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Rock-soil skeleton increases water infiltration

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ABSTRACT: A widespread assumption among researchers and technicians is that stony soils are more susceptible to degradation. However, the role of rock fragments in the hydrology of stony soils, especially in regard to infiltration, is still a research gap. The aim of this study was to test the hypothesis that an increase in rock fragments in the soil profile increases the water infiltration rate. Infiltration tests using a double-ring infiltrometer were conducted on February 11, 2021, and December 11, 2022, at three sites of Entisols with different fractions of rock fragments. The results supported the hypothesis of this study. The infiltration rate was up to sixteen times greater in profiles whose horizons had at least 60 % rock fragments in relation to profiles with a lower fraction of rock fragments. These findings provide evidence that some stony soils may not be as susceptible to degradation by water erosion as it was suposed.

Keywords: stony soils, soil water flow, double-ring infiltrometer.

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INTRODUCTION

Shallow and stony soils with rock fragments (RF) (particles with an effective diameter between 2 and 250 mm) occur on all continents (Poesen and Lavee, 1994; Ma and Shao, 2008). The shallow depth of the soil profile limits water storage and water availability for plants, and the high percentage of RF may hinder the use of mechanization, restricting agricultural use. However, the growing demand for food and renewable energy sources has expanded agricultural frontiers to various areas of shallow and stony soils (Laurance et al., 2014; Arias et al., 2019), whose real limitations and potentialities are still poorly understood.

As these soils occur in more steeply sloped terrains (Hlaváčiková and Novák, 2014) and have shallow depth and extensive RF, a widespread assumption among researchers and technicians is that these soils are more susceptible to degradation, particularly by water erosion (Stuart and Dixon, 1973; Constantz et al., 1988; Ingelmo et al., 1994; Zavala et al., 2010; Gordillo-Rivero et al., 2014). Research on rocky soils or soils with RF has increased significantly since 2003, but the measurements that have been made of hydrological processes and properties are still insufficient to clarify the role of RF in soil hydrology and susceptibility to degradation in rocky soils (Zhang et al., 2016). Water infiltration, for example, is rarely measured in rocky soils. It is a process that simultaneously involves the effect of surface conditions and the internal properties of the soil profile on water flow and can help to study the role of RF on soil hydrology. In addition, the infiltration rate provides crucial data for designing soil use and management techniques to prevent soil degradation.

Several studies have evaluated the effect of rock fragments (RF) on soil infiltration. However, the results are divergent and most of them have only investigated infiltration under conditions where RF were added on the soil surface or partially incorporated into the top layer of the soil.

The presence of rock fragments on the soil surface can either decrease or increase infiltration (Brakensiek and Rawls, 1994). For example, some studies have shown that increasing the proportion of RF on the surface or partially incorporating RF has caused a reduction in infiltration and increased surface runoff (Stuart and Dixon, 1973; Constantz et al., 1988; Poesen et al., 1990; Ingelmo et al., 1994; Simanton and Toy, 1994; Wu et al., 2021). Other studies have reported an increase in infiltration with an increase in the fraction of RF on the soil surface (Simanton et al., 1984; De Figueiredo and Poesen, 1998; Mandal et al., 2005; Pahlavan-Rad et al., 2020). However, these results might not accurately reflect how RF naturally present throughout the entire soil profile affect infiltration.

Rock fragments within the soil profile can cause greater heterogeneity and complexity in the pore system (Weiler and Flühler, 2004; Sheng et al., 2012; Zhao et al., 2020). Predicting the impact of such complex pore systems on water transport properties in the soil is a huge challenge, even with modeling (Gubiani et al., 2023). In these cases where the prediction or use of hydraulic properties of profiles without RF can be inaccurate, field measurement is a fundamental strategy for investigating the effect of RF on infiltration. Studies have shown that direct measurements of infiltration rate, such as those conducted with double-ring and disc infiltrometers, can be applied in rocky soils (Baetens et al., 2009; Verbist et al., 2010). These direct measurement techniques enable a more accurate assessment of the infiltration rate and prove to be particularly relevant when considering the presence of RF in the soil profile.

