To: Dr Martijn Westhoff
Associate Editor
HESS

From: Dr Jamil A. A. Anache
Corresponding author
EESC-USP

December 7th, 2018

Dear Dr. Westhoff,

Re: Manuscript reference HESS-2018-415

Please find attached a revised version of our manuscript entitled "**Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado**" by Jamil A. A. Anache, Lívia M. P. Rosalem, Edson Wendland, Cristian Youlton and Paulo T.S. Oliveira for publication in Hydrology and Earth System Sciences. We are also sending the items: changes marked, and response to reviewers' comments (revision notes).

Note that in "Revision Notes" the original editor and reviewer comments are in **bold** and author responses are in normal text throughout. Pages and lines indicated in the "Revision Notes" refer to the "Revised Manuscript". In "Changes Marked" we highlight the changes made in the text that were indicated in the comments from the editor and reviewers.

We would like to thank the editor and reviewers for their kind words in support of our manuscript and for their time spent reviewing our text. The manuscript has been revised in accordance to their comments, which were highly insightful and enabled us to improve the quality of our manuscript.

We hope that the revisions in the manuscript and our accompanying responses will now meet the requirements for publication in Hydrology and Earth System Sciences.

Thank you again for your consideration.

Yours sincerely,

Jamil A. A. Anache
Post-doctoral research fellow at the Computational Hydraulics Laboratory
São Carlos School of Engineering, University of São Paulo

Revision Notes

Editor's comments

ECC1: Dear Authors, you have received three reviews, which all provided clear feedback on how to improve the manuscript. Although all questions raised by the reviewers should be adressed, I consider two of them as rather important ones:

ECC2: Referee 1 correctly mentioned that dS/dt is a water residual (including storage, recharge and deep infiltration). I think it is important to make that clear from the beginning.

AR-ECC2: Thank you for this important remark concerning the dS/dt definition along the text. We agree that it is essential to make it clear that it represents the water balance residual, which includes soil water storage, deep infiltration and subsurface flow. Thus, we standardized all the dS/dt mentions, and we referred it as the water balance residual.

ECC3: Referee 2 mentioned the time lag between precipitation and GW recharge. Even if the hydraulic conductivity of the unsaturated soil is not 10^-3 but 10^-1, the travel time for a rain drop to reach the groundwater will still be in the order of 1 year. This means that the groundwater fluctuations are completely disconnected to what happens on the surface. The GW fluctuations also reflect a much larger area than the plot scale. So maybe, the GW fluctuations should be left out of the analysis completely. Instead the focus should be on the top soil (up to the rooting depth?).

AR-ECC3: Thank you for this remark. The idea of comparing the water balance results with the groundwater table fluctuations from wells located in wooded Cerrado and pasture land covers was to evaluate if the surface hydrological processes would reflect in the groundwater level. We inserted this approach because in our previous studies we have found the influence of land cover and land use (LCLU) in the water table fluctuations (Lucas and Wendland, 2015; Lucas et al., 2015; Oliveira et al., 2017; Leite et al., 2018) (page 11, line 8 – line 18). Furthermore, it is important to note that the unsaturated zone thickness and material, topography and aquifer hydraulic conductivity were similar in both wells, and their locations represent homogenous surface conditions, as they are not located in the edges of the LCLU that they represent. We added brief discussion in the chapter 3.2 to address the limitations of the assumptions regarding the groundwater table fluctuation in comparison with the water balance. We also removed Figure 4, as Figure 3F reflects the same phenomena with less evidence to it, as the effects of LCLU on groundwater level tend to be non-linear and difficult to analyze as they result from complex interactions between LCLU and hydrological processes (Han et al., 2017). Additionally, by removing completely the groundwater fluctuations from our manuscript, we may loss an interesting hypothesis for further investigations in this subject, and not mentioning the fact that the study site is located above the outcrop zone of a major aquifer in South America, the Guarani Aquifer System (GAS), thus, the groundwater plays an important role on the site contextualization.

It is also important to make clear that the wells show the groundwater table fluctuations in the respective areas (Cerrado and pasture covers) and not for a small plot as suggested by the Reviewer 2. We have inserted a brief sentence to make it clear to the readers. (page 11, line 26 – line 29).

ECC4: On top of these two comments, I have another comment about the error calculations: When calculating the water balance residuals, a lot of uncertainty lies in the evaporation estimates. The error is not only coming from random noise in the measurements, but also from the used formulation (e.g. Penmann-Monteith vs. Priestley-Taylor). Besides that, the fact that you come up with a lower error estimate for the Cerrado site, seems to arise from the fact that in PM more parameters are required, which all sum-up in the error calculation (Eq. 11) (unless you have a clear idea on the error in the Priestly and Taylor coefficient).

AR-ECC4: Thanks for pointing this out. We performed a new uncertainty assessment considering the Priestley-Taylor coefficient estimation errors and we found a standard error with similar order of magnitude of the PM method. This leaded to a more homogeneous and fair comparison between the different LCLU water balance outcomes. We updated Table 5 and Figure 4, which contains the results from the data uncertainty chapter.

ECC5: Please make also sure that units for all equations are correct (this is not the case for (at least) Eq. 3). Also be aware that multi-letter variables should be avoided (see the mathematical requirements at https://www.hydrology-and-earth-system-sciences.net/for_authors/manuscript_preparation.html). With kind regards, Martijn Westhoff.

AR-ECC5: We appreciate the advice and corrections concerning the mathematical requirements. We double-check all equations, units and variables through the text to ensure the compliance of the journal rules. In addition to the mathematical requirements, we made the datasets available in a data repository (HydroShare), following the journal recommendations (page 14, line 16 – line 18).

Reviewer 1 comments

We would like to thank the anonymous Referee 1 for the kind words in support of our manuscript and for the time spent reviewing our text. Here, we replied the referee's comments, which were highly insightful and enabled us to improve the quality of our manuscript. Note that the original referee's comments are identified as R1Cxx and written in **bold**, and the authors' responses are labeled as AR-R1Cxx. In addition, all comments are numbered (xx).

R1C1: The paper treat an important topic in the frame of LCLU for the Cerrado of Brazil. Until now only very few studies with experimental site data (see Oliveira, Nobrega) cover the Cerrado Biome in Brazil (most deals with Amazon rainforest). Problem statement is clear and well written.

