significant impact when compared to native forest. For example, the area converted to pasture resulted in almost 20 times higher runoff, while conversion to sugarcane resulted in 5 times higher soil loss. Not only land cover plays a major influencing factor, but also weathering exposing time. Areas under the same land cover and environmental conditions had different rates of soil loss and runoff due to long-term exposure effects such as soil crusting. Our findings have high relevance for the hydrological and agricultural community by demonstrating (i) the magnitude of trade-off in terms of soil loss and runoff due to land cover changes and (ii) that soil loss should not be assumed to be a linear process over time, as it is commonly assumed.

1. Introduction

Soil is a vital natural resource that provides unique and essential ecosystem services for human life, however, soils are currently threatened by soil erosion (Rajbanshi et al., 2023). Accelerated erosion imposes many environmental and economic issues, being one of the most significant environmental problems that affects 80 % of agricultural areas worldwide (Olsson et al., 2019). Erosion leads to the removal of soil particles, organic matter, and nutrients from one area through rill, gully, splash, and sheet erosive processes (Bertoni and Lombardi Neto, 2017). The removal of fine particles (clay and silt) and organic matter from the soil reduces its stability and water storage capacity, increasing its vulnerability to crusting and water stress (Stroosnijder, 2009) and reducing its productive capacity (Panagos et al., 2018). Removed particles are transported through the watercourses, altering the water quality (e.g., turbidity, oxygen level, etc.) and disturbing and destroying microhabitats (Graf et al., 2016). Particles carried by rivers can be deposited along the channel, resulting in the raising of riverbed level (Paul and Biswas, 2019), channel clogging, flooding, and alteration of surface–subsurface water connectivity (Schwamback et al., 2022b). These implications go beyond environmental aspects. For example, the rise of river bed levels due to accumulated sediments increases the

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vulnerability of riverside populations to flood events, while the loss of nutrients reduce agricultural production threatening food security (Wolka et al., 2018) and imposes the use of fertilizers (Silva et al., 2021). Future loss of agricultural productivity associated with declining water quantity and quality may reshape the current economic, social, and geopolitical scenarios (Mohamed et al., 2015).

In developing countries, the economy is commonly based on agriculture, and combined with the demand for the expansion of urban centers, large natural territories have been converted into agricultural and urban areas (Rajbanshi et al., 2023). Similar reasons led to the LULC conversion in Brazil, turning it into a major environmental threat (Caballero et al., 2022). The country lost 963,357 km^2 between 1985 and 2018 (Pacheco and Meyer, 2022), an area larger than Tanzania, of its originally forested area to mostly cattle and cropland expansion, while pasture expanded by 46 % and agriculture by 172 % (Caballero et al., 2022). Among the Brazilian biomes, the Cerrado (Brazilian Savanna) is considered one of the 25 global biodiversity hotspots (Norman et al., 2000). Since the mid-twentieth century, the Cerrado ecoregion has undergone agricultural expansion leading to a loss of more than 50 % of the native forest vegetation (Pompeu et al., 2024) while less than 3% are conserved within demarcated areas of protection (Costa Junior et al., 2012), threatening not only the flora but also the fauna that shelters in it.

Landscape alteration through the conversion of natural areas into agricultural or urban areas interferes with local fluxes at different scales and forms (Procházka et al., 2019; Zhai et al., 2021). Compared to dense forest vegetation, agricultural areas commonly present: lower evapotranspiration rates (Roderick and Farquhar, 2011), a more shallow root system that is less efficient in creating preferential pathways for infiltration (Zhou et al., 2008), reduced leaf area for rainfall interception, lower production of potential organic matter used for the agglutination of soil particles, and constant agricultural management that destabilizes and disrupt the surface soil layers (Rajbanshi et al., 2023; Schwamback et al., 2020). In addition to those exemplified effects, changes in LULC impact other aspects such as the vegetation roughness, albedo, infiltration capacity, root depth, architectural resistance, leaf area index (LAI), and stomatal conductance (Aghsaei et al., 2020; Srivastava et al., 2020). The removal of the original vegetation leaves the soil vulnerable if soil and water conservation practices are not being performed (Rajbanshi et al., 2023). There are many recent examples of research on the influence of vegetation on soil loss and runoff in Brazil (Anache et al., 2019; Borges Neto et al., 2023; Caballero et al., 2022; Fonseca et al., 2022; Rápalo et al., 2021; Schwamback et al., 2020; Youlton et al., 2016), China (Chen et al., 2020; Ebabu et al., 2023a; Ma et al., 2023; Zhang et al., 2021; Zhao et al., 2022), Ethiopia (Desta et al., 2021; Ebabu et al., 2023a), Portugal (Nunes et al., 2011a), Spain (Milazzo et al., 2022), Switzerland (Bettoni et al., 2023), and at a global scale (Hu et al., 2021; Rajbanshi et al., 2023). Among the main long-term harm related to soil loss described in these studies is the loss of topsoil, a nutrient-rich layer of soil that is critical for plant growth and takes centuries or even millennia to replenish naturally (Wu and Tiessen, 2002).

A better understanding of the physical processes that determine the hydrological fluxes under different land use and conservation practices is crucial to achieve efficient use of water, conservation of natural resources, and minimization of anthropogenic impacts (Anache et al., 2018). Long-term *in-situ* investigations promote the development of models and the reduction of their uncertainties (parameter estimation, model assumptions, calibration/validation, etc.), improvement of agricultural efficiency, and at the same time promote sustainable development. Through field studies, information can be provided for the development of new technologies and solutions for maintaining the hydrological cycle, despite rapid changes in land use and cover (Nóbrega et al., 2017; Strassburg et al., 2017). In Brazil, some preliminary studies on the influence of land use and land management on the hydrological cycle have been per- formed at different scales, from laboratory benches and experimental plots (Anache et al., 2019; de Almeida et al., 2018; Merten et al., 2015; Nacinovic et al., 2014; Oliveira et al., 2015; Rita Souza Fonseca et al., 2023; Youlton et al., 2016) to experimental basins (Almagro et al., 2019; Lucas and Wendland, 2016; Machado et al., 2016; Mattos et al., 2019; Melo et al., 2020; Nóbrega et al., 2017). Even though there are examples of experimental plots worldwide with more than 20 years of monitoring (Klik and Rosner, 2020), most studies in Brazil contain short-term data (lasting less than 3 years) and are insufficient to provide solid conclusions about the implementation of extensive land management practices (Anache et al., 2017).

Research investigating the influence of land cover changes on erosion can be carried out using experimental plots, which are artificially delimited slopes where surface runoff is directed to a single outlet for monitoring, being considered a standard technique for studying surface runoff and erosion (Guo et al., 2015). Despite the high cost and time needed for the installation and maintenance of these structures (Sun et al., 2014) in a small area, hydrological variables can be precisely monitored under different land covers, cultivation practices, and soil management. The main examples of successful use of this method are the development of the Universal Soil Loss Equation (USLE by Wischmeier and Smith, 1978) and its variations (RUSLE by Renard, 1997 and MUSLE by Williams, 1974) on last century, while there are still nowadays development of runoff and soil loss estimations (Bagarello et al., 2015; Flanagan et al., 2007; de Almeida et al., 2018).

Besides the efforts in monitoring runoff and soil erosion to understand how they are affected by changes in land cover and land management, there is still a lack of understanding of the behavior of the hydrological phenomena when land cover and management are maintained consistently over long periods in subtropical areas. Additionally, most previously published studies usually only have volumetric data that provide information regarding the amount of runoff resulting from a sequence of precipitation events that might continue for several days, while our study employed an automatic monitoring that enables hydrological monitoring with high temporal resolution (ten minutes). Our paper aims to present the temporal pattern and LULC trade-off in runoff rate and soil loss from experimental plots under long-term LULC (bare soil, wooded Cerrado, sugarcane, and pasture) over the past decade in the Brazilian Cerrado ecoregion. For this purpose, this paper provides: (1) a timeline of runoff and soil loss over time when kept under the same LULC, (2) an analysis of main drivers (precipitation duration and intensity and land cover) for runoff/soil loss, and (3) a comparison between runoff/soil loss rates, and soil characteristics of plots kept under bare soil but constructed 10 years apart.