Our hypothesis is that an increase in RF in the soil profile increases the infiltration rate. There is evidence that with the increase in RF and the consequent reduction in fine soil particles (particles with effective diameter <2 mm), the spaces between the RF are not completely filled (Fies et al., 2002), which creates preferential flow (Cerdà, 2001; Zhou et al., 2011; Buchli et al., 2013; Sohrt et al., 2014; Hou et al., 2023) and may facilitate infiltration. Testing this hypothesis is important to expand knowledge about the hydrology of stony soils, which will assist in planning land-use and defining practices to mitigate the degradation of these soils. It also helps to overcome the lack of infiltration data on stony soils (Rahmati et al., 2018). Thus, this study aimed to evaluate the aforementioned hypothesis through measurements with a double-ring infiltrometer in Entisols with diverse fractions of RF.

MATERIALS AND METHODS

Study site and soil characterization

Infiltration experiments were carried out in a cultivated area located in the municipality of Ivorá, Rio Grande do Sul State, in southern Brazil. Three sites with different fractions of rock fragments were selected to represent extreme conditions (lowest and highest) and an intermediate condition of RF content in the area. These sites were called Low RF, Medium RF, and High RF (Figure 1).

At each site, a pit was opened, and three distinct layers were identified based on the soil morphological properties, such as texture and color. The sequential depth of layers in the profiles is as follows: Low RF, 0.00-0.20, 0.20-0.40, and 0.40-0.65 m; Medium RF, 0.00-0.15, 0.15-0.35, and 0.35-0.55 m; and High RF, 0.00-0.10, 0.10-0.25, and 0.25-0.40 m. Based on the morphological properties of the layers (data not shown), the profiles were classified as *Neossolo Regolítico* (Humic Dystrudept), *Neossolo Regolítico* (Typic Udorthent), and *Neossolo Litólico* (Lithic Udorthent), according to the Brazilian

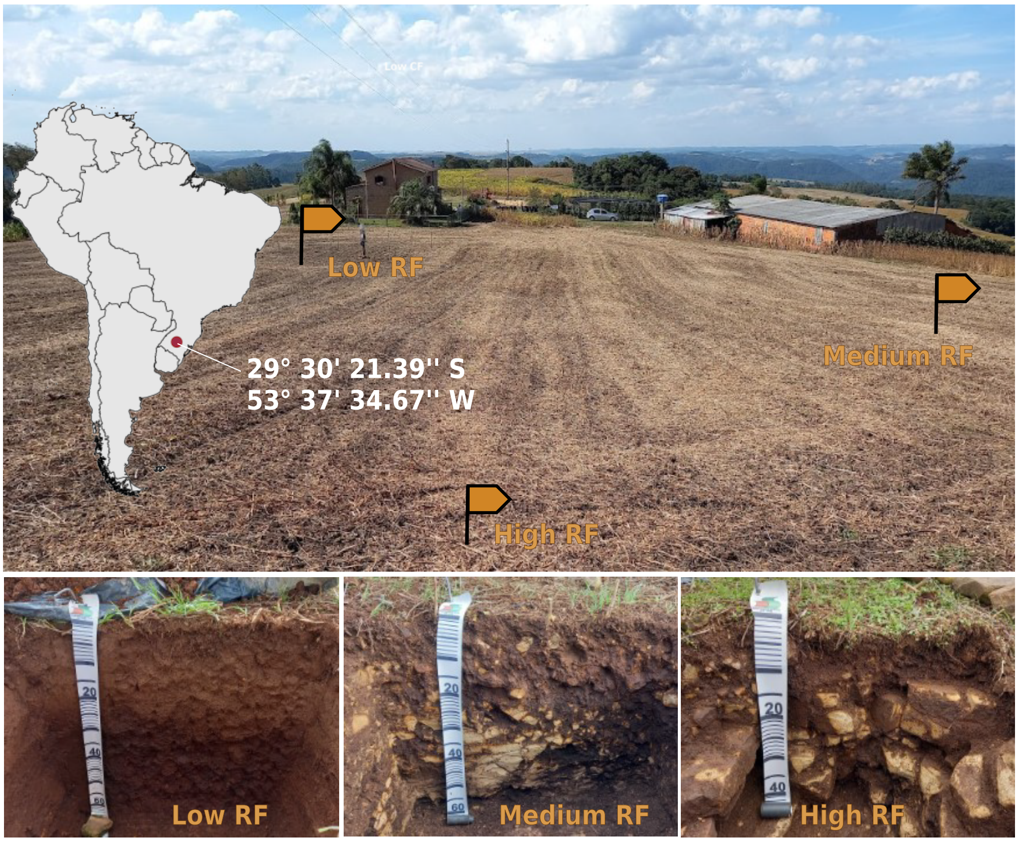

Figure 1. Location of the study area and an overview of the landscape and evaluated soil profiles. RF: rock fragments.