AR-R1C1: Thank you for recognizing the importance of the topic described by our manuscript. We replied and solved, when possible, all the concerns and remarks found along the text to improve its comprehension and quality.

R1C2: In the space of row 3 – 10 an outlook on the process of further Cerrado conversion should be added and why sugarcane in the study area will be important in this process of LUC.

AR-R1C2: Thank you for the suggestions. We added the following paragraph on page 2 (line 11-line 16): "In the context of the Cerrado biome, the conversion of undisturbed vegetation and pasturelands to mechanized crop systems (e.g. sugarcane, corn and soybeans) indicates that this region in Brazil has a dynamic LCLU situation (Lapola et al., 2013). The sugarcane is the Brazilian backbone for energy security, as the ethanol production is the third most cultivated crop after soybeans and corn, reflecting the increasing demand for automotive fuels along the years (Leal et al., 2013; Rodrigues et al., 2018). Thus, the country is the world second largest ethanol producer and the Cerrado comprises the sugarcane expansion frontier due to the availability of water and pasturelands for the crop expansion (Bellezoni et al., 2018).."

R1C3: The aim of the study is well written (row 25-28). Experimental instrumentation is detailed described and adequate for the aim of longterm monitoring between the different land uses and Cerrado sensu stricto.

AR-R1C3: We appreciate your comment.

R1C4: In 2.2 following should be added for understanding the calculations later: Page 3: Time interval of soil water measurements (daily?) As basic information were ksat measurements done to understand the importance of infiltration to the groundwater of the Entisols?

AR-R1C4: The soil moisture was measured every 10 minutes; however, we used daily averages, as our temporal resolution in the present study was daily. We added the following sentence on page 3 (line 17

– line 18): “All instruments recorded data every 10 minutes, except the pressure transducers, which logged the groundwater table twice a day.” We have ksat information of the study area, added on section 2.1 (page 3, line 9 – line 10): 102.279 mm h-1 (20 cm depth); 11.302 mm h-1 (50 cm depth); and 19.813 mm h-1 (100 cm depth). We added this information in the revised version of the manuscript.

R1C5: Page 4 row 3: it seems better to define surface runoff as Qsur or Of (overland flow) instead of Q, because in most hydrological studies Q is defined as total discharge (see hydrological terms).

AR-R1C5: Thank you for the suggestion. We changed the abbreviation for surface runoff along the text, figures and tables to O_F (overland flow).

R1C6: Evapotranspiration was calculated in the standard form on the base of Penman-Monteith (ETo). Water stress coefficient was calculated on a daily base (implied soil water measurements daily ? see above).

AR-R1C6: Yes, the water stress coefficient (K_S) was calculated using the daily soil moisture from the FDR probes. We clarify the instruments measurement interval previously (AR-R1C4). It is also mentioned on page 5, line 11 that the K_S was calculated at a daily basis.

R1C7: Include in table 3 and text page 5, row 25-28: what was assumed for the rooting zone of the Cerrado plot? Zf

AR-R1C7: The method that was used to calculate the evapotranspiration for the Wooded Cerrado did not used the rooting zone depth as an input parameter as shown in Eq. 7. However, we added the wooded Cerrado rooting zone depth in section 2.2 (page 4, line 8 – line 11), when we give more details about the land covers investigated in this study: “The soil root zone in the wooded Cerrado may reach up to 18 m (Rawitscher, 1948). However, most of the water used for plants’ transpiration comes from the first layers (up to 7.5 m) (Canadell et al., 1996; Oliveira et al., 2005; Garcia-Montiel et al., 2008).”

R1C8: Statistical data analysis was done well with good uncertainties estimations.

AR-R1C8: We appreciate this comment.

R1C9: Chapter 3. With the tables and figures the results are consistent documented and described. Discuss more on page 8, row 20-25: why in table 5 results for Eta differed (because of different sites with different rainfall amounts, because of different methods e.g. Nobrega.

AR-R1C9: This is an important remark. We appreciated the recognition of our Tables and Figures consistency. We noted significant different values among the listed studies due to the multiple locations and methods considered. Our main idea was to evidence this huge variability among the reference studies. Thus, we added an extra piece of discussion on page 9 (line 7 – line 8) to clarify the main reason for these differences and change the paragraph structure. “(…) (Table 4) due to the diverse rainfall patterns among the study sites and the different methods used to measure or estimate the evapotranspiration."

R1C10: Page 8 row 30 following: discuss more the uncertainty of Cerrado vegetation rooting zone for the evapotranspiration calculation (depth of rooting zone you used is very sensitive for the residual in the water balance.

AR-R1C10: Thank you for this important remark. Actually, the methods used for the evapotranspiration estimates in the wooded Cerrado did not use the root depth as input parameter (see Equation 7). However, we recognize that it is important to discuss about the root zone depth in this paragraph. Thus, we added a brief discussion stating about the root zone uncertainty in the Cerrado (page 9, line 18 – line 21). "However, the root zone depth of an undisturbed vegetation such as the wooded Cerrado is uncertain and may vary according to the soil characteristics (Canadell et al., 1996) and water table level (Leite et al., 2018). It may influence the plants' transpiration (Rawitscher, 1948; Oliveira et al., 2005), and consequently the water balance residual."

R1C11: Results for LUC to pasture are well in accordance to other studies, role of soil compaction should be discussed for this land use (see Nobrega 2017 and Meister et al. 2017).

AR-R1C11: Yes, it is true to say that soil compaction in pasturelands will affect the water balance results. Thus, we changed the text at this point (page 10, line 8 – line 10) to consider the suggested studies, in order to enrich our discussion: "Additionally, the deforestation and agricultural land uses may increase soil compaction, as the LCLUC influence the hydrological patterns along the soil profile by evident modifications in the soil characteristics (bulk density, infiltration capacity, etc.) (Lamparter et al., 2016; Meister et al., 2017; de Almeida et al., 2018)."

R1C12: Page 9 row 25 on: the chapter is misunderstanding comparing with Fig 4 (water table changes): Row 26: water balance residuals represent not only soil water storage, as defined before (includes also deep infiltration – groundwater recharge !); authors argues that cerrado remove water from deeper soil horizons (that's right), but groundwater fluctuation is much higher in pasture and sugarcane (why?.

