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Water infiltration in the domains of the Brazilian Tropical Savanna: what do we really know?*

Gleicon Queiroz de Brito¹, Johnny Rodrigues de Melo Murta², Sérgio Fernandes Mendonça Filho³, Luiz Felipe Salemi⁴

¹ Doutorando em Ciências ambientais pela Universidade de Brasília (UnB). Núcleo de Estudos e Pesquisas Ambientais e Limnológicas (NEPAL), Faculdade UnB de Planaltina (FUP), CEP: 73.345-010, Planaltina (DF), Brasil, Tel.: (+55 61) 99633-9513, gleicon_brasileiro@hotmail.com (corresponding author). ² Doutorando em Ciências ambientais pela Universidade de Brasília (UnB). Núcleo de Estudos e Pesquisas Ambientais e Limnológicas (NEPAL), Faculdade UnB de Planaltina (FUP), CEP: 73.345-010, Planaltina (DF), Brasil, Tel.: (+55 61) 98350-0066, johnnymurta@yahoo.com.br. ³ Mestre em Ciências ambientais pela Universidade de Brasília (UnB). Núcleo de Estudos e Pesquisas Ambientais e Limnológicas (NEPAL), Faculdade UnB de Planaltina (FUP), CEP: 73.345-010, Planaltina (DF), Brasil, Tel.: (+55 61) 98283-9001, agro.sergiofernandes@gmail.com. ⁴ Professor do Programa de Pós-graduação em Ciências ambientais da Universidade de Brasília (UnB). Núcleo de Estudos e Pesquisas Ambientais e Limnológicas (NEPAL), Faculdade UnB de Planaltina (FUP), CEP: 73.345-010, Planaltina (DF), Brasil, Tel.: (+55 61) 98363-7041, lfsalemi@unb.br. * Part of the master's thesis of the first author.

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ABSTRACT

Water infiltration is a key process in groundwater-river recharge. However, it is poorly known in the Brazilian Tropical Savanna (biome with different natural ecosystems, such as savannas, native grasslands, and forests). Thus, we carried out a review on soil water infiltration in different natural ecosystem types within the domains of the Brazilian Tropical Savanna. We collected articles from the Web of Science, Periódicos CAPES, and Scholar Google databases. We found 15 articles (including 22 assays) with studies prevailing in the Midwest region of Brazil. The mean and median infiltration capacity of all studies was 792 and 567 mm h⁻¹, respectively. The majority of the studies (12 articles) did not clearly define which specific type of ecosystem was studied. Furthermore, most of the studies were carried out in Oxisols. Generally, the studies had a low sample size to characterize soil properties. A better description of ecosystem type, as well as a more significant sample size, are needed to understand infiltration in natural ecosystems of the Brazilian Tropical Savanna. Given the limitations of the studies available, our review showed that it is still too early to synthesize and to make an in-depth discussion on such topic in such huge and heterogeneous biome.

Keywords: phytopsiognomy, soil, native vegetation.

Infiltração de água nos domínios da Savana Tropical Brasileira: o que realmente sabemos?

RESUMO

A infiltração de água é um processo chave na recarga de rios e aquíferos. Entretanto, é pouco conhecido no Cerrado brasileiro (bioma com diferentes ecossistemas naturais, tais como as formações savânicas, camprestres e florestais). Assim, realizou-se uma revisão sobre a infiltração de água no solo em diferentes tipos de ecossistemas dentro dos domínios do Cerrado brasileiro. Os artigos coletados foram das bases de dados Web of Science, Periódicos CAPES e Google escolar. Foram encontrados 15 artigos (que incluem 22 ensaios) presentes em sua maioria na região Centro-oeste do Brasil. A média e a mediana da capacidade de infiltração de todos os estudos foram 792 e 567 mm h⁻¹, respectivamente. A maioria dos estudos (12 estudos) não define claramente qual o tipo de ecossistema foi avaliado. Além disso, a maioria dos estudos foram realizados em Latossolos. Em geral, os estudos tiveram um número amostral baixo para caracterizar as propriedades do solo. Diante disso, uma melhor descrição do tipo de ecossistema avaliado, bem como um número amostral mais significativo são necessários para compreender a infiltração de água nos ecossistemas naturais do Cerrado brasileiro. Em razão das limitações dos estudos encontrados, essa revisão mostrou que ainda é cedo para sintetizar e aprofundar a discussão deste tema em um bioma tão grande e heterogêneo.