Soil Classification System (Santos et al., 2018) and (in parentheses) Soil Taxonomy (Soil Survey Staff, 2014).

Particle size distribution was characterized according to Schoeneberger et al. (2021) in soil samples collected from each layer (Table 1), expressing the percent in weight of pebbles and coarse gravel (CCG, 250 - 20 mm), medium and fine gravel (MFG, 20 - 2 mm), coarse sand (CS, 2 - 0.25 mm), fine sand (FS, 0.25 - 0.05 mm), silt (0.05 - 0.002 mm), and clay (<0.002 mm). The sand, silt, and clay fractions were determined following the methodology described by Gubiani et al. (2021). Initially, 20 g of the soil fraction, previously sieved through a 2 mm sieve, was shaken in a 1 mol L^{-1} NaOH solution for 2 h. Subsequently, the sand fraction was separated by washing the dispersed sample through a 0.053 mm mesh sieve. The clay fraction was determined using the pipette method (Gee and Bauder, 2018). Finally, the silt fraction was calculated by subtracting the combined weight of the sand and clay fractions from the total weight.

As an additional measurement for characterization, soil bulk density was determined using the clod method (Blake, 1965) on three undisturbed blocks collected from each layer of the soil profiles, following the methodological protocol described by Pereira et al. (2023).

Double-ring infiltrometer tests

Infiltration tests with a double-ring infiltrometer (inner ring diameter of 0.20 m and outer ring diameter of 0.40 m) were performed near each of the three soil profiles described above. Three sets of double-rings were set up around each profile, spaced two meters apart. The rings were inserted into the soil surface to a depth of 0.05 m. Infiltration was measured on February 11, 2021 (soybean at the R5.1 phenological stage), and the rings remained until the second measurement, on December 11, 2022 (soybean at the V6 phenological stage). The measurements were performed following the methodology described by Reynolds et al. (2002), when the soil water content was around field capacity. A constant hydraulic head of 0.05 m was kept in both rings by applying the Marriott principle in a water supply reservoir. The infiltrated water was recorded at intervals of approximately 10 min at the beginning of the tests, followed by longer intervals as the infiltration rate decreased. Each test lasted around 3 h and was completed when at least five successive readings indicated that the infiltration rate was approaching stability. The average of the last five infiltration rates was considered an estimate of the steady-state infiltration rate.

Statistical analysis

Distribution of the steady-state infiltration rate could not be considered normal even after scale transformations. Therefore, the effect of RF abundance on the steady-state infiltration rate was evaluated by the non-parametric Kruskal-Wallis test. Differences in the steady-state infiltration rate among profiles were detected by the Nemenyi test at a 0.05 % probability of error. These tests were run with the KW_MC SAS macro (Elliott and Hynan, 2011). The cumulative infiltration was presented and analyzed graphically.

RESULTS

Particle size distribution shows high variability of RF among the sites where infiltration was measured (Table 1 and Figure 1). In the three layers of the High RF profile, at least 60 % of the particles were RF, with 50 % being coarse gravel (CCG, 250-20 mm). In the Medium RF profile, RF was also detected in all layers, but coarse gravel was present only in the second and third layers. The Low RF profile had RF only in the last layer (RF <15 %), with 7 % of the RF in the coarse gravel class. Silt and clay were the fine earth fractions (<2 mm) with higher percentages in the soil profiles (Table 1). The Low RF profile had a higher average percentage of silt (46 %) and clay (25 %) compared to the silt and clay of the Medium (14 % and 7 %, respectively) and High (11 % and

12 %, respectively) RF profiles (Table 1). Soil bulk density ranged from 1.15 Mg m^{-3} (0.10-0.25 m layer of the High RF profile) to 1.45 Mg m^{-3} (0.00-0.10 m layer of the Low RF profile (Table 1). The Low RF profile exhibited a higher mean value of bulk density (1.4 Mg m^{-3}) compared to the Medium and High RF profiles (1.18 Mg m^{-3}).

The highest (100 mm h^{-1}) and lowest (6 mm h^{-1}) median steady-state infiltration rates occurred at the site with the highest (High RF) and lowest (Low RF) fraction of RF, respectively (Figure 2). The steady-state infiltration rate in the Medium RF site was in between that of the High RF and Low RF sites but did not differ statistically. The steady-state infiltration rate in the High RF site was sixteen times higher than that of the Low RF site.