AR-R1C12: Thank you for this important question. We explained this issue on page 11 (line 8 – line 18, and line 21 – line 24). This happens because more water reaches the water table in the pasture in comparison with the Wooded Cerrado. In the wooded Cerrado, the water uptake by the vegetation is higher due to the deeper and denser root system in comparison with pasture and sugarcane. In the sugarcane and pasture, the soil water that was not consumed by the plants and neither evaporated, it continues to infiltrates along the unsaturated zone and the water uptake by the plants becomes unfeasible as the roots are shallow. Consequently, more water becomes available for deep infiltration, and this is evidenced by the significant water table fluctuation, which means that maybe there is a higher groundwater recharge under the pasture in comparison with the wooded Cerrado (Fig 3f). This is explained in detail in section 3.2. Sections 3.1. and 3.2. had their contents changed due to the new information added in Fig. 3.

R1C13: It will be fine, if table or figure with the soil water content over the measurement period can be added, than it can be seen how the unsaturated soil zone react different between land uses and cerrado. – In Fig. 4b 2015 there is a remarkable water table deepening, but high surplus of dS/dt – why?

AR-R1C13: We inserted a Figure showing the soil water content along the monitoring period and we attached in this revision as Fig. 3e. To answer the question about the water table deepening in 2014, we added a piece of discussion in the text (page 10, line 32 – line 33): "In the well located in the pasture, the water table fluctuated negatively along 2014 and 2015 due to the drought that happened in 2014 (Getirana, 2015). The water surplus of 2015-2016 happened due to the La Niña phenomena, that raised the rainfall pattern after the long dry season of 2014-2015 (Kakatkar et al., 2018). Consequently, the water table raised along 2016-2017."

R1C14: Discussion chapter 3.4 (should be enlarged a little with): Result that pasture and sugarcane increase surface runoff and decrease Eta are very common (not surprising); but for the residual (increased significantly) it must be discussed more carefull with differentiation in the role of deep infiltration (groundwater recharge relative high, interflow in the slope?, change of soil water content – see the measurements – not used for the discussion; infiltration rates between Cerrado and land use types are comparable? Compare with literature results.

AR-R1C14: Thank you for the suggestion. We added an explanation and new citations (a number of 8) to explain why the groundwater fluctuation is higher in the pasture well than in the Cerrado: "Therefore, the aquifer recharge rates, evidenced here by the groundwater table fluctuation (Fig. 3F), may be reduced in forested areas in comparison with agricultural landscapes due to the atmospheric and vegetation water demands, and the increased soil water retention capacity (Adane et al., 2018; Dias et al., 2015; Wang et al., 2018; Tseng et al., 2018). This validate the information that the LCLU significantly impacts groundwater recharge (Scanlon et al., 2005; Scott et al., 2014; Lucas et al., 2015; Dawes et al., 2012)" (page 13, line 11 – line 15). In addition, phrases on lines 3, 4, 26 and 27 (page 13) were added to complete the discussion. This issue was mainly discussed along the section 3.3, which was significantly improved in the revised version of the manuscript. The hole of section 3.4 is to evidence the hydrological trade-offs caused by the potential LCLUC explored by our study.

R1C15: Conclusions: page 12, row8: avoid term change in soil water storage (you mean the residual, much more than soil water storage (see above) Page 12 row 11,12: no documentation that higher infiltration rates in wooded Cerrado compared to pasture and sugar cane – add this in the paper.

AR-R1C15: We changed the term "soil water storage" through the text to "water balance residual" and we defined this terminology on session 2.3 (page 4, line 15 – line 16). "The water balance residual (dS/dt) includes subsurface flow, soil water storage, deep percolation and groundwater recharge." We commented along the text that due to the decreased runoff of the wooded Cerrado in comparison with pasture, sugarcane and bare soil, more water infiltrates through the soil and become readily available for the plants' consumption (page 10, line 14 – line 15): "These reduced surface runoff rates in the wooded Cerrado increase soil water infiltration in comparison with pasture, sugarcane and bare soil. Thus, higher infiltration rates increase plant water availability (Krishnaswamy et al., 2013)."

R1C16: I agree, that such long term monitoring studies must be done, to compare it with often done pure water balance simulation studies. Point out in 4., what for important results in detail are valuable for further studies and water balance modelling for Cerrado Biome. In total: acceptance with mayor revision

AR-R1C16: We acknowledge the insightful comments about our manuscript and the kind words in support of its publication. We added in conclusions that our results are useful for future research, both for discovery and modeling sciences.

R1C17: Please add in the references: PROCESS-BASED MODELLING OF THE IMPACTS OF LAND USE CHANGE ON THE WATER BALANCE IN THE CERRADO BIOME (RIO DAS MORTES, BRAZIL) Sarina Meister, Rodolfo L. B. Nobrega, Wolfgang Rieger, Ronja Wolf and Gerhard Gerold ERDKUNDE 2017, 71/3, 241-266 Lamparter, G.; Nóbrega, R.. L. B.; Kovacs, K.; Amorim, R. S. and Gerold, G. (2016): Modelling hydrological impacts of agricultural expansion in two macro-catchments in Southern Amazonia, Brazil. In: Regional Environmental Change. https://doi.org/10.1007/s10113- 016-1015-2

AR-R1C17: Thank you for the suggested references. As commented in AR-R1C11, we cited these studies to support the discussion of our results.

Reviewer 2 comments

We would like to thank the anonymous referee 2 for the kind words in support of our manuscript and for the time spent reviewing our text. Here, we replied the referee's comments, which were highly insightful and enabled us to improve the quality of our manuscript. Note that the original referee's comments are identified as R2Cxx and written in **bold**, and the authors' responses are labeled as AR-R2Cxx. In addition, all comments are numbered (xx).

R2C1: The authors assess the impact of four different land uses (bare soil, sugarcane, pasture and wooded cerrado) on water balance components (mainly runoff and actual evapotranspiration) monitored in experimental plots (5 m width, 20 m length and 9% slope). The paper is potentially interesting for the readers of Hess, however it requires major revisions.

AR-R2C1: We appreciate the reviewer's comments and suggestions and we recognize that our manuscript requires more detailed descriptions of some topics listed by Reviewer 2. We hope to solve the problems found along the text to improve its comprehension and quality. In addition, it is important to remark that this is a site-specific study, and the discussion and conclusions stated in here are based on field observed data, without any pretention to generalize to a larger area. Our scope was to investigate the hydrological process in detail by adopting the hillslope scale as the design criteria of the experimental setup. Thus, our results will help further studies supporting them with 5-year experimental data that confirms the significant influence of the land use in the water partitioning in a subtropical region.

