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RESEARCH ARTICLE

Groundwater recharge decrease with increased vegetation density in the Brazilian cerrado

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Abstract
Large areas of the Brazilian savanna (cerrado) have been converted into farmland in recent years; however, little attention has been paid to the consequences of this land use and land cover change on groundwater recharge. Here, we assessed groundwater recharge in different physiognomies of the cerrado located in an outcrop area of the Guarani Aquifer System. Water table fluctuations were measured from October 2011 through August 2013, by 58 monitoring wells distributed on four physiognomies of the undisturbed cerrado. We used multiple monitoring wells located in "campo limpo" (cerrado grassland), "campo sujo" (shrub cerrado), "campo cerrado" (open wooded cerrado), and "cerrado *sensu stricto*" (wooded cerrado), cover types. Recharge rates were computed for each well using the water table fluctuation method. The measured precipitation for hydrological years 2011–2012 and 2012–2013 were 1247 and 1194 mm, respectively. We found values of average annual recharge of 363 ± 87 mm, 354 ± 85 mm, 324 ± 78 mm, and 315 ± 76 mm for "campo limpo," "campo sujo," "campo cerrado," and "cerrado *sensu stricto*," respectively. Our results suggest that recharge tends to decrease with the increase in the density of vegetation (grassland to woodland). These results indicate that water table depth may have an influence on the cerrado physiognomies or vice versa. Furthermore, replacement of undisturbed dense cerrado with croplands will likely alter recharge dynamics. Therefore, sound management of land use and land cover is needed to ensure future groundwater quantity and quality.

KEYWORDS
deforestation, forest hydrology, infiltration, savanna, vadose zone

1 | INTRODUCTION

In the last 2 years, several cities of southeastern Brazil have grappled with their worst drought in nearly 80 years (Escobar, 2015). Water reservoirs in the states of São Paulo, Rio de Janeiro, Minas Gerais, and Espirito Santo reached unprecedented low levels. In January 2015, the Cantareira reservoir, which normally supplies water to about 9 million residents in the Metropolitan Region of São Paulo, bottomed out at 5% of storage capacity (The Guardian, 2015). The water crisis in this region has affected water availability for public water supply, hydropower generation, industrial activities, and agriculture. The southeastern region is responsible for 55% of Brazil's gross domestic product, and therefore, water scarcity has generated serious concerns about the economy and has led the general population and state and federal governments to think about and discuss water as never before.

To improve water availability in southeastern Brazil, the state and federal governments have studied the possibility of increasing groundwater use, mainly in the Guarani Aquifer System (GAS), the largest (~1.2 million km^2) transnational boundary groundwater reservoir in South America (Lucas, Oliveira, Melo, & Wendland, 2015). The GAS in the Brazilian territory covers part of the states of Goiás, Mato Grosso do Sul, Minas Gerais, São Paulo, Paraná, Santa Catarina, and Rio Grande do Sul. However, approximately one half of the outcrop areas of the GAS are located in the cerrado biome, the main agricultural expansion region in Brazil (Oliveira et al., 2014). Large areas of undisturbed cerrado have been converted into farmland in recent years, and considering that Brazil holds a great potential for further agricultural expansion, it is expected that deforestation rates will not decrease in the near future (Gibbs et al., 2015; Lapola et al., 2014).

There is evidence that the Brazilian cerrado deforestation has the potential to change several components of hydrological processes (Coe, Latrubesse, Ferreira, & Amsler, 2011; Loarie, Lobell, Asner, Mu, & Field, 2011; Oliveira et al., 2014, 2015a; Oliveira, Nearing, & Wendland, 2015b). However, few studies have been undertaken to investigate the hydrological processes at the field scale in the cerrado (Oliveira et al., 2015a, 2015b). Therefore, there is a scarce knowledge particularly about canopy interception, throughfall, stemflow, runoff, infiltration, percolation, subsurface flow, and groundwater recharge in the cerrado (Oliveira et al., 2015a). In addition, little attention has been paid to the consequences of land use and land cover changes on groundwater recharge.