The cumulative infiltration was higher in the profiles with a greater fraction of RF, but in one replicate of the Low RF profile, the cumulative infiltration was higher than that of the Medium RF site (Figure 3). In the High RF site, in which there was at least 60 % RF in all layers of the soil profile (Table 1), the cumulative infiltration approached 800 mm (Figure 3) after 2.5 h, while in the Medium RF (RF >60 % in the second and third layer) and Low RF (RF <15 % in the last layer) sites (Table 1), the accumulated infiltration after 2.5 h was close to 400 and 350 mm, respectively (Figure 3).

DISCUSSION

We evaluated the hypothesis that the infiltration rate increases with the fraction of RF in the soil profile. The measurements of steady-state infiltration rate (Figure 2) in locations with different fractions of RF support this hypothesis. The steady-state infiltration rate in the High RF profile was 16 times greater than in the Low RF profile (Figure 2). These results contrast with those of studies that observed a reduction in infiltration with an increase in RF on the surface or RF partially incorporated in the soil profile (Stuart and Dixon, 1973; Constantz et al., 1988; Poesen et al., 1990; Ingelmo et al., 1994; Simanton and Toy, 1994; Wu et al., 2021). Opposite results for relationships between infiltration rate and RF show that infiltration does not depend solely on the quantity of rock fragments. A plausible hypothesis to explain the positive relationship between infiltration and RF is the occurrence of preferential flow in soils with RF. In soil with a large fraction of RF, there may be insufficient fine particles to fill the spaces between the RF (Fies et al., 2002).

Table 1. Particle size distribution and bulk density (BD) of evaluated soil profiles

Location	Layer	BD	CG	MG	Coarse sand	Fine sand	Silt	Clay
	m	Mg m^{-3}			%			
Low RF	0.00-0.10	1.45	0	0	15	8	55	22
	0.10-0.35	1.36	0	0	11	8	48	33
	0.35-0.55	1.39	7	7	9	20	35	22
	Average	1.40	7	7	11	30.6	46	25
Medium RF	0.00-0.15	1.20	0	23	14	19	29	15
	0.15-0.35	1.20	57	18	6	2	11	6
	0.35-0.55	1.16	99	0	0	0	1	0
	Average	1.18	52	13	7	7	13	7
High RF	0.00-0.10	1.20	61	8	0	11	10	10
	0.10-0.25	1.15	50	6	13	4	13	14
	0.25-0.40	1.20	60	4	9	5	10	12
	Average	1.18	57	6	7	6	11	12

Coarse gravel (CG, 250 - 20 mm), medium and fine gravel (MG, 20 - 2 mm), coarse sand (CS, 2 - 0.25 mm), fine sand (FS, 0.25 - 0.05 mm), silt (0.05 - 0.002 mm), clay (< 0.002 mm).

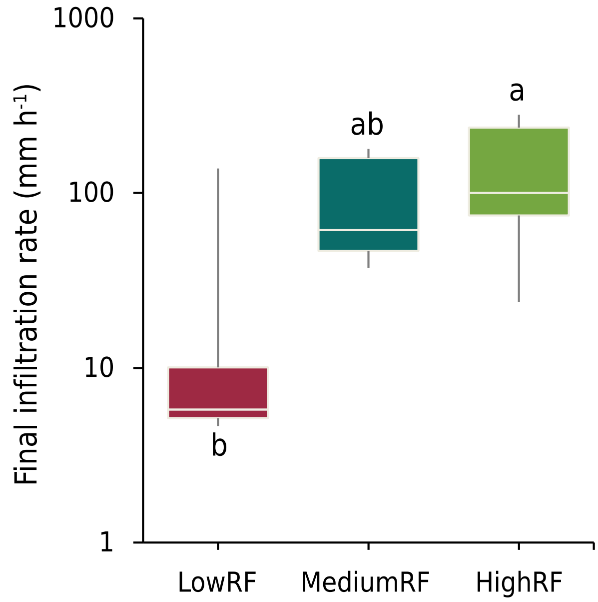

Figure 2. Steady-state infiltration rate at locations with low, medium, and high rock fragments (RF).

The resulting empty spaces favor the occurrence of preferential flow (Cerdà, 2001; Zhou et al., 2011; Buchli et al., 2013; Sohrt et al., 2014; Hou et al., 2023). In addition, the RF in contact with each other form a rigid rock-soil skeleton that protects the soil from compaction and maintains porosity (Nasri et al., 2015).