R2C2: In sub-Section 2.2 ("Experimental setting and instrumentation"), please clearly describe the monitoring infrastructure (refer to Fig. 2) by adding information on soil moisture probes, monitoring wells which are described in other parts of the manuscript. Please add the thickness of the unsaturated zone (40 m) in Fig. 2.

AR-R2C2: Thank you for the suggestion. We added the thickness of the unsaturated zone in Fig. 2 and additional information was added in section 2.2 (page 3, line 17 – line 25) to better describe the monitoring wells and soil moisture probes.

R2C3: Not clear Kc-values for sugarcane in Table 2. Do they refer to monthly values during the growing season? How do you obtain field capacity and saturated hydraulic conductivity? Please specify the root zone depth for sugarcane and wooded cerrado.

AR-R2C3: Thank you for requesting this information. The Kc value vary along the year. We specified in a new version of Table 2 the months that the different Kc values are referring to. We obtained the soil field capacity and saturated hydraulic conductivity using Büchner funnels and Richards extraction chambers (information to be added in the revised manuscript). The root zone depth for sugarcane was specified on Table 2 (see the second column). However, the root zone depth for the wooded Cerrado was specified in the revised version in section 2.2 (page 4, line 8 – line 11): "The soil root zone in the wooded Cerrado may reach up to 18 m (Rawitscher, 1948). However, most of the water used for plants' transpiration comes from the first layers (up to 7.5 m) (Oliveira et al., 2005; Canadell et al., 1996)".

R2C4: In sub-Section 3.2 ("Groundwater table fluctuation"), the results are suspicious. The authors declare Ks=10-3 m d-1 for a sandy soil (very low if compared to tabulated values, see publications of Clapp and Hornberger, 1978; Schaap et al., 2001; Twarakavi et al., 2009 to mention a few). The main problem is the relationship between water storage change and water table fluctuation in Fig. 4. If Ks=10-3 m d-1, and hypothesizing full saturation of soil profile, we can apply the Darcy law with the unit gradient and water takes about 4000 days to bypass 40 m of soil and reach the water table. Please check if I am wrong. If I am approximately right, the relationship between soil water storage change and water table fluctuation should be influenced by a time lag.

AR-R2C4: Thank you for the remark. Our idea was to verify the aquifer hydraulic conductivity in both wells (pasture and wooded Cerrado) to be sure that the wells conditions were the same and consequently comparable in terms of water table fluctuation. The hydraulic conductivity mentioned in the section 3.2 was obtained by a slug test. Therefore, it is not referring to the hydraulic conductivity for the sandy soil from the unsaturated zone. In fact, it is referring to the aquifer hydraulic conductivity, which is a sandstone. The soil hydraulic conductivity in the upper layers of the soil (up to 1 m depth) is around 10-1 m d-1. Thus, the soil porosity, and consequently, the soil hydraulic conductivity may vary along the unsaturated zone. We totally agree that there is a time lag between the water infiltration and the aquifer recharge, thus, we added extra pieces of discussion on section 3.2 (pages 10 and 11) to clarify that the effects observed on the groundwater table fluctuation tend to be non-linear and difficult to analyze as they result from complex interactions between LCLU and hydrological processes (Han et al., 2017). We also believe that the discussion from section 3.2 states a new hypothesis to be tested in further studies, in order to check the time lag between surface water interactions and groundwater recharge in contrasting LCLU (page 11, line 16 – line 18).

R2C5: The main concern of this study is that the authors draw general conclusions on a small-scale, quite "homogeneous" test-site (experimental plots of 5 m width, 20 m length and 9% slope) by ignoring large-scale spatial heterogeneity of soil properties and topography. Hence this study can be considered as a preliminary survey for a more ambitious scientific investigation.

AR-R2C5: We appreciate your concern about the scale factor. There is a need to understand the water partitioning in the Cerrado region at multiple scales (Oliveira et al., 2014). In this study, our priority was to investigate the water balance at the hillslope scale in multiple land uses. The choice of the evaluated LCLU was based on the current LCLUC dynamics in the Cerrado described in the introduction and in the comment AR-R1C2. In the future, the findings of the present study can be used for data validation in spatial scale studies and be part of a multi-scale approach to evaluate the water balance in the Cerrado.

Reviewer 3 comments

We would like to thank the anonymous referee 3 for the kind words in support of our manuscript and for the time spent reviewing our text. Here, we replied the referee's comments, which were highly insightful and enabled us to improve the quality of our manuscript. Note that the original referee's comments are identified as R3Cxx and written in **bold**, and the authors' responses are labeled as AR-R3Cxx. In addition, all comments are numbered (xx).

R3C1: This paper describes an experimental approach at the hillslope scale concerning the possible water partitioning trade-offs due to the LCLUC dynamics. I think this paper is relevant since it studies water flux in the Cerrado biome. The manuscript is interesting and well written. The results are original and represent an important contribution to the understanding of hydrological processes in the Cerrado. However, my main concern is that the problem statement is not clearly defined and that the field experimental description is not sufficient as it is. I think the paper is well written and the relevant literature cited, however it requires major revisions.

AR-R3C1: We appreciate the reviewer feedback about our manuscript and the time spent during the reading and further revision. Here, we express our accordance with the relevant given suggestions. We also added the information in the revised version of the manuscript. We deeply revised the problem statement, which is mainly based on the lack of field studies in the tropics considering different land uses and an undisturbed condition (Cerrado). We recognize that it could contain more arguments involving the need of field observed data for both modeling and discovery sciences.

Suggested corrections:
R3C2: All acronyms of the equations that are in the text should be in italic and the equation with the unit (equation 8).

AR-R3C2: Thank you for the correction. We changed this along the text according to the instructions.

R3C3: Page 3: The figure 1, is it to highlight Brazil? the most important is the monitoring, the details in the photos are too small. Please improve visibility.

AR-R3C3: Thank you for your suggestion. We wanted to highlight the study area context by printing the country larger than the other information. However, we recognized that it is more important to show the reader more information about the study site itself. Thus, we made a new Fig.1 considering this important suggestion.