Palavras-chave: fitofisionomia, solo, vegetação nativa.

Introduction

Savannas occur where trees and grasses interact to create an ecosystem that is neither

grassland nor forests (Scholes and Archer, 1997). Tropical savannas are widely distributed in South

America, Africa, Asia, and Australia (Pennington et al., 2018). A great emphasis has been given to biological conservation studies in these savannas (Furley, 2006; Pennington et al., 2018). Nevertheless, the hydrological processes of these types of ecosystems are still poorly understood (Oliveira et al., 2015; Strydom et al., 2019). This type of knowledge is highly needed for conserving and safeguarding savanna biomes and their related aquatic ecosystems (Latrubesse et al., 2019). That is the case of the Brazilian Tropical Savanna regionally known as “Cerrado”. Knowledge of hydrological processes such as stemflow (Honda and Durigan, 2017), evapotranspiration (Cabral et al., 2015; Oliveira et al., 2015), groundwater recharge (Oliveira et al., 2017; Santos and Koide, 2016) is still emerging. However, many processes such as infiltration, percolation, runoff generation, interception still deserve attention. This is especially important for Brazil since headwaters of important Brazilian rivers such as the Tocantins-Araguaia, São Francisco, and Paraná are within the Cerrado domains (Lima and Silva, 2005) running towards others biomes such as the Amazon (Tocantins-Araguaia river) and Atlantic Forest (Paraná river). Furthermore, Cerrado is also relevant for groundwater recharge of important groundwater systems such as the Guarani aquifer. One half of the outcrop area of Guarani aquifer is within the Cerrado biome (Oliveira et al., 2017). As one might notice, the Cerrado has strategic importance with regards to water resources in Brazil (Lima, 2011; Latrubesse et al., 2019).

Given the hydrological importance of the Cerrado, understanding the hydrological processes intrinsically linked to groundwater-river recharge, such as soil water infiltration, is crucial. Water that infiltrates into the soil recharges both soil and groundwater. The latter sustains the baseflow, which is a critical source of water during the dry season where savannas occur. Moreover, low infiltration leads to surface runoff which, in turn, might lead to peak flows during the wet season and erosion (Cecílio et al., 2003; Bruijnzeel, 2004; Lipiec et al., 2006; De Moraes et al., 2012; Scopel et al., 2013) with consequences for the provision of adequate water in terms of quality and quantity. The latter is critical during the dry season since the reduction in infiltration opportunities leads to the diminishment of recharge during the wet season turning dry season flow lower (Bruijnzeel, 2004).

Though the Brazilian Tropical Savanna, as its name suggests, is dominated by savannas, Cerrado has a diversity of ecosystem types ranging from grasslands (Campo limpo and Campo sujo),

to savannas (*e.g.* Cerrado denso, Cerrado típico, Cerrado ralo, Palmeiral, Veredas, Parque de Cerrado) and forests (*e.g.* Cerradão, Mata seca – seasonally dry forest and Mata de galeria – riparian forests) coexisting, in many cases, side-by-side in a complex mosaic (Eiten, 1972; Ribeiro and Walter, 2008; Ball et al., 2015). Thus, considering the diversity of ecosystem types, Cerrado might be broadly referred as a biome where savannas dominate but are not the single type of ecosystem. This diversity of ecosystem/vegetation types is also related to a high biological diversity (Eiten, 1972; Myers et al., 2000; Ribeiro and Walter, 2008) and possibly to a variety of hydrological processes occurring at different rates in adjacent ecosystems (Oliveira et al., 2017).