2. Materials and methods

2.1. Study area and experimental design

Field monitoring was performed at the Arruda Botelho Institute (IAB), Itirapina, central region of the State of São Paulo (latitude 22°10′S, longitude 47°52′W, 790 m.a.s.L.), Brazil (Figure 1). The region has an average annual rainfall of 1486 mm and a humid subtropical climate (Cwa, Köppen classification system, Alvares et al., 2013) with hot and humid summer (October–March, mean temperature of 23.6 °C and 77 % of annual rainfall) and dry winter (April–September, mean temperature of 19.5 °C and 23 % of annual rainfall). The characteristic soil of the study area is Orthic Quartzarenic Neosol (Arenosols at the World Reference Base for Soil Resources), which has a sandy texture, deep, permeable, and well-drained, acid, and poor in nutrients (EMBRAPA, 1997), more information is given in Table 1.

Soil porosity (micro, <0.08 mm, macro, >0.08 mm, and total), organic matter, and cation exchange capacity (CEC) of samples collected at 15, 30, and 60 cm depth are given in Figure 2, while complementary soil physical composition is given in Table 1. Microporosity is associated with intrinsic water retention and capillarity, while macroporosity is related to soil drainage and water availability for root uptake.

Fig. 1. Study area location and photographs of experimental plots.

Agricultural (Sugarcane and Soybean) soil samples had a higher total porosity (46–49 %) than wooded Cerrado (35 %) and bare soils (30–39 %) due to continuous soil preparation for plantation and weed control (based on data from soil samples at 15 cm depth shown at Figure 2). The organic matter at 15 cm depth was highest in the Wooded Cerrado (49 $g.dm^3$) compared to agricultural (22–36 $g.dm^3$) and bare soil (13–22 $g.dm^3$). Lastly, CEC represents the amount of cations that soil can store and permute for other cations during biochemical processes. At 15 cm depth, CEC presented a similar behavior as observed with porosity with Wooded Cerrado presenting a higher concentration (63 $mmol.dm^3$) compared to agricultural plots (47–51 $mmol.dm^3$) and bare soil (23–35 $mmol.dm^3$). At deeper depths, there is a significant reduction in CEC, organic matter, and porosity showing less dependency on land cover.

Soil loss and runoff have been continuously monitored in

Table 1
Pedological characteristics of the study area.

Depth (cm)	Bulk density ($g.cm^{-3}$)	Sand (%)	Silt (%)	Clay (%)	pH	Particle Density ($g.cm^{-3}$)	Hydraulic Conductivity ($mm.h^{-1}$)
15	1.399	85	4	11	4.73	–	–
30	1.499	83	4	13	4.55	2.64	147.31
60	1.495	81	5	14	4.52	2.65	117.01
90	1.501	81	8	12	4.33	2.65	129.34

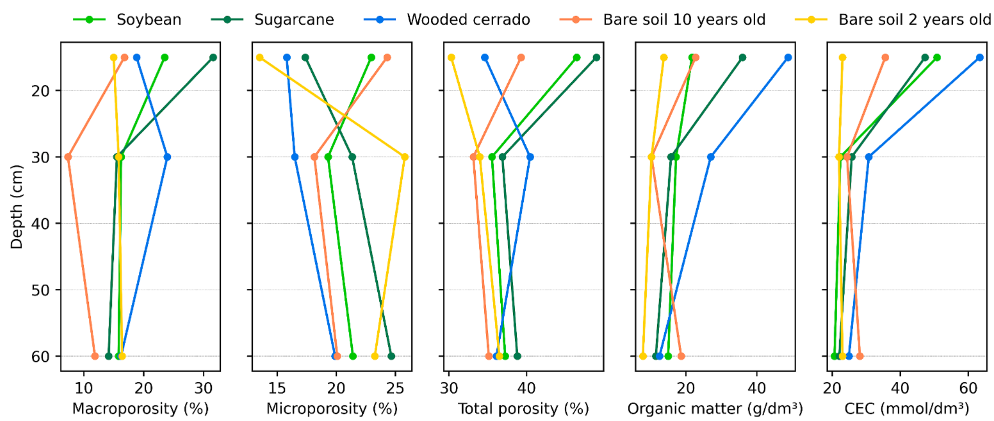


Fig. 2. Microporosity (%), macroporosity (%), total porosity (%), cation exchange capacity (CEC, $mmol.dm^3$), and organic matter ($g.dm^3$) at 15, 30, and 60 cm depth at experimental plots under wooded Cerrado (CS), sugarcane (SC), soybean (SB), and bare soil 10 years old (B10) and bare soil 2 years old (BS2) land covers.

experimental plots installed in 2011 (Oliveira et al., 2015). The plots are 5 m wide and 20 m long with a 9 % uniform slope and delimited by metal sheets approximately 30 cm high. The experiments are carried out in three replications for each land covers and mean values were used in the following analysis to minimize random observations. The plots are disposed in two study areas. Area 1 contained plots with four land covers: (i) sugarcane (SC) planted under the contour technique with 1.5 m spacing between the rows. In the mature stage, it reaches 2 m in height, harvested annually in November, and replanted every four years; (ii) pasture (PS, Brachiaria *decumbens*) with height canopy between 5 and 30 cm used for cattle grazing. The grazing occurs in 30-day rotations, where 10 animals weighing about 420 kg each are allowed to graze on one ha of land for 5 days. The pasture plots were replaced with soybean in November 2019 to follow the same agricultural land cover change that the surrounding farm implemented; (iii) soybean (SB), cultivated annually during part of the rainy season (November-March), and kept in fallow during the remaining months of the year; (iv) bare soil implemented in 2011 (BS10) and 2020 (BS2), kept without vegetation by glyphosate application, and manual weeding. Comparing soil samples of bare soil plots (Table 1 and Figure 2), we believed that erosive processes over a decade resulted loss in pedological changes of the surface layers, and thus, a new set of bare soil plots were installed in the area to investigate the temporal component in the hydrological responses. Lastly, Area 2 was covered by a natural forest: Cerrado *sensu stricto*, also known as wooded Cerrado (WC), an undisturbed woodland typical of the central area of Brazil of approximately 330 ha.

2.2. Precipitation, runoff, and soil loss observations

Once the maximum infiltration capacity of the soil is reached during a precipitation event, the surface runoff follows the slope and the metallic borders until the outlet of the plot, subsequently collected in 310 L tanks. The total runoff (see equation (1) after rainfall events were determined by using the storage tanks' water level-volume calibration curves (Oliveira et al., 2015; Youlton et al., 2016). We used tipping buckets flow meters (TBs) to measure the temporal variation of the surface runoff. This allows temporal analyses of the runoff data, with the identification of the beginning and the end of the flow, as well as peak and total flow. The TBs were designed, calibrated (Schwamback et al., 2022a), and installed at the outlet of plots SC, SB, BS10, and BS2 plots in 2021.

The sediment concentration present in the runoff after each event was determined gravimetrically in the laboratory by analyzing the water samples collected after measuring the storage tanks' water level. The same gravimetric process was used for the solid mass of soil collected from the experimental plot border that did not reach the storage tanks. Thus, the total soil loss after a rainfall event was composed of the sum of the product between sediment concentration and runoff volume with the dry mass of soil retained in the collectors (see equation (2). Our data set comprehends a total of 2796 monitored events and it is freely available for further analysis at https://zenodo.org/doi/https://doi.org/10.5281/zenodo.10009738. A distribution of monitored events is given in Supplemental material 1.

$$E = e/A \tag{1}$$

$$S = \frac{((w^*e) + s)}{A} {}_* \frac{1}{100} \tag{2}$$

where E is the runoff coefficient (mm) after each rainfall event, e is runoff measured on the storage tank (liters) after each rainfall event, S is the soil loss coefficient (ton/ha) after each rainfall event, w is the sediment concentration (g/l) in the water samples collected after measuring the storage tanks' water level, s is the dry soil mass (g) collected from the runoff border that did not reach the storage tanks, and A is the contributing area.