R3C4: Page 3: In sub-Section 2.2 Experimental setting and instrumentation-better describe the part of the monitoring. What was the measuring range for each equipment? What are the distances between the equipments? What is the size of the plot? What are the characteristics of the forest? (DBH, Height, Density)

AR-R3C4: Thank you for these important questions. Concerning the measuring range of each equipment, we added this information on Table 1. The distance between sites 1 and 2 are 1.7 km. Site 1 has 9 plots placed side by side (approximately 2.5 meters of distance between each plot) (see Figure 1). Also in site 1, there is a meteorological station that concentrates almost all sensors placed at that site at one point, except for the soil moisture probes. They are connected to the meteorological station, but they are placed inside the plots (there is one placed inside the first sugarcane plot, and 20 m to the left, there is another one placed inside the first pasture plot). Site 2 has 3 plots inside a tropical woodland (wooded Cerrado) and due to the tree density and topography, the plots are approximately 5 to 10 meters distant from each other. Approximately 50 m to the north from the plots, there is a meteorological tower (11 m height) containing all the sensors placed at site 2. Concerning the forest characteristics, the wooded Cerrado area used in this study has 15522 individuals per hectare, the height of most of the trees is about 8 m, and the diameters (DBH) are predominantly between 3 and 7 cm (Reys et al., 2013). We added extra information in section 2.2 in order to better describe the instruments' positions (page 3, line 17 – line 25) and the forest characteristics (page 4, line 6 – line 9).

R3C5: In table 1: Were used different equipment for monitoring the same variable in different plots (i.e. soil moisture)? What is the error of each piece of equipment? some tests were carried out to know the difference between devices?

AR-R3C5: Thank you for this important remark. We used the same model of soil moisture probes in the different measurement points (see Table 1). We added the maximum error of each piece of equipment in Table 1. The soil moisture probes had their first use in our study sites and they were all previously calibrated with soil samples from our study sites.

R3C6: In figure 2, Why did not your measure soil moisture in the Bare soil? Please explain.

AR-R3C6: Thank you for the question. We had not enough ports in the datalogger to connect another soil moisture probe to monitor the bare soil plot. In addition, we did not have a piece of equipment available to perform such monitoring.

R3C7: Page 4: The paragraphs in lines 5 to 13, should be inserted in the sub-section 2.2.

AR-R3C7: We agree that this information suits on section 2.2. However, we added these paragraphs in section 2.3 (water balance components) because each of them is describing how we obtained each of the water balance components: Page 4 (line 22 – line 23) describe how we monitor the rainfall; Page 4, line 24 – line 26 describe how we obtained the overland flow and how we calculated the runoff coefficient; Page 4, line 27 – line 29 describe how we estimated the reference evapotranspiration. Thus, we argue that removing these paragraphs from section 2.3, we may lose the sequence of the text. You can see that just after line 16 (page 4), we present Equation 1, which is also referred in line 16. Additionally, these paragraphs define how we obtained the input variables used in Equation. 1.

R3C8: Page 5: How and when do you obtain soil field capacity and saturated hydraulic conductivity?

AR-R3C8: We obtained the soil field capacity and soil wilting point using Büchner funnels and Richards extraction chambers (Richards, 1931). These tests were performed in the beginning of the experiment (2012) (Oliveira, 2014). We collected the samples with undisturbed structure in volumetric rings at depths of 20, 50 and 100 cm. These information were added to the text (page 5, line 29 – line 31). The soil hydraulic conductivity range found in the study area was added on page 3 (line 9 – line 10).

R3C9: Page 5, Table 3: remove this table, you can describe it in a paragraph.

AR-R3C9: Thank you for the suggestion. We removed Table 3 and a new paragraph was added after line 5 (page 6): "The Priestley and Taylor coefficients (α) calculated for a wooded Cerrado area close to the study site (Cabral et al., 2015) differed according to the season: 1.09 for Summer (December – March); 1.00 for Fall (March – June); 0.77 for Winter (June – September); and 0.98 for Spring (September – December).".

R3C10: Page 6: In sub-section 2.4 and 2.5 describe more about these topics.

AR-R3C10: Thank you for the suggestion. We completed these 2 paragraphs with additional information. We modified the paragraphs as reported below:

Section 2.4: Groundwater table fluctuation (page 6, line 24)
"The water table was registered twice a day (at 6 am and 6 pm) using pressure transducers (Diver, Schlumberger) placed inside two monitoring wells (well 1 located in the pasture area; and well 2 located inside the wooded Cerrado area). In the study site, both wells presented similar hydraulic conductivity according to the slug test (Bouwer and Rice, 1976) previously performed. We evaluated the aquifer hydraulic conductivity from both wells in order to validate the water table comparison among each other, as whether the aquifer condition in the wells were different, such comparison would not be fair. Both wells reach the water table at approximately 40 m depth in an unconfined sandstone formation (Botucatu formation), which belongs to São Bento Group of Mesozoic age. In addition, the soils above the aquifer that appears thought the unsaturated zone are Cenozoic sediments weathered from the sandstone (Wendland et al., 2007)."

Section 2.5: Data analysis (page 7, line 7)
"The normality assumption was tested using the Shapiro-Wilk test using a 95% confidence interval for rainfall, evapotranspiration, surface runoff and soil water storage datasets. The one-way analysis of variance (ANOVA) was applied to test the null and alternative hypothesis, that is, equality of surface runoff, evapotranspiration and soil water storage distribution functions between the four treatments (LCLU) versus the difference in distribution functions between at least two treatments. Additionally, the multiple comparisons between treatments were performed using the Tukey test (Montgomery, 2008).

The rainfall, evapotranspiration, surface runoff, water balance residual and soil moisture graphs were plotted using a daily basis timescale. The groundwater table fluctuation was plotted using a monthly timescale due to the noise typically found in this kind of measurement. In order to present the order of magnitude along the years, the data was also resumed annually in Tables and Figures."

R3C11: Page 8, Results and discussion: I think you need to further describe the results and compare with other papers. The study would have been of more interest to readers if various published water flux models had been tested using the data.

AR-R3C11: Thank you for your suggestion. As asked by other reviewers too, we improved the results' discussion by contrasting our outcomes with other studies in the revised manuscript to be submitted. This can be evidenced by the 27 new references included in the manuscript. Concerning the testing of water flux models, it was not part of our scope to test models using our data. We consider that water flux model testing with the data presented along this study should be part of a future study. Thus, we may add it as a recommendation along the discussion and also in the concluding remarks. We believe that the main contribution of our study is the long-term monitoring at the hillslope scale under subtropical conditions. Such kind of data is a resource for both discovery and modeling sciences. Additionally, we could draw significant conclusions by the comparisons of the contrasting land uses considered in this study.