As mentioned earlier, many studies dealt with hydrological processes within the Cerrado (Silva and Kato, 1998; Oliveira et al., 2014; Honda et al., 2015; Oliveira et al., 2015; Santos and Koide, 2016). Nonetheless, few of them focused on the infiltration process, which, as shown, is crucial for water resource management. For instance, when reviewing this subject, Hunke et al. (2015a) found only four infiltration studies carried out in Cerrado ecosystems, which are the main providers of ecosystem services related to water provision.

In this context, given the importance of the infiltration process to the functioning of ecosystems and catchments and the high diversity of the ecosystems within the Cerrado biome, the objective of this paper was to carry out a review on soil water infiltration in the various ecosystem types within the Brazilian Tropical Savanna.

Methods

Data collection

We conducted the research in May 2018. We collected data on soil infiltration capacity of phytophysiognomies within the domains of the Brazilian Tropical Savanna (“Cerrado biome”) from peer-reviewed papers published in Web of Science (research in core collection), Periódicos CAPES (research in advanced search) and Scholar Google. The timespan assessed in Web of Science, Periódicos CAPES and Scholar Google were, respectively, 1945-2017, 1997-2017 and no specific period. The key terms used for the research were “infiltration” AND “Cerrado” (Web of Science), “infiltração” AND “Cerrado” (Periódicos CAPES) and “infiltração no Cerrado” (Scholar Google). It was necessary to also use the key terms in Portuguese and to conduct the research in the Periódicos CAPES database because we expected

that most articles studying infiltration in the Cerrado biome would have been published in that language. In order to expand the search, we also explored the reference lists of the retrieved articles.

We selected the articles by its title and abstract. If necessary, we would read the entire article to confirm it had the essential information for this research (mean infiltration capacity in a phytophysiognomy of the Cerrado biome). We included the articles only if they met the following eligibility criteria: (i) presented the number of samples collected and (ii) central tendency measures of the results (mean of infiltration capacity). Once selected, information on soil type, ecosystem type (phytophysiognomy), infiltration method, number of samples, and location were extracted from each article.

We found 17 articles on the Web of Science database. Four out of 17 followed the eligibility criteria. With regards to Periódicos CAPES, our research resulted in 130 files: 127 articles and three textbooks. Finally, out of the 127 articles found on the Periódicos CAPES database, only eight followed the eligibility criteria. We also found six articles that followed the eligibility criteria on the Scholar Google database. Duplicates were excluded. After all, we found 15 articles.

Statistical analysis

We used descriptive statistics to synthesize the results. For this, central tendency, as well as variability measures, were obtained using Paleontological Statistic – PAST (Hammer et al., 2001) version 3.18.

Results

The research resulted in 15 articles (Souza and Alves, 2003; Alves et al., 2005; Alves et al.,

2007; Araújo et al., 2007; Gaspar et al., 2007; Rodrigues et al., 2007; Fontenele et al., 2009; Gomes Filho et al., 2011; Bono et al., 2012; De Castro et al., 2012; Vilarinho et al., 2013; Silva et al., 2014; Batista and Sousa, 2015; Hunke et al., 2015b; Cabral Filho et al., 2017) with 22 experiments (Table 1). The studies were widely distributed in the Brazilian territory (Figure 1A). The midwest region was the one with the highest number of studies (13 articles) (Figure 1B).

The mean (\pm standard deviation) and median of the infiltration capacity, including all phytophysiognomies, were, respectively, 752 (\pm 639.5) and 567 mm h⁻¹. There was a substantial variation within the observations (Figure 2). For instance, the infiltration capacity in the Cerrado sensu stricto ranged from 432 to 2040 mm h⁻¹ under the same soil type (Table 1). Grasslands (n = 2) had mean (\pm standard deviation) of 823 (\pm 923) mm h⁻¹ whereas savannas (n = 18) and forests (n = 2) had, respectively, 867 (\pm 730) and 497 (\pm 552) mm h⁻¹.