The plots have meteorological data (precipitation, relative humidity, temperature, solar radiation, wind speed, and direction) measured with an automatic weather station with continuous data at 10-minutes intervals. The station is located aside agricultural plots in study area 1 and at 1.6 km distance from study area 2. To compute rainfall duration and amount, we employed Rainfall Intensity Summarization Tool (RIST) from USDA, 2013. Events breakdowns occurred at 6 h and 1 mm and were considered erosive when higher than 10 mm.

The results are mainly summarized as long-term mean values, given by the mean of yearly runoff and soil loss over the period of field monitoring. To express the data variability, data standard variance is given along with mean values. Lastly, the differences among land covers in terms of yearly runoff and soil loss were conducted based on the Tukey test.

3. Results

In Table 2, we summarize the long-term mean soil loss and runoff monitored at the experimental plots. As expected, the forest land cover (Wooded Cerrado) had the lowest rate of soil loss (0.10 $ton.ha^{-1}.year^{-1}$), followed by agricultural land covers (0.16 to 0.57 $ton.ha^{-1}.year^{-1}$), and lastly by bare soil (22.4 to 27.8 $ton.ha^{-1}.year^{-1}$). Runoff had a similar pattern as soil loss: Wooded Cerrado had the lowest rate of runoff (2.0 $mm.year^{-1}$), followed by agricultural land (11.3 to 38.5 $mm.year^{-1}$) and bare soil (115.1 to 121.0 $mm.year^{-1}$). When looking specifically at the agricultural land covers, the highest soil loss was found for sugarcane, but the highest runoff was found for pasture, therefore it is not clear which agricultural land cover had the greatest environmental impact considering those two variables.

3.1. Trade-off between LULCs, runoff, and soil loss

In Figure 3 we provide a summary of trade-offs in terms of runoff and soil loss among the different land cover. Land conversion from wooded Cerrado to agricultural areas (soybean, pasture, and sugarcane) leads to a significant increase in runoff (1.5 to 5.5 times) and soil loss (5.6–19 times). The land cover changes among agricultural cover commonly found in Brazilian farms also lead to significant changes. When converting pasture to sugarcane, we found 3.6 times increase in soil loss, but a 3.4 times reduction in runoff. On the other hand, the conversion of soybean to sugarcane led to a 1.4 times reduction in runoff but increased soil loss at a rate of 3.0 folds. This mismatch between soil loss and runoff led to the switching position ranking of endangered land cover (Table 2). Areas exposed to environmental conditions without any cover in the short term (up to two years) were prone to intense runoff (up to 10 times) and soil loss (up to 176 times) compared to agricultural areas. The land cover change impact in terms of soil loss and runoff can also be seen through the annual timeline given in Supplemental material 2. We noted that the long-term pattern of soil loss and runoff experienced in pasture had a reduction of runoff and an increase of soil loss after 2019 due to conversion to soybean plantation. The runoff and soil loss event likelihood of occurrence based on the 10 years of monitoring data is given in Figure 4. Note from Figure 4 that the curves of soil loss events likelihood of occurrence of bare soil plots are sharp and that curves from plots with some vegetation are agglutinated and located far from bare plots curves. On the opposite, runoff curves from all plots (Figure 4) have mild inclination and are distributed over the plotting area, indicating that runoff is more sensitive to land cover change than soil loss.

Table 2
Long-term annual mean soil loss, runoff, standard deviation (SD), and runoff ratios regarding rainfall monitored in the study site. Data is based on a sample size of 2796 monitored events and considering a mean yearly rainfall of 1347 ± 195 mm.

Land cover	Mean soil loss ± SD ($ton.ha^{-1}.year^{-1}$)	Mean runoff ± SD ($mm.year^{-1}$)	Ratio between mean runoff and rainfall
Wooded Cerrado	0.10a ± 0.08	2.02a ± 1.14	0.15 %
Sugarcane	0.57a ± 0.70	11.33a ± 14.26	0.84 %
Soybean	0.19a ± 0.16	16.33a ± 9.54	1.21 %
Pasture	0.16a ± 0.17	38.47a ± 25.58	2.86 %
Bare Soil 2 years old	27.83b ± 13.60	115.14b ± 46.60	8.55 %
Bare Soil 10 years old	22.39b ± 10.66	120.99b ± 49.54	8.98 %

Note: a and b denote the statistical levels of the Tukey test means; that is, means followed by different letters are significantly different at 95% probability. Conversely, means followed by the same letter are not statistically different.

Our findings also demonstrate that not only usual mechanisms in the erosion process, such as land cover and precipitation, play a fundamental role in soil loss but also exposure over time. When we look in more detail at the annual time series (Supplemental material 1), we observe that in 2021, the plot recently converted from soybean to bare soil (BS2) had a significantly lower soil loss than the plot under the same land cover but exposed to weathering during 10 years (BS10). In 2022, BS2 and BS10 had similar soil loss, suggesting that superficial crusting and pore-clogging are evident after one year of weathering. Even though both areas had similar yearly runoff rates, 2021 and 2022 were exceptional and more erosive compared to the rest of the years, which may have helped to increase the mean soil loss in BS2 compared to the first monitoring years for the BS10 plot.

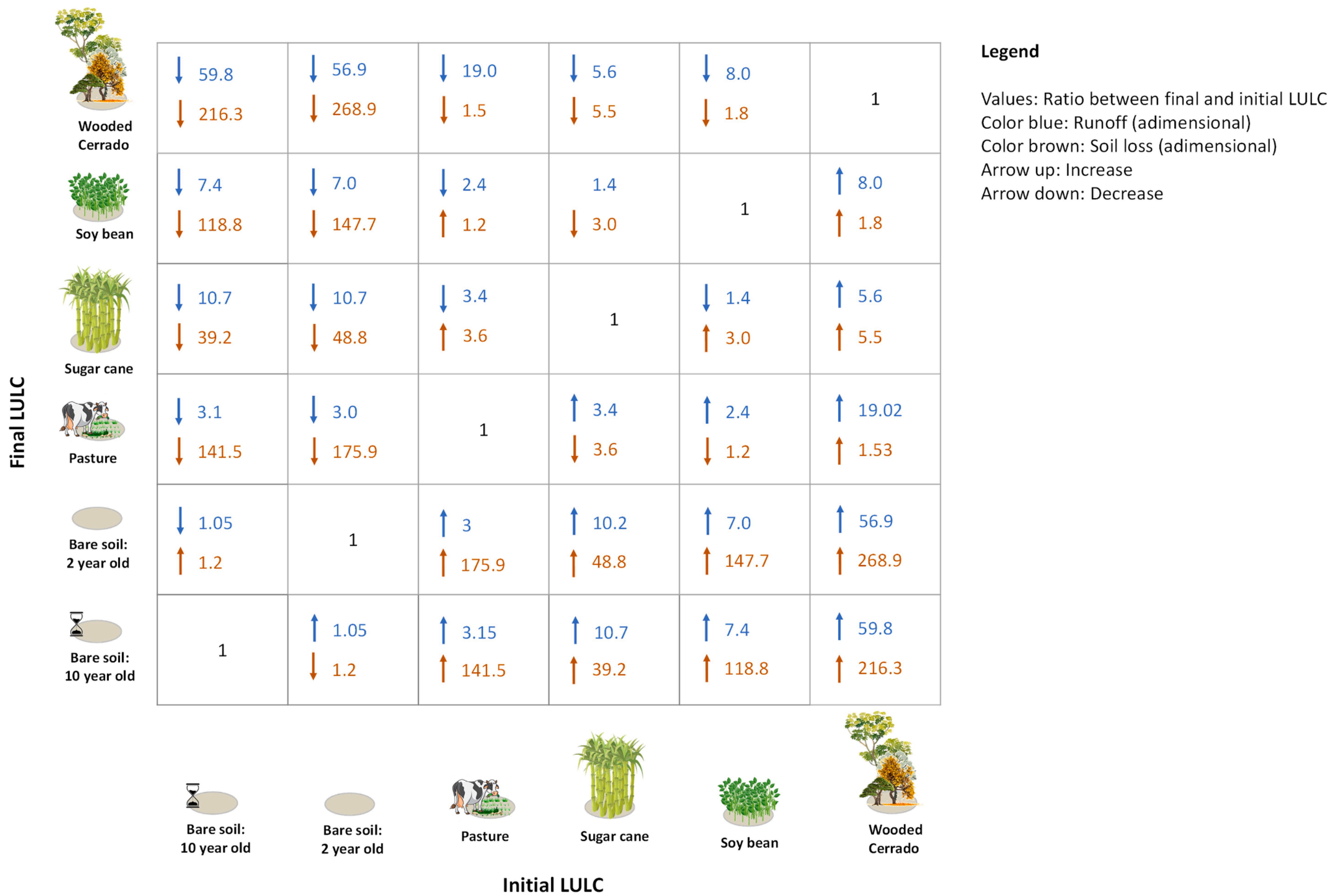
3.2. Land cover effects on runoff real-time monitoring