Interactions between groundwater and vegetation have drawn attention recently, mainly because of the impact of intense groundwater extraction on ecosystems (Scanlon, Reedy, Stonestrom, Prudic, & Dennehy, 2005; Zektser, Loáiciga, & Wolf, 2005) and increasing interest in the preservation and restoration of riparian zones and wetlands (Stromberg, Tiller, & Richter, 1996; Goodwin, Hawkins, & Kershner, 1997; Scott et al., 2014). Furthermore, hypotheses have been proposed suggesting that groundwater levels may determine vegetation density and diversity (Orellana, Verma, Loheide, & Daly, 2012). This issue has been recently discussed in the literature for the cerrado vegetation (Rossatto, de Carvalho Ramos Silva, Villalobos-Vega, Sternberg, & Franco, 2012; Villalobos-Vega et al., 2014); however, no consensus has yet emerged regarding the influence of water table levels on the characteristics of the undisturbed cerrado vegetation (Staver, Archibald, & Levin, 2011; Hoffmann et al., 2012; Silva, 2015).

The objective of this study was to assess groundwater recharge in different physiognomies of the Brazilian cerrado located in an outcrop area of the GAS. We also investigated how recharge rates can change with the density of vegetation and the possible consequences of the cerrado deforestation on groundwater recharge.

2 | DATA AND METHODS

2.1 | Study area

We conducted this study at the Itirapina Ecological Station (IES), a protected cerrado area of 2300 ha located in the municipality of Itirapina, São Paulo State (latitude 22°12′S, longitude 47°54′W, elevation: 750 m). This area has been preserved, and there are no records or indications of past fires over 20 years. According to the Köppen climate classification system, the climate in this area is Cwa humid subtropical, with a dry winter (April through September) and hot and rainy summer (October through March). The average annual precipitation is approximately 1500 mm. The study region is located in an outcrop area of the GAS, which is composed of eolian sandstones of the Jurassic (Botucatu formation) and fluvio-eolian sandstones of Triassic periods (Pirambóia formation) (Lucas & Wendland, 2015). The IES site presents flat areas (average slope steepness of 3%) with small variation in the elevation, as shown in Figure 1. The soil is classified in the Brazilian Soil Classification System (SiBCS) as Ortic Quartzarenic Neosol (RQo) with sandy texture in the entire profile (less than 15% clay). In this region, the topography and soil characteristics provide relatively small amounts of runoff and a rapid infiltration of water into the soil (Oliveira et al., 2015a, 2015b).

The cerrado is bordered by four of the five Brazilian biomes and has high biodiversity and a large variety of vegetation physiognomies and compositions (Oliveira et al., 2014). Usually, the physiognomies of the cerrado are divided into five classes that vary from open shrubby grassland to savanna to forest (Coutinho, 1978). We carried out this study on four physiognomies of the cerrado, which are described in Table 1. To obtain the basal area (area occupied by the cross-section of tree's trunk at breast height), all woody individuals with diameter at breast height ≥2.86 cm were measured in an area of 600 m^2 for each physiognomy, following Ferreira, Bustamante, Garcia-Montiel, Caylor, and Davidson (2007). Values of basal area and Shannon diversity index for each studied physiognomy are presented in Table 2. In general, the basal area and diversity index increase from "campo limpo" to "cerrado *sensu stricto*."