R3C12: Page 12 Conclusions: The conclusion reads more like a summary of the paper.

AR-R3C12: We recognize this aspect. Along the revision, we added substantial information in the results and discussion session. Therefore, in the revised version, we added other assumptions discussed thought the manuscript. (page 14, line 2 – line 6, and line 14 – line 15), mainly stating the two main reasons of a higher water consumption observed in the wooded Cerrado in comparison with pasture and sugarcane. The fact that we summarize the manuscript in the first paragraph of the conclusion is due to the need of remember the reader about the context of our study. In addition, some readers go straight to the conclusions in a first read of a paper and when we give at least a brief description of the study before giving the conclusions, we improve the comprehension of our scientific contributions. However, we added more information along the conclusions to reinforce the accomplishment of the objectives and complete the main findings.

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Changes Marked

Hydrological trade-offs due to different land covers and land uses in the Brazilian Cerrado

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Abstract. Farmland expansion in the Brazilian Cerrado, considered one of the largest agricultural frontiers in the world, has the potential to alter water fluxes on different spatial scales. Despite some large-scale studies being developed, there are still few investigations in experimental sites in this region. Here, we investigate the water balance components in experimental plots and the groundwater table fluctuation in different land covers: wooded Cerrado, sugarcane, pasture and bare soil. Furthermore, we identify possible water balance trade-offs due to the different land covers. This study was developed between 2012 and 2016 in the central region of the state of São Paulo, Southern Brazil. Hydrometeorological variables, groundwater table, surface runoff and other water balance components were monitored inside experimental plots containing different land covers; the datasets were analyzed using statistical parameters; and the water balance components uncertainties were computed. Replacing wooded Cerrado by pastureland and sugarcane shifts the overland flow (up to 42 mm yr^{-1}), and soil water storagebalance residual (up to 504 mm yr^{-1}).), and may affect groundwater table behavior. This fact suggests significant changes in the water partitioning in a transient land cover and land use (LCLU) system, as the evapotranspiration is lower (up to 719 mm yr^{-1}) in agricultural land covers than in the undisturbed Cerrado. We recommend long-term observations to continue the evaluations initiated in this study, mainly because tropical environments have few basic studies at the hillslope scale and more assessments are needed for a better understanding of the real field conditions. Such efforts should be made to reduce uncertainties, validate the water balance hypothesis and catch the variability of hydrological processes.

Keywords: Water balance, hillslope hydrology, sugarcane, pasture, Brazilian Cerrado.

1 Introduction

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Brazil has significant areas used for extensive grazing over pasture, farmland (mainly soybeans and sugarcane), and part of these areas were mostly occupied by the native Cerrado, which decreased significantly in the last century (Marris, 2005). It is estimated that 52.2% of the original Cerrado area is now occupied by pasturelands and croplands, 0.8% by other land uses and 47% remains undisturbed (Beuchle et al., 2015). The conversion from native Cerrado to pastureland, and afterwards, to sugarcane, can be considered a potential land cover and land use change (LCLUC) in southeastern Brazil

(Alkimim et al., 2015). However, few studies investigate the effects of the LCLUC dynamics (Bonan, 2008; Loarie et al., 2011; Grecchi et al., 2014).

In the State of São Paulo, the minimum area required by the Brazilian forest code to maintain native forests in the Cerrado biome (20% of the total area of an estate) is not reached in much of the state (Soares-Filho et al., 2014). These areas were primary resources for expansion of the agricultural frontier in the tropics (Gibbs et al., 2010; Lapola et al., 2013), and these changes may cause significant disturbances in the hydrological processes (Loarie et al., 2011; Oliveira et al., 2014; Oliveira et al., 2015; Nobrega et al., 2017). These processes in tropical and subtropical zones are different from other regions across the world due to the increased solar energy availability and rainfall, calling for the need of basic field studies, long-term data acquisition and availability, and the development and application of mathematical models (Wohl et al., 2012; Burt and McDonnell, 2015).

In the context of the Cerrado biome, the conversion of undisturbed vegetation and pasturelands to mechanized crop systems (e.g. sugarcane, corn and soybeans) indicates that this region in Brazil has a dynamic LCLUC situation (Lapola et al., 2013). The sugarcane is the Brazilian backbone for energy security, as the ethanol production is the third most cultivated crop after soybeans and corn, reflecting the increasing demand for automotive fuels along the years (Leal et al., 2013; Rodrigues et al., 2018). Thus, the country is the world second largest ethanol producer and the Cerrado comprises the sugarcane expansion frontier due to the availability of water and pasturelands for the crop expansion (Bellezoni et al., 2018).

Native forests help to maintain the water cycle (Krishnaswamy et al., 2013; Ghimire et al., 2014). The evapotranspiration appears as a key component in the aquifer recharge control in the Guarani Aquifer System (GAS) outcrop zone ~~(Wendland et al., 2007; Lucas and Wendland, 2015)~~(Wendland et al., 2007; Lucas and Wendland, 2015; Lucas et al., 2015). Thus, water partitioning in these areas should be well understood in order to have the responses from different land covers and land uses (LCLU), allowing the evaluation of possible water balance trade-offs due to the LCLUC (Krishnaswamy et al., 2013; Ghimire et al., 2014; Frank et al., 2014) caused by environmental and economic needs (Barretto et al., 2013).

In Brazil, many large-scale studies on water balance were developed in some hydrographic regions in the country (Paiva et al., 2013; da Paz et al., 2014; Oliveira et al., 2014; Melo et al., 2016). Nevertheless, experimental scale studies are still rare due to the local heterogeneities and uncertainties from hydrological measurements and estimates (Beven, 2006; Graham et al., 2010). Basic field-hydrology studies are important to improve the agricultural production efficiency while promoting sustainable development. Therefore, these studies are important to promote new solutions and techniques to maintain the water balance in spite of the rapid LCLUC (Dotterweich, 2013; Nobrega et al., 2017). Research of this kind can be done using experimental plots, which are delimitated hillslopes (control volume) where the overland flow is directed to one outlet (Sadeghi et al., 2013; Oliveira et al., 2015; Mwango et al., 2016; Oliveira et al., 2016; Strohmeier et al., 2016; Youlton et al., 2016b; Anache et al., 2017; Zhao et al., 2017; Anache et al., 2018).