As for soil types, most of the experiments were carried out in phytophysiognomies under Oxisols (Latossolos - 82%). However, Ultisols-plintaquults (Plintossolos - 9%) and Entisols-quartzpsammements (Neossolo Quartzarênico-9%) were also present.

Regarding the methods used, the double ring infiltrometer was the most used (14 articles), while the single ring infiltrometer was used only once. The sample size used had a wide variation (from 1 to 17 samples), but it was low in most of the studies (Table 1). On average, studies used three samples.

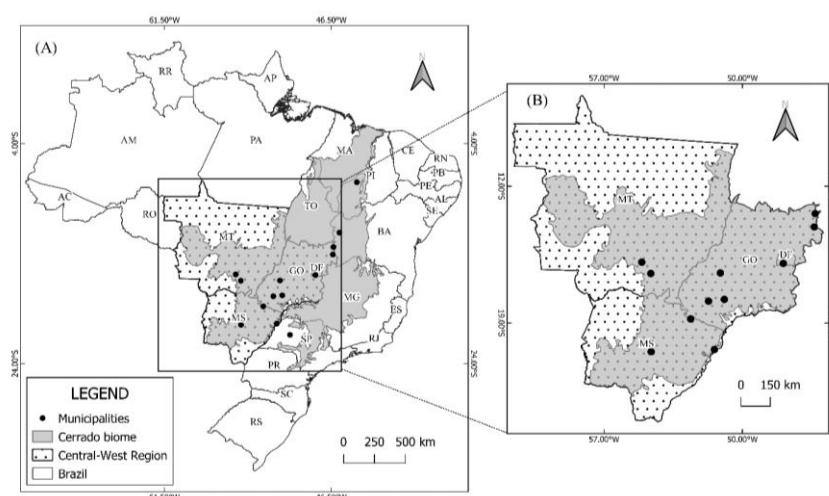


Figure 1. Municipalities of the sampling sites of water infiltration in the Cerrado biome.

Table 1. Studies of water infiltration in the Cerrado biome.

AUTHORS	MUNICIPALITY / STATE	ECOSYSTEM TYPE*	SOIL	METHOD	SAMPLE SIZE	INFILTRATION CAPACITY (mm h ⁻¹)
Souza and Alves (2003)	Selvíria / Mato Grosso do Sul	Cerrado (S)	Latossolo Vermelho Distrófico	Double ring	10	330
Alves et al. (2005)	Glicério / São Paulo	Cerrado (S)	Latossolo Vermelho Amarelo distrófico	Double ring	1	1165
Alves et al. (2007)	Selvíria / Mato Grosso do Sul	Cerrado (S)	Latossolo Vermelho distrófico	Double ring	5	300
Araújo et al. (2007)	Brasília / Distrito Federal	Cerrado <i>stricto sensu</i> (S)	Latossolo Vermelho Amarelo distrófico	Double ring	3	2040
Gaspar et al. (2007)	Posse / Goiás; São Domingos / Goiás; Luís Eduardo Magalhães / Bahia	Cerrado ralo (S)	Latossolo Vermelho Amarelo	Double ring	4	702
		Cerrado (S)	Latossolo Vermelho Amarelo	Double ring	5	1009.4
		Cerrado (S)	Neossolo Quartzarênico	Double ring	1	2556
		Vereda (S)	Neossolo Quartzarênico	Double ring	1	396
		Cerrado <i>stricto sensu</i> (S)	Latossolo Vermelho Amarelo	Double ring	1	432
		Campo limpo (G)	Latossolo Vermelho Amarelo	Double ring	1	1476
		Cerrado (S)	Latossolo Vermelho Amarelo	Double ring	1	1620
Rodrigues et al. (2007)	Selvíria / Mato Grosso do Sul	Cerrado (S)	Latossolo Vermelho	Double ring	3	600
Fontenele et al. (2009)	Uruçuí / Piauí	Cerrado nativo (S)	Latossolo Amarelo Distrófico	Double ring	3	356
Gomes Filho et al. (2011)	Jataí / Goiás	Cerrado <i>stricto sensu</i> (S)	Plintossolo Háplico	Double ring	1	242
		Campo limpo (G)	Plintossolo Háplico	Double ring	1	170
Bono et al. (2012)	Campo Grande / Mato Grosso do Sul	Cerradão (F)	Latossolo Vermelho Distrófico	Double ring	4	888.3
De Castro et al. (2012)	Chapadão do Sul / Mato Grosso do Sul	Mata seca (F)	Latossolo Vermelho Distrófico Típico	Double ring	5	106.8
Vilarinho et al. (2013)	Rondonópolis / Mato Grosso	Cerrado nativo (S)	Latossolo Vermelho Distrófico	Double ring	1	360
Silva et al. (2014)	Rio Verde / Goiás	Cerrado (S)	Latossolo Vermelho distroférico	Double ring	4	568.9
Batista and Sousa (2015)	Iporá / Goiás	Cerrado caducifólio (S)	Latossolo Bruno Escuro	Double ring	1	565.2
Hunke et al. (2015b)	Jaciara / Mato Grosso	Cerrado (S)	Latossolo Vermelho Escuro Distrófico	Single ring	17	1047
Cabral Filho et al. (2017)	Rio Verde / Goiás	Cerrado (S)	Latossolo Vermelho distroférico	Double ring	1	504.3