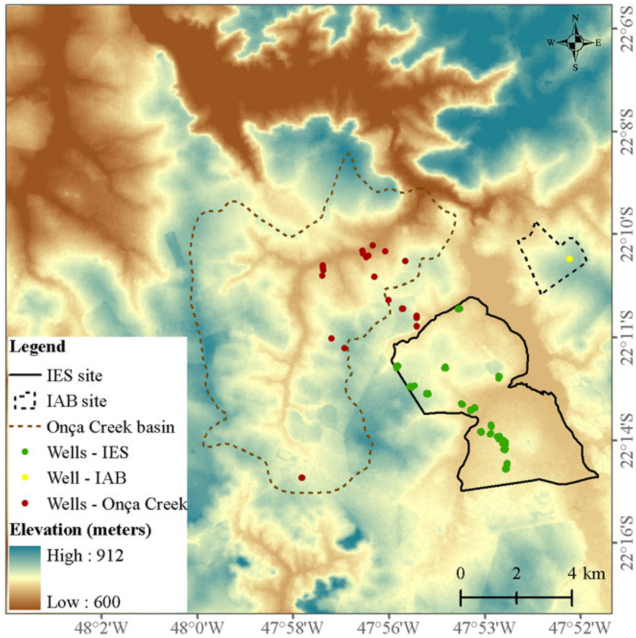

FIGURE 1 Location of study areas

An automated tipping bucket rain gauge (model TB4) was used to measure rainfall depth on a 10-min interval. This rain gauge was located at the Instituto Arruda Botelho (IAB) site in an open area approximately 4 km away from the IES site (Figure 1). We also used water table level data from a monitoring well ("cerrado *sensu stricto*" physiognomy) located at the IAB site (Oliveira et al., 2015a). Values of specific yield were obtained from previous studies developed at the Onça Creek basin, which has similar hydrogeological characteristics to that found at the IES site (Lucas & Wendland, 2015; Wendland, Gomes, & Troeger, 2015; Figure 1).

2.2 | Monitoring wells

We drilled 57 monitoring wells up to 7 m in depth using an auger at the IES site during the dry season peak (August) of 2011. Water table fluctuations (WTFs) were measured every 15 days using a water level recorder (Solinst, model 102) during October 2011 through September 2013. Table 3 shows the total and depth ranges of monitoring wells drilled in each of the cerrado physiognomies.

TABLE 1 Summary of characteristics of the cerrado physiognomies studied

Brazilian names	International names	Arboreous cover (%)	Height of trees (m)
"campo limpo"	Cerrado grassland	<1	<1
"campo sujo"	Shrub cerrado	<5	<2
"campo cerrado"	Open wooded cerrado	5–20	2–3
"cerrado *sensu stricto*"	Wooded cerrado	20–50	3–6
"cerrado *sensu stricto*" dense[a]	Cerrado woodland	50–70	5–8

Source: Furley, 1999; Ferreira and Huete, 2004.

[a]Physiognomy located at the IAB site.

TABLE 2 Basal area and Shannon diversity index for each physiognomy studied

Physiognomies	Basal area (m^2 ha^{-1})	Shannon diversity index
"campo sujo"	1.12–2.10	1.67–2.06
"campo cerrado"	4.58–7.73	1.69–2.75
"cerrado *sensu stricto*"	11.40–22.50	2.43–3.00
"cerrado *sensu stricto*" dense[a]	27.75	4.03

[a]Physiognomy located at the IAB site. We did not find woody individuals with diameter at breast height ≥2.86 cm in the "campo limpo" physiognomy.

2.3 | Computing groundwater recharge

The WTF method was used to compute groundwater recharge using the bi-weekly measurements of the water table elevation in each monitoring well from October 2011 through September 2013. The WTF method provides an estimate of groundwater recharge considering an analysis of water level fluctuations in a well (Healy & Cook, 2002). This method is based on the assumption that a rise in water table elevation observed in unconfined aquifers is caused by the arrival of recharge water at the water table (Scanlon, Healy, & Cook, 2002):

$$R = Sy\frac{\Delta h}{\Delta t} \quad (1)$$

where R is the groundwater recharge ($L\ T^{-1}$), Sy is specific yield (dimensionless), h is water table height (L), and t is time (T). Δh corresponds to the difference between the peak of the rise and the lowest point of the extrapolated antecedent recession curve at the time of the peak. The extrapolated antecedent recession curve is the hydrographic trajectory that the water level at the monitoring well would have followed in the absence of any water level rise (Healy & Cook, 2002).

To determine suitable values of the specific yield in the Onça Creek basin, Wendland et al. (2015) collected several undisturbed soil samples at depths corresponding to the variation zone of the groundwater level and evaluated the samples in the laboratory. Values of Sy ranged from 8.5% through 15.9%. Considering that the IES site has similar hydrogeological characteristics (geology, and soil texture and structure) as the Onça Creek basin, we used a mean specific yield value of 12% (Wendland et al., 2015). As there are uncertainties in the recharge estimate by the WTF method, associated mainly with uncertainty in the Sy values (Coes, Spruill, & Thomasson, 2007), we applied an uncertainty factor of ±24% in recharge estimates according to results from a previous study conducted in the Onça Creek basin (Lucas et al., 2015).

2.4 | Statistical analyses

To evaluate the significance of the linear correlation between the recharge, basal area, and average water table level, we used the Student's t-test with a 95% confidence level. Furthermore, to assess if there were significant differences between the values of recharge for the cerrado physiognomies, we used one-way analysis of variance with a Tukey post hoc test at the 95% confidence level.