The objective of this study is to evaluate the water fluxes in different LCLU: wooded Cerrado (also known as Cerrado *sensu stricto*), sugarcane, pasture and bare soil. In addition, we identify possible water balance trade-offs due to the different LCLU, compute the uncertainties for each water balance component and propagate the error separately for each LCLU.

2 Material and methods

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2.1. Study sites and regional setting

The study sites are located in the Arruda Botelho Institute (IAB) in Itirapina, SP, Brazil (latitude 22º 11’ 5” S, longitude 47º 51’ 11” W, elevation 790 m a.m.s.l.) (Fig. 1). The area is inside two major hydrological hotspots in the country: the Guarani Aquifer System (GAS) (Wendland et al., 2007; Oliveira et al., 2017) outcrop zone and the Cerrado Biome. Site 1 is located under agricultural land covers (pasture, sugarcane and bare soil); while site 2 is located under the wooded Cerrado. The climate in the region is humid subtropical (Cwa, Köppen), with a hot and wet summer and a dry winter (Alvares et al., 2014). The average annual rainfall and temperature are 1486 mm yr^{-1} and 21.5 °C, respectively (Cabrera et al., 2016). Additionally, the soil is sandy and it is classified as an Entisol (Oliveira et al., 2016)Additionally, the soil is sandy, it is classified as an Entisol (Oliveira et al., 2016), and its saturated hydraulic conductivity ranges from 11.30 mm h^{-1} to 147.31 mm h^{-1} along the superficial layer (first meter) (Oliveira, 2014; Youlton et al., 2016b).

Insert Fig. 1

2.2 Experimental setting and instrumentation

The experiment began in October, 2011 (Oliveira et al., 2015; Oliveira et al., 2016; Youlton et al., 2016b; Youlton et al., 2016a) and it is still in operation. This study considered the data collected during five years (2012-2016). It contains manual and automatic instruments, as well as permanent structures, all assembled in the two sites (Fig. 2). Two monitoring wells, meteorological stations (tripod and tower), and twelve steel-made bounded plots are the permanent structure. The instruments are described according to their positioning and function (Table 1). All instruments recorded data every 10 minutes, except the pressure transducers, which logged the groundwater table twice a day. The distance between sites 1 and 2 are 1.7 km. Site 1 has nine plots placed side by side (approximately 2.5 m of distance between each plot). Also in site 1, there is a meteorological station that concentrates almost all sensors placed at that site at one point, except for the soil moisture probes. They are connected to the meteorological station, but they are placed inside the plots (there is one placed inside the first sugarcane plot, and 20 m to the left, there is another one placed inside the first pasture plot). Site 2 has three plots inside a tropical woodland (wooded Cerrado) and due to the tree density and topography, the plots are approximately 5 to 10 m distant from each other. Approximately 50 m to the north from the plots, there is a meteorological tower (11 m height) containing all the sensors placed at site 2.

Insert Fig. 2

Insert Table 1

The plots were designed to adequately represent the process heterogeneities (Sadeghi et al., 2013): ~~3~~three replicates for each LCLU, 5 m width, 20 m length, and 9% slope gradient. The plots located at site 1 contain three different LCLU: (i) Pasture (*Brachiaria decumbens*) established 20 years ago, used for grazing and plant heights varying between 5 and 30 cm. The animals' (cattle) rotation period is 30 days (10 animals per hectare) and each one weighs approximately 420 kg. The animals remain in the area for 5 days in each rotation; (ii) contoured planted sugarcane (*Saccharum officinarum*) on beds spaced 1.5 m apart. The plantation was established in October 2011, the canopy reaches at least 2 m high, and it was harvested every November; (iii) bare soil plots were maintained without plant cover by manual tillage and glyphosate application. The plots located at site 2 have the same experimental design as site 1 and contain (iv) wooded Cerrado as vegetation. The Cerrado comprises tropical vegetation in which the trees do not form a continuous canopy, however, it presents woody components of six to ~~seven meters~~7 m high (Alberton et al., 2014). The Cerrado vegetation is fire-resistant, it is considered a biodiversity hotspot and supports long dry periods (Brannstrom et al., 2008). Concerning the woodland characteristics, the wooded Cerrado area used in this study has 15522 individuals per hectare, the height of most of the trees is about 8 m, and the trees' diameters at breast height (DBH) are predominantly between 3 and 7 cm (Reys et al., 2013). The soil root zone in the wooded Cerrado may reach up to 18 m (Rawitscher, 1948). However, most of the water used for plants' transpiration comes from the first layers (up to 7.5 m) (Canadell et al., 1996; Oliveira et al., 2005; Garcia-Montiel et al., 2008).

2.3 Water balance components

The water balance components (Eq. 1) were monitored over 5 years (2012-2016) in a control volume defined by the bounded plots placed within the experimental sites. We considered different techniques to monitor these components according to the LCLU conditions. The ~~soil water storage was calculated as the~~ water balance residual (dS/dt) ~~and~~ includes subsurface flow, soil water storage, deep percolation, and ~~subsurface flow~~groundwater recharge.

$$\cancel{\frac{dS}{dt} = P - Q - ET}\ \frac{dS}{dt} = P - O_F - E_T$$

(1)

Where: P is the rainfall (mm); ~~Q~~O_F is the surface runoff (mm); E_T is the evapotranspiration (mm); and dS/dt ~~is~~includes the soil water storage, subsurface flow and deep percolation (mm) during time t (day, month or year).

The rainfall was monitored using a tipping bucket (Model TB4-L, Hydrological Services) with a gauging resolution of 0.254 mm (Table 1). The rainfall data was registered every 10 minutes, in order to obtain rainfall intensity and duration.

Rectangular experimental plots directed the overland flow to tanks at the end of the slope, where the volume was measured at times after rainfall events. We also calculated the runoff coefficient for each LCLU using a genetic algorithm to minimize the squared errors between observed and estimated runoff values using the rational method (Wang, 1991).

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The reference evapotranspiration (E_{To}) was calculated on a daily-basis using the Penman-Monteith equation parameterized by FAO 56 methodology (Allen et al., 1998). Afterwards, the evapotranspiration (E_T) values were obtained for pasture and sugarcane land uses using Eq. 2.