*Ecosystem type described: S = Savanic, G = Grassland, F = Forest.

As for phytophysiognomies, the majority of studies did not define the type of phytophysiognomy properly. We found an unstandardized pattern of terms including "Cerrado nativo", "Cerrado caducifólio" and "Cerrado -

floresta tropical subcaducifólia". Such terms were assumed to be a savanna, generally described as Cerrado (see Figure 3), given they had no clear system of classification, such as those by Coutinho (1978) or Ribeiro and Walter (2008).

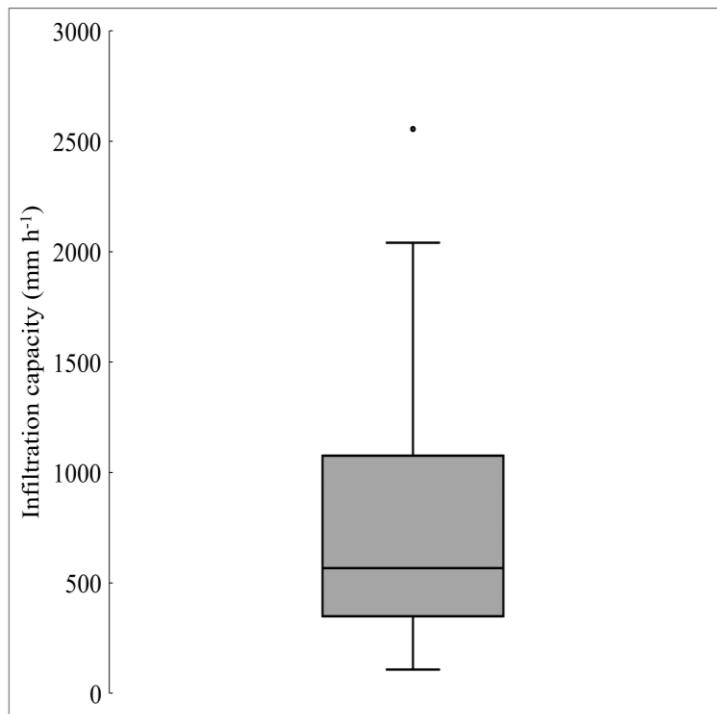


Figure 2. Boxplot of the infiltration capacity studies in the Cerrado biome. The horizontal lines inside the boxes indicate the medians (Q2), the lower horizontal lines of the boxes indicate the first quartile (Q1), and the upper horizontal lines of the boxes the third quartile (Q3). The horizontal lines on the bottom are minimum values, and the horizontal lines on the top are maximum values.