3 | RESULTS AND DISCUSSION

3.1 | Water table elevations

The measured precipitation for hydrological years 2011–2012 and 2012–2013 were 1247 and 1194 mm, respectively. These rainfall values were approximately 20% less than the historical mean of 1500 mm $year^{-1}$ (1973 to 2013 observed at the climatological station from the University of São Paulo, located approximately 3 km from the study area; Oliveira et al., 2015a). We found that the measured water table level for each monitoring well was dependent on the recent precipitation, and the water table response time tends to be lagged and dampened the thicker the vadose zone (Figure 2). For example, the

TABLE 3 Depth of wells for each of the cerrado physiognomies studied

Cerrado physiognomies	Number of wells	Minimum depth (m)	Maximum depth (m)	Average depth (m)	Standard deviation (m)
"campo limpo"	20	1.4	2.7	2.2	0.3
"campo sujo"	20	2.4	6.9	4.3	1.4
"cerrado cerrado"	10	2.3	7.0	4.7	1.9
"cerrado *sensu stricto*"	7	5.2	7.0	6.2	0.7
"cerrado *sensu stricto*" dense[a]	1	—	42.0	—	—

[a]Physiognomy located at the IAB site.

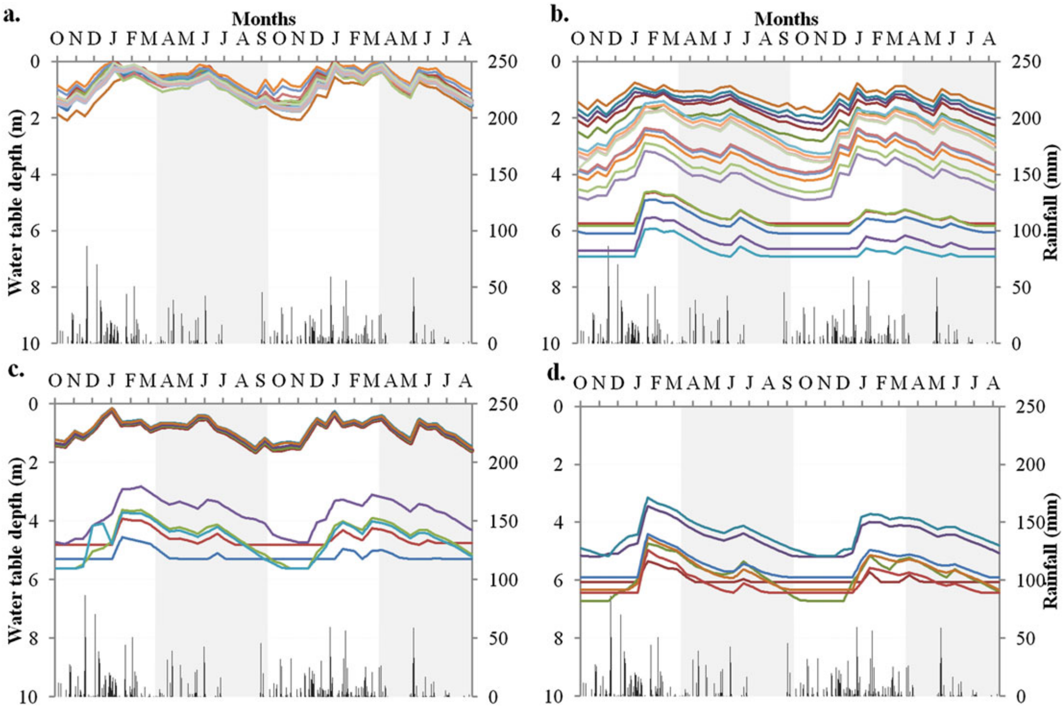

FIGURE 2 Measured water fluctuation in each monitoring well from October 2011 through August 2013 for (a) "campo limpo," (b) "campo sujo," (c) "campo cerrado," and (d) "cerrado *sensu stricto*." The gray-shaded bars show the dry seasons. These data are available in the Supporting Information