In addition to the analysis of the effects of land cover on long-term and annual runoff events, we also studied the effects upon event scale using flow meter tipping buckets (Figure 5). In general, we observed that agricultural areas (SB and SC) had higher initial infiltration capacity and therefore, experienced runoff production with some delay compared to the bare soil plots. The sugarcane plot had, most of the time, a lower peak flow compared to soybean plots. On the other hand, the runoff hydrographs for uncovered plots were shorter and directly connected to rainfall events, mainly due short water concentration time associated with the small area (100 m^2) and slope length (20 m) of plots. During a rainfall event with 1.3 mm/min maximum intensity, bare soil areas had a peak of 11 L/min (BS1) and 13 L/min (BS10), while soybean and sugarcane had a peak flow of 7 L/min and 100 mL/min, respectively (Figure 5b). Figure 5c shows the runoff response with multiple peak flows due to a rainfall event that lasted almost six hours, common in the tropical zone during the rainfall season. The hydrographs from the bare soil plots show that even though they had similar mean annual runoff, the older area (BS10) had shorter duration runoff than the recently exposed area (BS2).

3.3. Correlation between precipitation features, runoff, and soil loss

By correlating runoff (abscissa) and soil loss (ordinate) data from all experimental plots (Supplemental material 3) we note that there is a clear correlation among these variables. However, analyzing individual land covers (Figure 6) we observed that each land cover had a distinct relationship with soil loss and runoff, given by the correlation and slope of the regression curve. For example, BS10 had a steep (Soil loss = 0.159 runoff) and significant ($R^2 = 0.6$, p-value < 0.05) relationship between soil loss and runoff, while SC and PS had weak relations and significant ($R^2 = 0.38$ and 0.02 respectively) and other land covers had not significant relations (p-value > 0.05). Besides the limitation of having short-term observations, most field experiments rely on monitoring only runoff, since soil loss data require numerous soil sample collection and laboratory analysis. Through the regression equations (Figure 6), soil loss can be estimated at event scale based on the runoff data from the tipping bucket (Figure 5) or in other study areas for monthly or yearly time scale. Note that this application is based on specific conditions studied, like soil type, climate, and the development stage of vegetation.

The runoff generation is a function of well-known characteristics, such as land use (density, root distribution, and height) and pedology (porosity, particles density and distribution, compaction, and organic matter), but also related to the intensity, sum, and duration of precipitation events. Significant differences in runoff generation related to total precipitation and duration among plots are given in Figure 7. All agricultural plots showed a linear tendency of increasing runoff with increasing precipitation amount, but the highest runoff values were associated with shorter duration considering the same precipitation amount. The wooded Cerrado plot showed a damping effect, being less dependent on rainfall duration and amount, and more susceptible to



Final LULC \ Initial LULC	Bare soil: 10 year old	Bare soil: 2 year old	Pasture	Sugar cane	Soy bean	Wooded Cerrado
Wooded Cerrado	↓ 59.8 / ↓ 216.3	↓ 56.9 / ↓ 268.9	↓ 19.0 / ↓ 1.5	↓ 5.6 / ↓ 5.5	↓ 8.0 / ↓ 1.8	1
Soy bean	↓ 7.4 / ↓ 118.8	↓ 7.0 / ↓ 147.7	↓ 2.4 / ↑ 1.2	1.4 / ↓ 3.0	1	↑ 8.0 / ↑ 1.8
Sugar cane	↓ 10.7 / ↓ 39.2	↓ 10.7 / ↓ 48.8	↓ 3.4 / ↑ 3.6	1	↓ 1.4 / ↑ 3.0	↑ 5.6 / ↑ 5.5
Pasture	↓ 3.1 / ↓ 141.5	↓ 3.0 / ↓ 175.9	1	↑ 3.4 / ↓ 3.6	↑ 2.4 / ↓ 1.2	↑ 19.02 / ↑ 1.53
Bare soil: 2 year old	↓ 1.05 / ↑ 1.2	1	↑ 3 / ↑ 175.9	↑ 10.2 / ↑ 48.8	↑ 7.0 / ↑ 147.7	↑ 56.9 / ↑ 268.9
Bare soil: 10 year old	1	↑ 1.05 / ↓ 1.2	↑ 3.15 / ↑ 141.5	↑ 10.7 / ↑ 39.2	↑ 7.4 / ↑ 118.8	↑ 59.8 / ↑ 216.3

Fig. 3. Trade-off in terms of runoff and soil loss due to land cover change (wooded Cerrado, sugarcane, soybean, pasture and bare soil).

runoff under intermediate rainfall duration and intensity. Bare soil plots are also less sensitive to rainfall parameters but yield high rates of runoff and soil loss under most rainfall occurrences, even short and low-intensity ones. The occurrence of soil loss is linked to the transport of particles that can be dislodged by the intensity of rainfall, and the amount carried depends on the volume of generated runoff. Researchers have already confirmed the phenomenon of first-flush, which depicts a higher quantity of particles at the beginning of precipitation (Bartley et al., 2006; dos Santos et al., 2017) and Figure 7 g shows this phenomenon, where shorter duration rainfall leads to high concentration of carried particles. Lastly, from Figure 7 we also found that longer precipitation duration and amount lead to higher erosion for unvegetated soil.

4. Discussion

It is well known that land cover plays an important role in the hydrological cycle (Rajbanshi et al., 2023; J. Zhao et al., 2022). However, the quantitative impact in terms of runoff and soil loss due to land cover changes for the Brazilian Cerrado Ecoregion based on long-term field monitoring has not yet been well established. We studied the trade-off in terms of runoff and soil loss rates between common agricultural land cover (pasture, soybean, sugarcane) compared to forest (wooded Cerrado) and bare soil. Our experiments (Figure 3) identified different rates of runoff and soil loss among agricultural land covers and that those variables are not directly aligned. It was not possible to point out which crop is more environmentally harmful in terms of both soil loss and runoff. However, the impact of agricultural practices compared to the native forest was obvious: almost 20 times higher runoff (pasture) and 5 times higher soil loss (sugarcane). The results demonstrate the significant relationship between land cover changes and precipitation events in the subtropical climate, soil loss increases with the increase in runoff in plots without covering (Figure 6, as found by Wang et al., 2014), whereas soils with vegetation enhance the infiltration rate, lowers runoff, and reduce erosion (Derpsch et al., 2014).

Our findings were based on long-term data collection experiments (up to ten years), especially relevant for tropical and subtropical areas with agricultural aptitude such as the case of Brazil and the wooded Cerrado. We found that 3.2 % of the total rainfall created overland flow (runoff) in the plots covered with pasture. In the natural forest (Wooded Cerrado) this percentage was only 0.16 % (Table 2). From Procházka et al. (2019) we see that land cover also altered the water flows for a catchment with pasture that had an average annual runoff of approximately 60 % of the total annual precipitation, while the forested area had a runoff equivalent to 34 %. From our monitoring, other agricultural land cover produced smaller rates of runoff from annual rainfall: 1.32 % (soybean) and 0.91 % (sugarcane). Regarding the long-term mean annual soil loss rates ($ton.ha^{-1}.year^{-1}$) of heavily disturbed land (Table 2), BS2 and BS10 surpassed the maximum acceptable soil loss rate for deep, permeable, and well-drained soils as the Neosolo (12 $ton.ha^{-1}.year^{-1}$, Bertoni and Lombardi Neto, 2017). On the other hand, the mean annual soil loss rate for moderately disturbed land due to agriculture (PS, SB, and SC) and natural land (WC) were far below the minimum acceptable soil loss rate proposed by Bertoni and Lombardi Neto (2017) and previous mean soil loss estimated for the state of São Paulo (30 $ton.ha^{-1}.year^{-1}$, Medeiros et al., 2016). Among many factors, the lower monitored soil loss rates can be mainly due to compaction at PS and conservation practices employed in the studied agriculture plots, such as no-tillage, which is an increasing adopted practice, but still not completely adopted as a conventional practice in Brazilian agriculture.