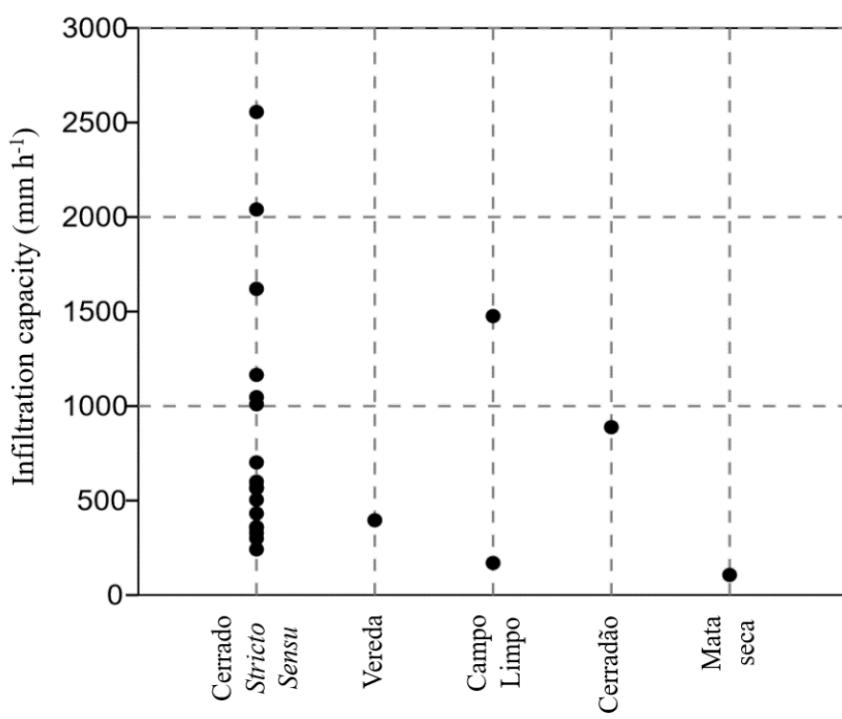


Figure 3. Infiltration capacity per ecosystem type of the Cerrado biome (each point represents the mean of infiltration capacity in the assays).

Discussion

Hunke et al. (2015a) found four studies dealing with infiltration in ecosystems of the Cerrado biome. In the present paper, we add 11 articles. Most of these papers were within the Brazilian scientific literature (in Portuguese), which were not broadly available. Assuming a direct comparison of different methods is possible, mean values for Brazilian savannas (*Cerrado sensu stricto*) were generally one order of magnitude higher than those recently reported for granitic derived soils in an African savanna (Strydom et al., 2019). Forest ecosystems were one order of magnitude lower than a forest in the Amazon (1200 mm h⁻¹; Neil et al. (2013)) but at the same magnitude than those reported for the Atlantic Forest (200 mm h⁻¹; Lozano-Baez et al. (2019)). Grasslands within the Cerrado, in turn, had infiltration capacity one order of magnitude higher compared to natural grasslands in China (20 mm h⁻¹; Zhang et al. (2013)).

Most of the studies found here were concentrated in the midwest region of Brazil on Oxisols. Approximately 50% of the Cerrado biome is estimated to be on Oxisols, which are the dominant soils (Hunke et al., 2015a) and they have been used for large-scale agricultural activity due to its suitability to agriculture since they are present in low relief areas (flatlands) and are deep, well drained soils (Farias and Zamberlan, 2014). In such pedological and geomorphological setting, many studies were carried out to assess the effect of land-use change on soil physical-hydraulic properties such as soil bulk density, aggregate stability (Hunke et al., 2015). Although Oxisols are the dominant soils, other ten soil types have been found within the Cerrado region (Reatto and Martins, 2005). Thus, there is a need to understand infiltration capacity and other soil hydraulic properties in soils such as Inceptisols and Ultisols, which are usually present in more dissected landscapes. These other soil types might be the ones remaining with preserved Cerrado vegetation if the current agricultural expansion remains unaltered.