"campo limpo" has a smaller thickness of the vadose zone and density of vegetation than the "cerrado *sensu stricto*." Thus, the water table under "campo limpo" tends to change rapidly with the precipitation, whereas in "cerrado *sensu stricto*," the travel time of the water is longer and tends to show a delayed response time to elevate the water level after several days of a rain event (Figure 2a and d). This can also be observed in the other physiognomies where wider range of the water table level was found (Figure 2b and c). We noted periods of flatness in five wells in "campo sujo" (CS6, CS7, CS8, CS9, and CS10), two in "campo cerrado" (CC6 and CC7), and three in "cerrado *sensu stricto*" (CSS1, CSS5, and CSS7; Supporting Information). These may be related to the monitoring method (manual measurement every 15 days, which may thus miss measurements of declines or rises in water table) or that the aquifer was falling below the bottom of the well. This missed information may have generated an underestimate of recharge estimates in these wells. Therefore, in future studies, it will be necessary to drill deeper wells and use an automatic sensor for a daily monitoring of these wells.

We did not find a water table level response to precipitation events in the monitoring well located under the "cerrado *sensu stricto*" (IAB site, data not shown). The average water table level in this well was 35 m deep; therefore, it is likely that the recharge was either negligible or very diffuse (smoothed out and steady throughout the year) and not detectable as a discrete water level rise. We also found the same characteristic in five 7-m-deep wells located in "campo cerrado" and "cerrado *sensu stricto*" (Supporting Information). This may happen because the flux of water reaching groundwater table may be in balance to groundwater outflow (water recharge is equaled the outflow; Oliveira et al., 2015a). Also, these physiognomies have a high density of vegetation and consequently have more rainfall interception and root-water extraction to support transpiration process (Oliveira et al., 2014, 2015a). This could have resulted in less, or possibly even negligible, recharge.

We noted a significant ($p < .05$) correlation between average water table depth and tree basal area (Figure 3a) that may indicate an

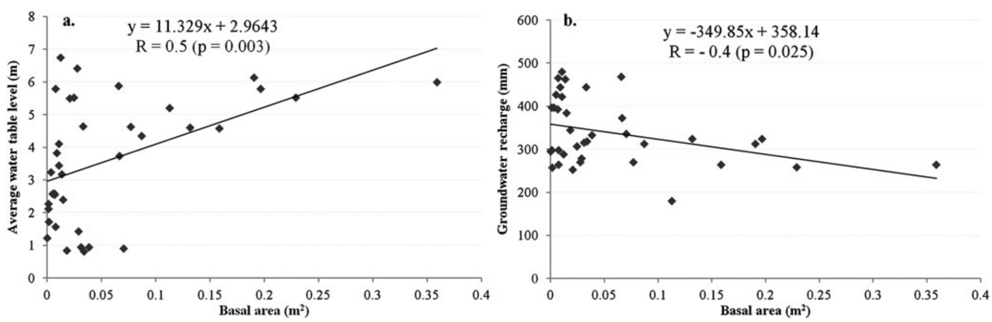

FIGURE 3 Correlations between (a) average water table level and basal area; and (b) groundwater recharge and basal area of the cerrado physiognomies studied

influence of groundwater depth on plants features. Villalobos-Vega et al. (2014) studied 10 monitoring wells with water table depths ranging from 0.18 to 15.56 m in an undisturbed cerrado and also found little WTFs in regions with deep water tables. They found that these regions tend to exhibit greater tree abundance and diversity than sites with shallow water tables. Therefore, our results collaborate with the author's statement that the water table depth may exert a strong influence on variations in tree density and diversity in the undisturbed cerrado. However, other environmental factors such as fire (Hoffmann et al., 2012; Staver et al., 2011) and soil nutrients (Silva et al., 2013) may also influence variation in cerrado physiognomies. A better understanding of these multiple environmental factors is needed to predict the future distributions of grassland, savanna, and forest biomes under changing climate, carbon dioxide (CO_2) concentrations, and disturbance regimes (Hansen et al., 2001; Baudena et al., 2015).