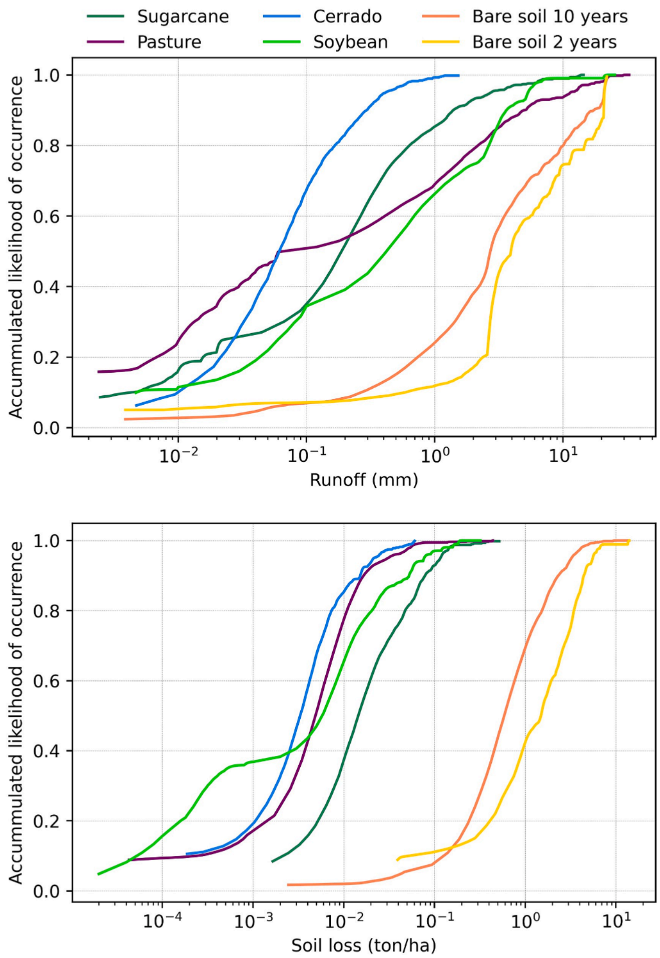


Fig. 4. Accumulated likelihood of occurrence of monitored runoff and soil loss events occurring in experimental plots under wooded Cerrado, sugarcane, soybean, pasture and bare soil (10 and 2 years old) land covers.

Based on other Brazilian studies under similar LULC to the present study (Brito et al., 2005; Castro et al., 2022; Engel et al., 2009; Marchioro and Augustin, 2007; Moreira et al., 2015; Youlton et al., 2016), the monitored mean soil loss and runoff are within the spectrum of previous measurements. The divergent research outcomes in terms of runoff and soil loss rates among croplands indicate that the impact of land cover and cropping practices on runoff generation and soil loss production is highly dependent on the study area's context (Ebabu et al., 2023b), such as rainfall pattern, compaction, and slope. Long-term field studies in hydrology are scarce, especially regarding erosion and runoff, which are costly and time-consuming (Preiti et al., 2022). Nonetheless, obtaining site-specific data is crucial for soil erosion estimation that will aid in devising suitable soil and water conservation measures in regions where land use and management practices vary and have a significant impact on agriculture, such as Brazil.

Soil erosion and runoff processes are closely interconnected and alterations in one process will inevitably affect the other. However, we found that soil loss is less sensitive to land cover and precipitation changes than runoff (see Figure 3), which impacted the relative ranking of land covers based on runoff and soil loss. Similarly, Zhao et al. (2022) and Maetens et al. (2012) observed that the variability in soil loss was smaller compared to the variability in runoff among different LULCs. Despite runoff being the main driver of soil loss, this relation is not always directly interconnected (see Figure 5). This can be attributed to the dominant influence of runoff as the primary driver of surface erosion, while surface erosion itself is influenced by various other controlling factors, such as soil management practices, rainfall intensity, soil erodibility, organic matter production, root distribution, and leaf area index (Knapen et al., 2007). Chen et al. (2020), Liu et al. (2021), and Rajbanshi et al. (2023) had also studied the trade-off between soil loss and runoff, and Chen et al. (2020) pointed out that some conservation practices (eg. Non-tillage) may reduce runoff, but not necessarily soil loss. Examining the trade-offs between soil erosion and runoff reduction capacity of conservation practices allows us to grasp this equilibrium and pinpoint the most appropriate measures for soil conservation (runoff and/or soil loss reduction) based on specific physical and management conditions.

The presence of vegetation cover shields the soil from direct erosive forces, as the roots of these plants bind the soil particles together, safeguarding them against washout (Rajbanshi et al., 2023). The disturbances or absence of natural vegetation cover caused by agricultural activities frequently render the ground vulnerable to the impact of raindrops, resulting in soil crusting and compaction Bluett et al., 2019). This, in turn, reduces soil porosity, permeability, and infiltration, hinders vertical nutrient transport, and amplifies runoff and soil loss (Gharibreza et al., 2020), as we observed in Figure 4, Table 2, and Figure 7.

Soil cover plays a crucial role in dissipating the kinetic energy of raindrops, thereby directly influencing erosion and surface runoff. The presence of a higher quantity of slender leaves can expedite the transposition process through vegetation, reducing splash effects from raindrops and shear stress over the ground (Almeida et al., 2021). Besides the soil moisture preceding the precipitation, the duration and amount of rain events are important factors for the detachment and transport of soil particles, being rainfall amount the main factor for erosion generation among those two (dos Santos et al., 2017). Raindrops displace soil particles, and in cases of undisturbed flow, meaning without the influence of raindrops, the flow must exceed a critical condition for particle detachment to occur (Kinnell, 2020). The transport of these sediments depends on the runoff velocity (Zhang, 2019), and torrential rains characterized by high rain intensity and erosive energy, which commonly occur in tropical and subtropical regions such as Brazil (Browning and Sawyer, 2021). When comparing the runoff and erosion relationship with rain amount and duration among agricultural land covers (Figure 7), the greatest range of surface runoff values is observed for pasture, while the bands of soil loss remain similar to the other plots with crops. As grazing intensity increases, rises soil compaction and reduction of land cover, resulting in higher runoff compared to soybean and sugarcane plots, which are under yearly cropping renovation. Despite this, a soil cover of over 50 % provides protection for particle detachment (Nunes et al., 2011b; Sauer and Ries, 2008). From Figure 7, it seems that there is a decreasing trend in average soil loss as the precipitation duration increased for all analyzed plots, indicating an inverse relationship between those variables. This trend can be partially attributed to frontal rainfall events that can lead to prolonged rainfall lasting more than six hours (dos Santos et al., 2017), wherein continuous mild precipitation consolidates the soil surface, reducing the chance of soil detachment (Bartley et al., 2006). Conversely, when examining shorter-duration rains, an opposite relationship is observed, with an increase in sediment production and runoff generation, both similar results found by Almeida et al., 2021. Most of those events are convective-type that besides being short, are unpredictable and intense, turning tropical and subtropical areas particularly susceptible to higher soil loss (Fagbohun et al., 2016; Kinnell, 2020) and runoff (Browning and Sawyer, 2021). Furthermore, this rainfall type may not allow for the formation of a thin bedding of fine soil particles that protects the underlying soil from erosive stresses of runoff and the impact of raindrops, as described by Hairsine et al. (1999). Besides our effort in correlating rainfall and erosional processes, those are non-linear phenomena, once vegetation and precipitation have competing influences: increased precipitation leads to higher sediment yield and favors vegetation growth, while vegetation would then inhibit erosion (Saco and Moreno-De Las Hera, 2013; Langbein and Schumm, 1958).