Preferential flow due to incomplete filling and protection of porosity by RF are plausible explanations for higher infiltration rates in the High RF and Medium RF sites (100 mm h^{-1} and 61 mm h^{-1}, respectively) compared to the location without RF (6 mm h^{-1}), which does not create such conditions (Figure 2). Therefore, in soil with RF only on the surface or partially incorporated in the top layers of the soil profile, a decrease in infiltration with increasing quantity of RF is plausible (Stuart and Dixon, 1973; Constantz et al., 1988; Poesen et al., 1990; Ingelmo et al., 1994; Simanton and Toy, 1994; Wu et al., 2021). In those cases, RF on the surface or the partially incorporated RF decreases the effective infiltration area and do not promote preferential flow inside the soil profile below the layer affected by RF.

The higher infiltration rate and cumulative infiltration in the Medium and High RF profiles (Figures 2 and 3) may be related to the presence of large gravel fragments (coarse gravel - CG) within the soil layers of these profiles (Table 1 and Figure 1). The literature presents conflicting results regarding the effect of particle size on water flow in the soil. While some studies suggest that smaller fragments decrease infiltration and larger fragments increase it (Brakensiek and Rawls, 1994), others indicate that smaller rock fragments play a more significant role than larger ones in protecting soils against degradation, particularly concerning water erosion (De Figueiredo and Poesen, 1998; Guo et al., 2010). The results of this study suggest that the presence of larger fragments may increase infiltration and maintain porosity, likely due to the protection of macroporosity (Nasri et al., 2015) and incomplete filling (Fies et al., 2002). Furthermore, the lower values of bulk density in the Medium and High RF profile (1.18 Mg m^{-3}) compared to the Low RF profile (1.4 Mg m^{-3}) indicate that the presence of larger fragments plays a role in protecting macroporosity and reducing soil compaction.

The higher infiltration rate and cumulative infiltration in the High RF site (Figures 2 and 3) provides evidence in a direction opposed to the assumption that rocky soils are