Regarding methods, the most used method was the double ring (14 out of 15 studies). On the one hand, the use of the same method would, at first, lead us to directly compare the results found in different papers. On the other hand, this method has shortcomings. First, it generally requires a long time to achieve infiltration stability. For example, Bono et al. (2012) reported that it took six hours to reach steady infiltration rates in one single measurement. Second, a long time, along with the

high amount of water required for each measurement, might have led to the generally low sample size used, which, in turn, makes comparison among studies, even under the same method and soil type, cautious. It is generally necessary to use a high sampling effort ($n > 15$) to represent soil hydraulic properties (Hassler et al., 2014), given its high spatial variability (Bonell et al., 2010). Thus, given the low number of samples used in many articles, infiltration capacity has been probably under/overestimated. The only studies that reached a reasonable amount of samples ($n \geq 10$) were those by Souza and Alves (2003) and Hunke et al. (2015b). Based on these two studies, soil infiltration capacity is generally high for Brazilian savannas (ranging from 300 to 1000 mm h⁻¹).

Our study detected a need to characterize and define properly the ecosystem in focus. The lack of uniformity in describing the variety of ecosystems in this biome has been in place for a long time (Eiten, 1972; Coutinho, 1978; Ribeiro and Walter, 2008). Most of the studies shown here had an agronomic focus, using the Cerrado ecosystems solely as a control. This fact justifies the lack of care in describing the Cerrado ecosystems with a high degree of precision. Given the aforementioned hydrological importance of the Cerrado and the high pressure under which they are subject (Strassburg et al., 2017), we advocate the need to carry out studies providing the Cerrado ecosystems a primary role instead of secondary as was the case of most of the agronomic studies shown here. In this sense, in order to understand the ecosystems' diversity in terms of hydrological processes, it is important to clearly describe the ecosystem in focus. For instance, the generic description "Cerrado" used in many papers led us to assume the authors were dealing with savannas. However, such term refers to a general classification of the Cerrado *sensu stricto*, which, according to Ribeiro and Walter (2008), has four possible sub-classifications as follows: (i) Cerrado ralo, (ii) Cerrado denso, (iii) Cerrado típico and (iv) Cerrado rupestre. Such assumption was based on the fact that Cerrado *sensu stricto* usually occurs in Oxisols (*Latossolos*) (Eiten, 1972), such as the ones cited in many articles. Nevertheless, there is a substantial variation in the density of woody components from Cerrado ralo (a savanna with a low density of woody species) to Cerrado denso (a savanna with a high density of woody species), both ecosystems included under the term "Cerrado *sensu stricto*". Thus, it is clear that a higher precision is required in describing the ecosystems

studied provided that the vegetation type may influence the soil water infiltration (Silva and Kato, 1998; Brandão, 2006; Mendonça et al. 2009; Brady and Weil, 2013; Almeida et al. 2018).

Conclusion

So, what do we really know about water infiltration in the ecosystems within the Brazilian Tropical Savanna? Given the limitations of the studies available, our review showed that it is still too early to synthesize and to make an in-depth discussion on such a topic in such huge biome. In other words, the available data still preclude broad generalization regarding the infiltration capacity of the different types of ecosystems. Nonetheless, it did show a gap for more experimental research in such threatened biome, mainly in ecosystems (Ribeiro and Walter, 2008) such as riparian forests, Cerrado denso, Parque de cerrado, Palmeiral, Cerrado rupestre, Campo rupestre, Campo sujo, among others, in order to understand the hydrological processes such as infiltration in such diversity of ecosystems. This might be a fertile topic for collaboration between plant ecologists and hydrologists.

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