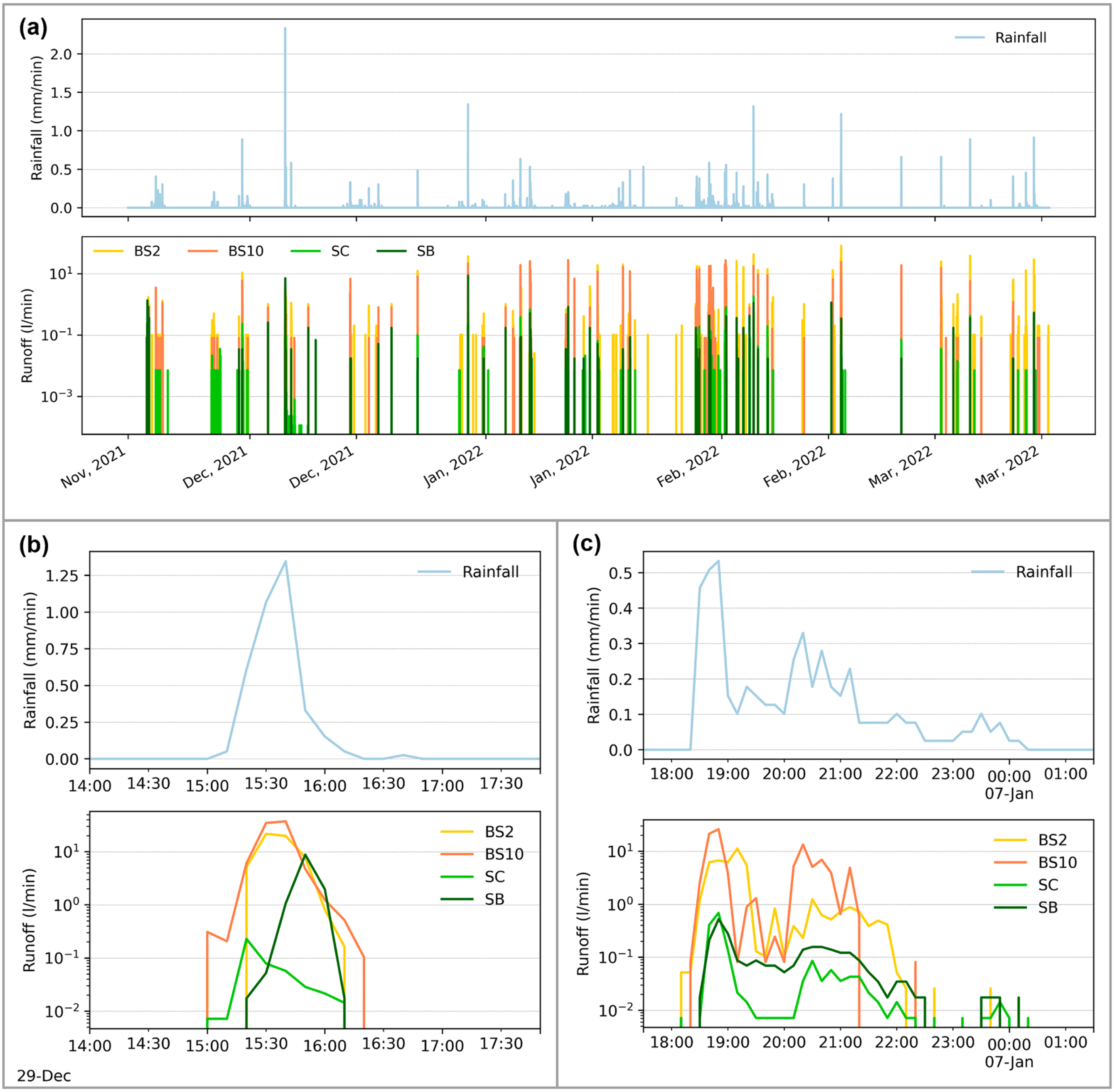


Fig. 5. Real-time runoff by large tipping buckets flow meters during rainy season (a) and event scale (b and c) monitored at experimental plots under bare soils 10 (BS10) and 2 (BS2) years old, soybean (SB), and sugarcane (SC) land covers.

We monitored runoff and soil loss in two experimental groups of plots kept under the same environmental conditions (no vegetation), differing from the number of years exposed to weathering. In the first year of weathering exposure, recent bare areas (BS2) presented a lower runoff compared to areas exposed to a long weathering process (BS10). In the second year of exposure, BS2 already reached a full power of environmental damage through high runoff and soil loss rates. Over ten years of monitoring (BS10), we did not find an increase in runoff, but a significant one in terms of soil loss, meaning that erosion is a time-exposing dependent process, as also pointed out by Zhao et al. (2022). Rodrigo-Comino et al., (2017) and Rodrigo-Comino et al., (2018) compared soil losses in vineyards and found that higher rates occurred in the first cropping years, mainly attributed to the damage that the vine plantation cause to soil. Similarly, our monitoring on sugarcane indicates the pick in the first years after crop renewing (see Supplemental material 2). However, the erosional process on bare soil plots over time is different since there is not growth of roots that creates preferential flow or leaves to reduce splash raindrop impact. The findings regarding erosional processes on bare soil have high relevance for the hydrological and agricultural community by demonstrating that soil loss should not be assumed to be a linear process over time (years), as it commonly is. The consideration of linearity may lead to inaccuracy and sub-estimations by hydrological models while simulating soil loss impact in agricultural areas.

When exposed, bare soils become less permeable over time due to the formation of soil crusts, which reduce infiltration, and consequently make the surface more cohesive (Hardie and Almajmaie, 2019). This trend was observed in the strongest correlations in BS10, where precipitation amount (0.62 over soil loss and 0.50 over runoff) and duration (0.48 over soil loss and 0.33 over runoff) exhibited significant influence

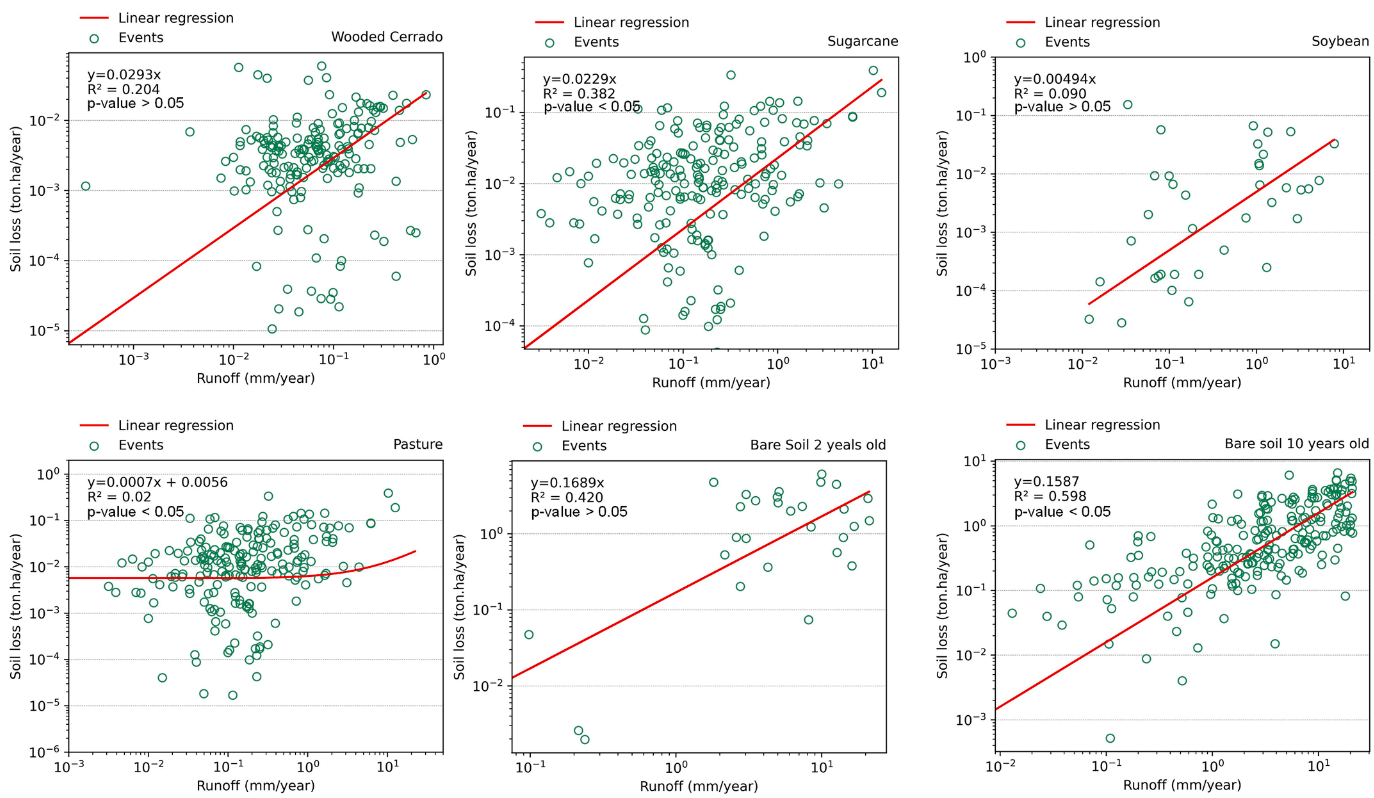


Fig. 6. Scatter of events and correlation equations between runoff and soil loss at experimental plots under wooded Cerrado, sugarcane, soybean, pasture and bare soil (10 and 2 years old) land covers.