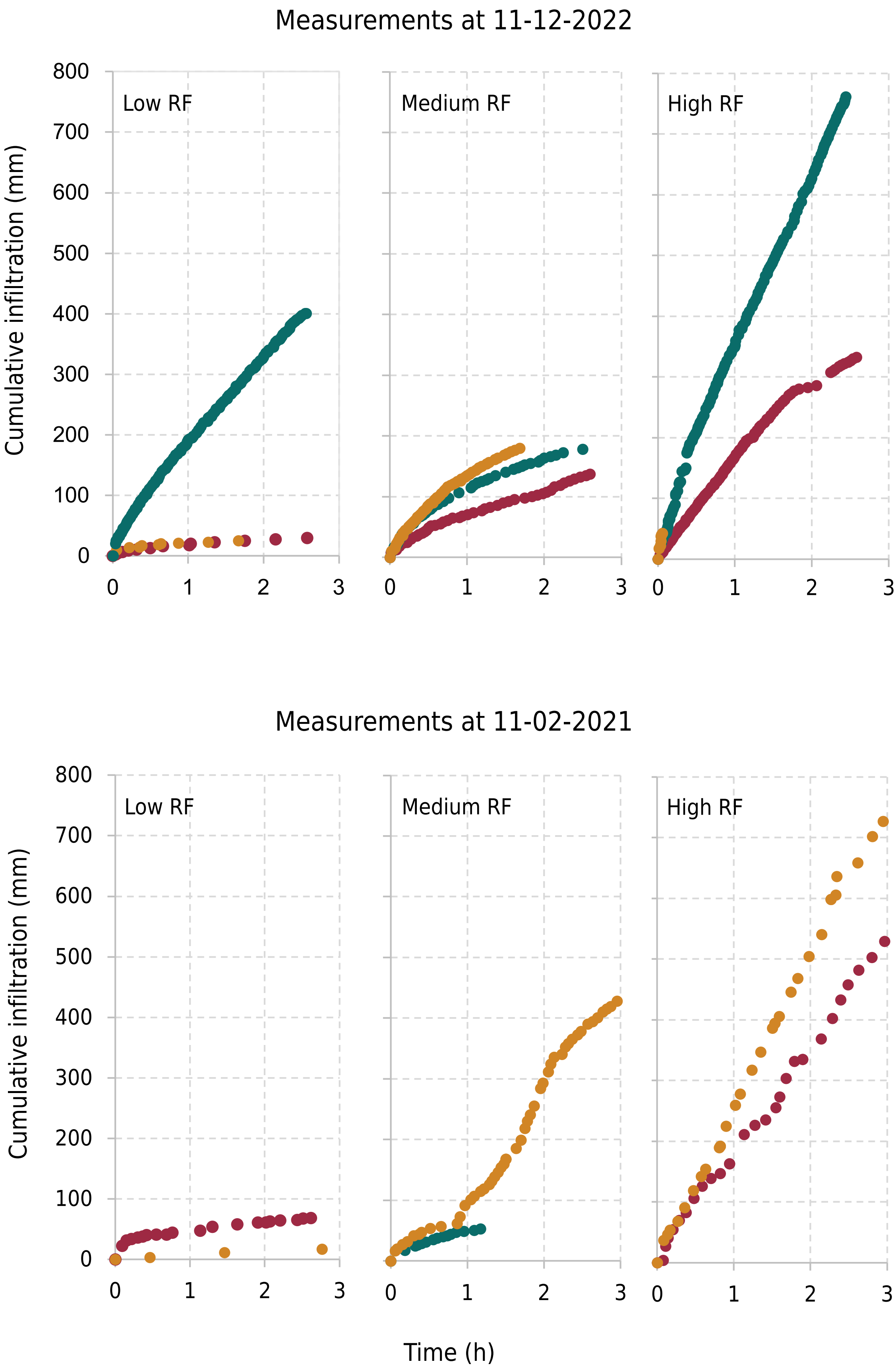

Figure 3. Cumulative infiltration at three (top) ad two (bottom) positions nearby the location with low, medium, and high rock fragments (RF). Different colors refer to different repetitions.

more susceptible to water erosion. However, it is important to acknowledge that compared to deep soils such as *Latossolos* (Oxisols), soils containing rock fragments typically have shallow depth, which limits their water infiltration capacity. However, from the results of this study, it is evident that the soil hydrological response changes considerably depending on the soil RF content. In soils with low RF (Low RF profile - Table 1 and Figure 1), the benefits from incomplete filling of the interfragmentary space and protection of porosity by the rock-soil skeleton for preferential flow do not occur, and consequently, infiltration is low (Figures 2 and 3), making these sites more susceptible to degradation by water erosion. As the RF content increases (Medium and High RF profiles - Table 1 and Figure 1), the contact between RF also increases, producing a rock-soil skeleton that protects the unfilled porosity and increases infiltration (Figures 2 and 3). In this case, the soil may be less susceptible to degradation, even though it is in mountainous regions favorable to erosive processes.

This study indicates the opposite of the assumption that rocky soils are more susceptible to degradation by water erosion. The increase in infiltration with the increase in RF (Figures 2 and 3) suggests that the chance of surface runoff may decrease in rocky soils. However, due to the variability of the porous system of rocky soils, the permeability of the underlying rock substrate, and the distance of rock fragments from the soil surface, the hypothesis of this study may by refined by testing in a more extensive group of rocky soils. Thus, further studies are needed to generate infiltration data for designing irrigation and drainage systems (Mahapatra et al., 2020) and for models parametrization (Borrelli et al., 2021) in rocky soils. Aditional studies are also needed to provide better and necessary knowledge about the hydrology of rocky soils. This would assist in the development of agricultural strategies capable of mitigating degradation in these soils.

CONCLUSION

The hypothesis that an increase in the fraction of rock fragments (RF) in the soil profile enhances the infiltration rate was supported by the measurements performed in this study. A positive relationship between the fraction of RF and the steady-state infiltration rate was observed. In profiles where 60 % RF was present in all layers of the soil profile, the infiltration rate was sixteen times greater. These findings provide evidence that some stony soils may not be as susceptible to degradation by water erosion as it was suposed. However, it is important to note that rock fragments in the soil do not completely eliminate the risk of erosion. Although soils with rock fragments may exhibit higher infiltration capacity, it should be considered that these soils often have limited depth, which reduces their water retention capacity and increases the potential for runoff and erosion. Therefore, even with the presence of rock fragments, there is still a possibility of accelerated erosion degradation in these soils. Due to the large variability of these soils, further studies are important for a better understanding of the effect of RF on infiltration and hydrology in rocky soils.

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AUTHOR CONTRIBUTIONS

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Writing – review & editing: Fabrício de Araújo Pedron (equal) and Paulo Ivonir Gubiani (equal).

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