3.2 | Groundwater recharge

We found values of average annual recharge (% of the average annual precipitation) of 363 ± 87 mm (29.7% of P), 354 ± 85 mm (29.0% of P), 324 ± 78 mm (26.5% of P), and 315 ± 76 mm (25.8% of P) for "campo limpo," "campo sujo," "campo cerrado," and "cerrado *sensu stricto*," respectively (Figure 4 and Table 4). The differences in recharge rates among the cerrado physiognomies were relatively small, with average recharge values around 300 mm year^{-1}. The Tukey multiple comparison test indicated that the means of estimated recharge in each physiognomy for the entire time series (2011–2013) and to the first hydrological year (2011–2012) were not significantly different (p > .05). However, there was a significant difference (p = .02) between the recharge in "campo limpo" and "cerrado *sensu stricto*" in the second hydrological year (2012–2013). In addition, Table 3 shows an increase of vadose zone thickness from "campo limpo" through "cerrado *sensu stricto*," which followed the same trend as did the vegetation density (Tables 1 and 2). These results suggest that recharge tends to decrease with the increase in vadose zone thickness and vegetation density (grassland to woodland). Several authors have reported that land use and land cover have a strong influence on the groundwater recharge (Jobbágy & Jackson, 2004; Scanlon et al., 2005; Scott et al., 2014; Lucas et al., 2015); however, this is the first report regarding the influence of different cerrado physiognomies on recharge rates.

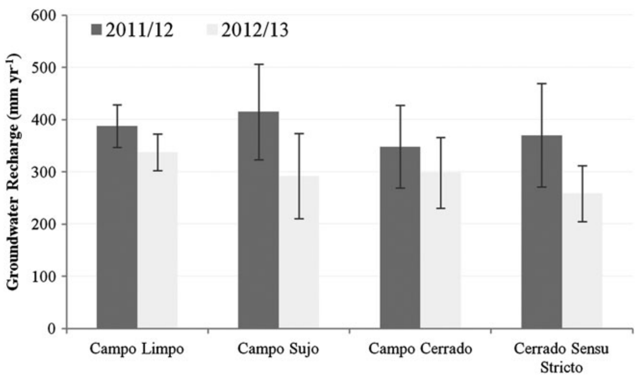

FIGURE 4 Average groundwater recharge (± error bars) for the cerrado physiognomies studied during the hydrological years of 2011/2012 and 2012/2013. Recharge rates did not significantly differ (p > .05) from each other in the entire time series (2011–2013) and in the first hydrological year (2011–2012), but the rates from "campo limpo" and "cerrado *sensu stricto*" did significantly differ (p = .02) in the second hydrological year (2012–2013)

Undisturbed cerrado areas tend to promote more infiltration than do areas in pasture and crops (Oliveira et al., 2015a, 2015b). However, the cerrado vegetation, mainly physiognomies of "cerrado *sensu stricto*" and "cerradão," has high values of the evapotranspiration (>800 mm year^{-1}), which result in smaller values of groundwater recharge than pasture and cropland (Oliveira et al., 2014, 2015a). For example, in the Onça Creek basin, Wendland, Barreto, and Gomes (2007) reported values of annual recharge (and water table depth) ranging from 145 to 703 mm year^{-1} (5–16 m) in pasture, 324 to 694 mm year^{-1} (9–22 m) in orange citrus, and 37 to 48 mm year^{-1} (21 m) in eucalyptus forests. In the same basin, Lucas and Wendland (2015) reported values of recharge in sugarcane of 248 ± 192 mm year^{-1}.

We found a significant (p < .05) inverse correlation between recharge and tree basal area, indicating that the groundwater recharge decreased with basal area increase (Figure 3b). Open cerrado physiognomies had significant groundwater recharge (nearly 30% of annual precipitation). However, dense cerrado such as "cerrado *sensu stricto*" tended to generate small recharge values. This behavior also occurs in areas forested by eucalyptus, where during the initial years after cultivation there are high values of recharge that tend to decrease significantly with increasing of tree size (Jobbágy & Jackson, 2004; Lucas & Wendland, 2015). We can expect, therefore, an increase in recharge with cropland expansion into dense cerrado areas. These findings also corroborate with Scanlon et al. (2005) who found no recharge in natural rangeland ecosystems, moderate-to-high recharge in irrigated agriculture (130–640 mm year^{-1}), and moderate recharge in non-irrigated

TABLE 4 Groundwater recharge values for the cerrado physiognomies studied

Cerrado physiognomies	Hydrological years	Average number of recharge events	Minimum (mm)	Maximum (mm)
"campo limpo"	2011/2012	6	314	480
	2012/2013	6	282	403
"campo sujo"	2011/2012	4	278	564
	2012/2013	3	156	408
"cerrado cerrado"	2011/2012	4	228	540
	2012/2013	4	132	360
"cerrado *sensu stricto*"	2011/2012	2	288	576
	2012/2013	2	192	360

agriculture (9–32 mm year^{-1}) in the southwestern United States. Moreover, an increase in surface runoff and soil erosion (Oliveira et al., 2015b) and a decrease in evapotranspiration (Loarie et al., 2011; Oliveira et al., 2014) are also expected with the conversion of the dense cerrado to croplands. In addition, the intensive use of agrochemicals in croplands may also bring a degradation of the water quality of runoff and groundwater recharge and thus compromise water availability in the future.