on both soil loss and runoff. Similarly, moderate correlations were also found between precipitation amount (0.20 over soil loss and 0.37 runoff) and duration (0.10 over soil loss and 0.40 over runoff) regarding runoff production in BS2. Bare soils demonstrated a tendency to decrease average soil loss with increasing rainfall duration, with consequently increased runoff, supporting the same relationship found in Almeida et al. (2021) and Kinnell (2020). Conversely, weaker correlations were observed between soil loss and precipitation characteristics for the other studied plots (PS, SC, WC, BS2), with no strong linear correlation detected. Regarding runoff, there was a moderate correlation between precipitation amount (0.34) and duration (0.15) in the PS plot. The stronger correlations occur with runoff rather than soil loss, given that the last is influenced by factors that alter erosive process variability (Zhao et al., 2022), while factors affecting runoff, such as soil impermeability, show a tendency to relate to runoff (Browning and Sawyer, 2021). Sugarcane and pasture exhibited similar patterns in generating average erosion in response to precipitation amount, while soybean showed a less consistent trend compared to other crops, likely influenced by shorter the amount of data available and yearly soil revolving for seeding.

In addition to data availability in the common event time resolution that other studies provide, our study provides a unique smaller monitoring time resolution of ten minutes through the use of flow meter tipping buckets (Figure 5). Due to our high-resolution flow meter tipping buckets, there were able to capture and identify that runoff peak and flow duration are dependent on the land cover. Within the agricultural class, SC plot experienced a more intense and longer runoff production than SB. In the extreme scenario, the complete abstention of vegetation can lead to a 50–125 fold higher runoff peak compared to SB and SC, respectively. Similarly, Bettoni et al. (2023) also point out that LULC affected not only total runoff and soil loss, but also the runoff hydrograph at event scale. Moreover, Bettoni et al. (2023) indicated that runoff peak occurs more rapidly in dry than in moist conditions. In areas with high soil water retention, during dry conditions rainfall lands on a partially impermeable surface, facilitating the rapid formation of surface runoff. The flow information regarding different LULC at fine time resolution may serve as input data for simulation and calibration of infiltration, runoff, and soil loss models in tropical and subtropical zones, which are rarely studied. By coupling the fine time resolution runoff data (Figure 5) with the runoff /soil loss curve (Figure 6), it is possible to obtain an estimation of the soil loss process over time also at fine resolution, as suggested Blöschl et al. (2019) towards fine resolution data collection in hydrology while listing the 23 gaps to guide future hydrology studies. The runoff/soil loss correlating curve (Figure 6) can be reproduced in other subtropical regions with similar environmental conditions aiming to estimate soil loss based on monitored runoff. Moreover, the setup monitoring station using the tipping buckets presented by Schwamback et al., (2022a) may be reproduced under other conditions and provide real-time monitoring at a low investment cost.

The impacts of land cover change go beyond runoff and soil loss, affecting also the infiltration and evapotranspiration rates, nutrient availability, and biochemical processes (Ma et al., 2023). These changes affect various factors, including surface roughness, which influences the movement of wind and water; albedo, which determines the amount of solar radiation absorbed or reflected; and infiltration capacity, which controls the extent of water penetration into the soil. Additionally, variations in root depth can impact water and nutrient uptake, while architectural resistance affects the movement of water through plant structures. The leaf area index and stomatal conductance are also crucial, as they regulate the exchange of water and gases between plants and the atmosphere (Otu-Larbi et al., 2021). Together, these factors shape the overall dynamics of hydrological processes, influencing water distribution, availability, and the health of ecosystems (Aghsaei et al., 2020). Moreover, the interconnected nature of these variables means that changes in one aspect can have cascading effects on others, underscoring the complex relationship between LULC and hydrology.

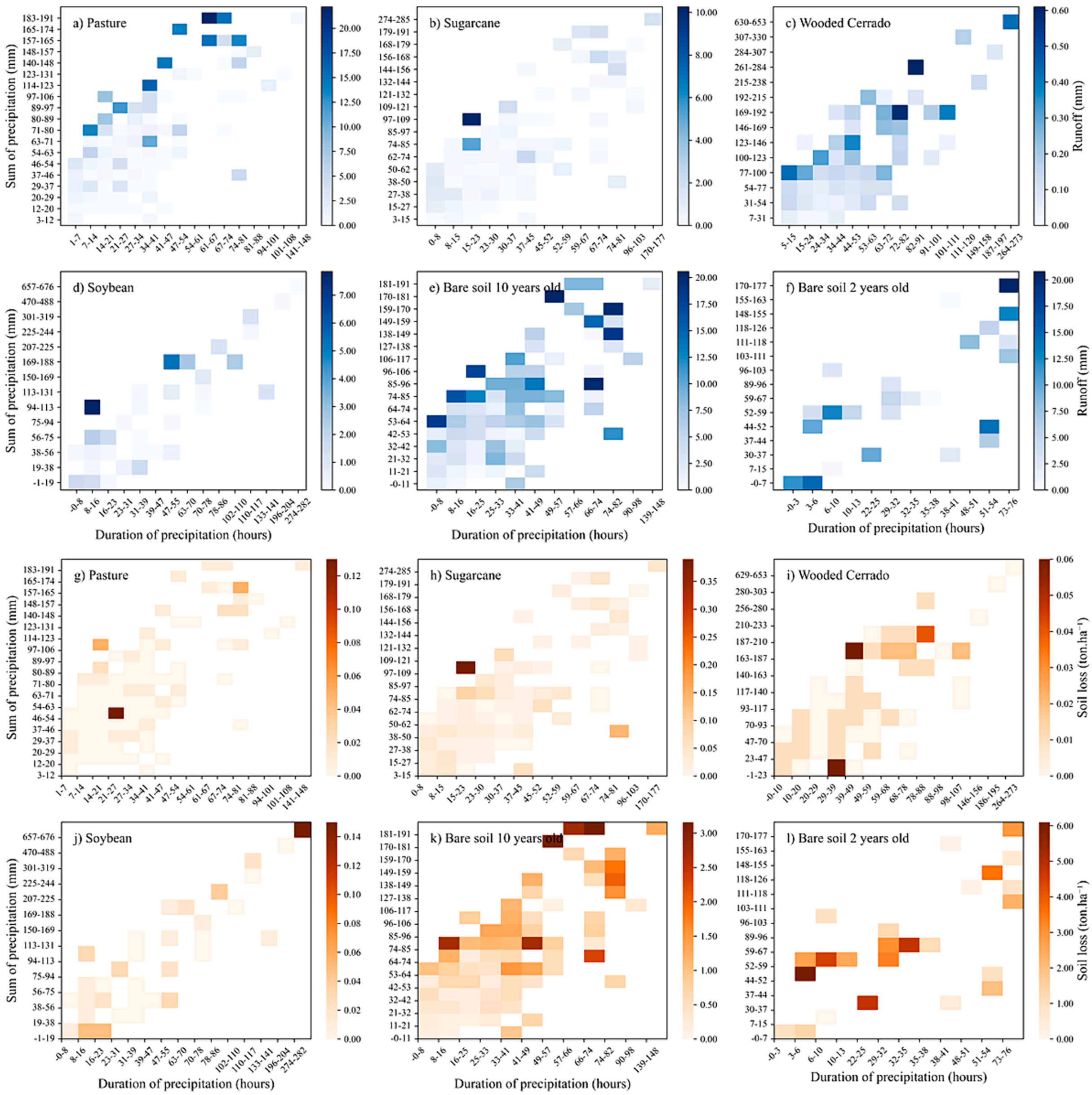


Fig. 7. Heat map of precipitation and runoff (subplots a, b, c, d, e, and f) and soil loss rates (subplots g, h, i, j, k, and l) monitored at experimental plots covered with wooded Cerrado, sugarcane, soybean, pasture and bare soil 10 and 2 years old. The precipitation and duration used in the analysis were accumulated up to the day of data collection.

To expand the understanding of the effects of LULCs on soil and water transport, we addressed variables (porosity, organic matter, and electric conductivity) that are indicators of soil physical and chemical health (Figure 2). The macroporosity affects root development and water and nutrient absorption, being an indicator of soil degradation (Silva et al., 2022). The conventional agricultural practice of soil revoking increased the macroporosity at 15 cm depth in SB and SC, in values that are even higher than at native forest (WC). However, this "benefit" is limited to near-surface conditions as deeper regions have lower macroporosity and higher compaction (given by apparent density in Table 1). According to Reichert et al. (2007), plants in soil with macroporosity below 10 % have limited root development, and following this threshold, BS10 plot (30 cm depth) already has an intense degradation level. The high organic production, deposition, and decomposition at WC plot is higher than the mean range observed at other plots over the same biome (20–30 %) (Villar, 2007), while agricultural plots are within, and bare soil plots are below the expected range. Low organic matter content reduces soil stability, water retention, infiltration capacity, and therefore, runoff production – main driver for soil transport during erosion (Mhazo et al., 2016). The organic matter also reflects on the soil nutrients availability expressed given by soil CEC. The quartzerenic soil, where experimental plots were installed, has a sandy texture, and following Sousa et al. (2004) CEC interpretation ranges applied for Cerrado biome, WC plot had a high CEC value, while agricultural plots had an adequate, and bare plots had low cations holding capacity. As soil reaches its infiltration capacity, soil particles are detached from the surface and transported toward the plot outlet. With it, goes nutrients that are essential for crops growth, as observed on near-surface soil samples at bare plots that had low organic matter and CEC values. Similarly, nutrients are washed out of agricultural land towards rivers and lakes, requiring more investments in agriculture while original nutrients lead to eutrophication (Zhang et al., 2021). We observed that soil samples from deeper zones (≥30 cm) were less affected by land cover change, as analyzed variables from different land cover are more similar at deeper depths, as there is a higher root density and biological activity near-surface. This highly sensitive zone corresponds to the topsoil area, a near-surface zone natural supply for most nutrients used in agriculture, and is also responsible for the interconnection between the atmosphere and subsurface processes such as percolation and aquifer recharge (Ben-Noah and Friedman, 2018). A topsoil zone with adequate organic matter, porosity, CEC, and other variables provides uncounted benefits: supplies energy to microorganisms in soil, provides glue to bind soil particles, helps to improve soil aeration, acts as a slow-release nutrient store-house, increases water-holding capacity of the soil, that finally leads to prevent surface sealing, runoff and erosion (Herre et al., 2022; Ma et al., 2023; Zhao et al., 2018). Therefore, we highlight that future soil qualitative and conservation studies related to land cover interactions should focus on depth up to 30 cm.

Research involving long-term trade-offs in runoff and soil loss due to land cover change has great potential to provide a better understanding of the actual and potential impacts of anthropogenic activities and to contribute to the development of policies aiming at sustainability. Xiong and Leng (2024) conducted an analysis of global soil erosion from the 2010 s to the 2090 s using 14 GCMs and future LULCC projections under SSP scenarios. They estimated an increase up to 11.3 % on SSP5-RCP8.5 scenarios, shedding light on an obscure future and highlighting the importance of soil conservation practices to mitigate the inevitable effect of climate change (Eekhout and Vente, 2022), such as contour, no-tillage, crop rotation, etc. Our dataset and results are valuable for the further calibration/validation of regional soil loss models, providing a comprehensive analysis of historical and projected erosion patterns, fundamental to the construction of reliable models. Based on regional models, researchers will be able to tailor mitigation strategies to specific scenarios, regions, and resources.

We would like to suggest the following subjects for the advance of the study topic: simulating the impact of climate changes in terms of soil loss, runoff, and infiltration capacity over those different land covers (as described before), coupling automated soil loss sampling and runoff monitoring, investigating the creation and intensification of preferential surface flow using cameras, studying the sediment transport process by using tracers, nutrient losses over different land cover, and compare the effect of implementing agricultural management practices.

5. Conclusion

Changes in land use and land cover in Brazil have resulted in the loss of 54 % of the native forest vegetation areas in the wooded Cerrado region in the last 50 years (Pompeu et al., 2024). Even though there are erosion/runoff experimental plots in this biome, most of them are short-term and covering specific agricultural species that limit comprehensive conclusions about LULC changes and climatic variables on erosive processes. This study presented quantitative relationships in the environmental trade-off, in terms of runoff and soil loss rates, between different agricultural land covers (pasture, soybean, sugarcane) compared to forest (wooded Cerrado) and bare soil. By comparing the rates on each land cover we can draw insight regarding the environmental impact of land conversion in this biome due to agriculture, with different outcomes depending on the specific conversion. Besides being unclear which agricultural land cover has greater environmental damage, the findings reveal that agricultural practices have a significant impact compared to the forest, with nineteen times more runoff and five times more soil loss. The loss of soil particles, runoff, and nutrients monitored over the last decades show that agricultural management practices without soil protection practices lead to fast soil degradation, threatening sustainable development and food production in the Cerrado ecoregion.

Our findings indicated that not only land cover poses a potential impact factor to soil loss, but also time of exposure. Areas with the same environmental characteristics with long-term environmental exposure of 10 years without land cover protection were more susceptible to soil loss than areas with short exposure. The findings have high relevance for the hydrological and agricultural community by demonstrating that soil loss should not be assumed to be a linear process over time and those findings will be included in future environmental modeling research. The current findings are based on the analysis of a unique data set of 2796 monitored runoff and soil loss events between November 2011 to April 2023. The data set is freely available for further data analysis, as we understand that long-term monitoring promotes advances on hydro-erosive studies (i) and supports policies aimed at sustainable development of agriculture (ii) in the Cerrado biome. The database and critical analysis pin the Cerrado, one of the largest and most threatened biomes in the world, in the worldwide big picture of well-described erosive regions.

The study's results highlight the urgent need for improved land management practices to combat soil degradation and promote sustainable agriculture. By demonstrating that conventional agricultural activities in the Cerrado biome result in significantly higher runoff and soil loss compared to forested areas, the findings underscore the importance of implementing soil protection measures such as cover crops, contour farming, and no-tillage, among others. These insights are critical for shaping land management policies not only in the Cerrado but also in other regions worldwide facing similar challenges of land degradation due to agricultural expansion. Future research should extend to diverse geographical areas, integrate climatic variables, and assess the effectiveness of various soil protection techniques across different agricultural systems. Incorporating socio-economic analyses and exploring technological innovations like precision agriculture will further improve the understanding and implementation of sustainable land management practices. This comprehensive approach will bolster global efforts to achieve food security, environmental sustainability, and climate resilience, providing valuable lessons for regions with similar ecological and socio-economic contexts.

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CRediT authorship contribution statement

Dimaghi Schwamback: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing. **Abderraman R. Amorim Brandão:** Formal analysis, Investigation, Software, Visualization, Writing – original draft. **Lívia M.P. Rosalem:** Conceptualization, Data curation, Formal analysis, Writing – original draft, Funding acquisition. **Paulo T.S. Oliveira:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing – original draft. **Jamil A.A. Anache:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing – original draft. **Edson Wendland:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Supervision, Writing – original draft. **Ronny Berndtsson:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Writing – original draft. **Magnus Persson:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data created is freely available

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2024.108412.

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