It is evident that land use and land cover change in different physiognomies of the undisturbed cerrado has the potential to modify the groundwater recharge dynamics. These impacts on recharge will depend on the extent of the change in cerrado physiognomies or cropland expansion areas. Furthermore, as the state and federal governments study the possibility of increasing groundwater use, mainly in the GAS, it is needed to understand that the groundwater withdrawal does not occur in the same period of time and volume as does groundwater recharge. Thus, the land use and land cover change will bring changes to the water dynamics that may appear gradually over time. A negative balance between recharge and discharge in an aquifer (groundwater overdraft) over the long run promotes aquifer depletion that can lead to reduction in discharge such as baseflow in rivers, generating water scarcity and riparian vegetation degradation (Stromberg et al., 1996; Scanlon, Longuevergne, & Long, 2012; Gorelick & Zheng, 2015).

Famiglietti (2014) showed a depletion in water storage during the last 10 years in several of the world's major aquifers in arid and semi-arid mid-latitude regions, including the GAS. The author warned that without sustainable groundwater use, global water security is at far greater risk than is currently recognized. Therefore, it is necessary to assess the land use and land cover change in order to create environmental zoning plans in this region that seek to conserve and preserve undisturbed cerrado areas and also to suggest appropriate and effective land use management practices for farmers (Oliveira, Alves Sobrinho, Rodrigues, & Panachuki, 2011). To ensure water quality and quantity for future generations, a robust comprehensive planning process must be developed and implemented, and in this study, we show findings that can contribute toward that aim.

4 | CONCLUSIONS

In this study, we assessed groundwater recharge in different physiognomies of the cerrado biome located in an outcrop area of the GAS. We measured WTFs from October 2011 through August 2013 in 58 monitoring wells distributed on four physiognomies of a protected area of the undisturbed cerrado. Recharge was computed for each well using the WTF method. This study represents one of the first steps toward filling the information gap on groundwater recharge in undisturbed cerrado, provides a better understanding of how recharge rates can change with the density of vegetation, and shows the possible consequences of cerrado deforestation on groundwater recharge dynamics.

The measurements for each monitoring well showed that the response time for altering the water table level tends to be a function of both the thickness of the vadose zone and the type of cerrado physiognomies. Physiognomies of less density of vegetation, such as "campo limpo," showed a rapid response time to elevation of the water level after precipitation events, whereas areas of denser vegetation ("cerrado *sensu stricto*") had a thicker vadose zone and a slower response time. These results indicated that water table depth may have an influence on the cerrado physiognomies or vice versa, that is, that the cerrado physiognomies have influenced the water table level.

We conclude that recharge tends to decrease with the increase in the density of vegetation (grassland to woodland). The physiognomies of the densest vegetation such as "cerrado *sensu stricto*" and "cerradão" tend to generate small recharge rates and may be negligible in sites with similar conditions to the IAB site. However, open cerrado physiognomies such as "campo limpo" and "campo sujo" promoted recharge rates greater than 350 mm year^{-1} (~30% of P), and therefore, this needs to be taken into account in hydrologic and climate models on regional and global spatial scales. Also, the recharge rates reported here represent the first ranges of values for undisturbed cerrado physiognomies and thereby can be useful for predicting the effects of future distributions of grassland, savanna, and forest biomes under changing climate. We stress that additional data, both from more wells and from longer data records, will be necessary to improve upon the reliability of these recharge estimates as well as being able to better discriminate whether these differences across different land covers are significant.

Land use and land cover changes in the cerrado have the potential to modify the groundwater recharge rates. Replacement of dense cerrado with cropland will likely increase groundwater recharge. On the other hand, replacement of open cerrado with forest trees such as eucalyptus may reduce recharge rates. Therefore, sound management of land use and land cover as well as an evaluation of alternative scenarios of groundwater use in this region is needed to ensure future groundwater quantity and quality. We provide here some findings that may be useful toward that target.

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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