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$$ET = K_s \cdot ET_c = K_s \cdot (K_c \cdot ET_o) \quad E_T = K_S \cdot E_{Tc} = K_S \cdot (K_C \cdot E_{To}) \tag{2}$$

Where: E_T is the real evapotranspiration (mm d^{-1}); Ks is the water stress coefficient (dimensionless); E_{Tc} is the crop evapotranspiration (mm d^{-1}); Kc is the crop coefficient (dimensionless); and E_{To} is the reference evapotranspiration (mm d^{-1}) (Eq. 3):

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$$ET_o = \frac{0.408 \cdot (R_n - G) + \frac{\gamma \cdot 900}{(T_{avg} + 273)} \cdot U_2 (e_s - e_a)}{s + \gamma \cdot (1 + 0.34) U_2} \tag{3}$$

$$E_{To} = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \frac{\gamma \cdot 900}{(T_{avg} + 273)} \cdot U_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot U_2)} \tag{3}$$

Where: s is the slope vapor pressure (kPa °C^{-1}); R_n is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}); γ is the psychometric constant (kPa °C^{-1}); U_2 is the wind velocity at 2 m height (m s^{-1}); 900 is the approximate value of all the equations´ constants (kJ^{-1} kg K d^{-2}); T_{avg} is the average daily temperature (ºC); e_s is the saturated vapor pressure (kPa); and e_a is the actual vapor pressure (kPa).

The water stress coefficient (Eq. 4) was calculated for each day i throughout the monitoring period. It uses the soil moisture monitored by the Frequency Domain Ratio (FDR) probes as the main input. When there is no or limited water available for the plants' transpiration, KsK_S < 1. Whenever the soil has water readily available for plant consumption, KsK_S = 1.

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$$Ks_i = \frac{TAW - Dr_i}{(1-p) \cdot TAW} \quad K_{Si} = \frac{T_{AW} - D_{r_i}}{(1-p) \cdot T_{AW}} \tag{4}$$

Where: T_{AW} is the total available water in the soil root zone (mm) (Eq. 5); Dri D_{r_i} is the water depletion in the soil root zone (mm) (Eq. 6) on day i; and p is the T_{AW} fraction that the crop roots can extract from the soil without suffering from water stress (dimensionless).

$$TAW = 1000 \cdot (\theta_{fc} - \theta_{wp}) \cdot Z_f \quad T_{AW} = 1000 \cdot (\theta_{fc} - \theta_{wp}) \cdot Z_f \tag{5}$$

Where: θ_{fc} is the soil field capacity (dimensionless); θ_{wp} is the soil wilting point; and Z_f is the root zone depth.

$$Dr_i = 1000 \cdot (\theta_{fc} - \theta_i) \cdot Z_f \quad D_{r_i} = 1000 \cdot (\theta_{fc} - \theta_i) \cdot Z_f \tag{6}$$

Where: θ_{fc} is the soil field capacity (dimensionless); θ_i is the average soil moisture along the root zone (measured by FDR probes); and Z_f is the root zone depth.

All the necessary data and coefficients to calculate the water stress coefficient (Ks) and the adjusted evapotranspiration rate (ET) are given in Table 2. K_S) and the adjusted evapotranspiration rate (E_T) are given in Table 2. It is worth mentioning that laboratory tests determined the soil field capacity and soil wilting point using Büchner funnels and Richards extraction chambers (Richards, 1931). The soil samples were collected with undisturbed structure in volumetric rings at depths of 20, 50 and 100 cm.

Insert Table 2

The wooded Cerrado evapotranspiration (E_T) rates were estimated using the Priestley and Taylor (1972) method (Eq. 7). This method was chosen due to its simplicity to calculate the energy balance for the study area and the fact that is suitable for the instrumentation available. The Priestley and Taylor coefficients (α) used to calculate the evapotranspiration were based on Cabral et al. (2015) measurements for a similar wooded Cerrado fragment located approximately 60 km away from the study site (Table 3. The Priestley and Taylor coefficients (α) differed according to the season: 1.09 for Summer (December – March); 1.00 for Fall (March – June); 0.77 for Winter (June – September); and 0.98 for Spring (September – December).

$$ET = \alpha \cdot \left(\frac{1}{\lambda}\right) \cdot \left[\frac{s \cdot (R_n - G)}{s + \gamma}\right] \quad E_T = \alpha \cdot \left(\frac{1}{\lambda}\right) \cdot \left[\frac{s \cdot (R_n - G)}{s + \gamma}\right] \tag{7}$$

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Where: α is the Priestly and Taylor coefficient (dimensionless), λ is the latent heat of vaporization (MJ m^{-2} d^{-1}); s is the slope vapor pressure (kPa °C^{-1}); R_n is the net radiation (MJ m^{-2} d^{-1}); G is the soil heat flux (MJ m^{-2} d^{-1}); and γ is the psychometric constant (kPa °C^{-1}).

~~Insert Table 3~~

The bare soil condition has no vegetation and, consequently, there is no transpiration. Thus, we applied the method developed by Ritchie (1972). This method has two phases: firstly, the soil evaporation is equal to the potential soil evaporation estimated using the Priestley and Taylor (1972) method adapted to free surfaces. During this phase, there is no water restriction (precipitation higher than evaporation) and the evaporation is governed by the available energy; secondly, the accumulated soil evaporation exceeds the precipitation and the soil evaporation is currently given as a function of the dry days that followed the last wet day. The evaporation cycle is interrupted and returns to the first phase whenever the precipitation exceeds the accumulated evaporation during the second phase.

2.4 Groundwater table fluctuation

The water table was registered twice a day (at 6 am and 6 pm) using pressure transducers (Diver, Schlumberger) placed inside two monitoring wells (well 1 located in the pasture area; and well 2 located inside the wooded Cerrado area). In the study site, both wells presented similar hydraulic conductivity according to the slug test (Bouwer and Rice, 1976) previously performed. We evaluated the aquifer hydraulic conductivity from both wells in order to validate the water table comparison among each other, as whether the aquifer condition in the wells were different, such comparison would not be fair. Both wells reach the water table at approximately 40 m depth in an unconfined sandstone formation (Botucatu formation), which belongs to São Bento Group of the Mesozoic age. Furthermore, the soils above the aquifer that appears thought the unsaturated zone are Cenozoic sediments weathered from the sandstone (Wendland et al., 2007). Additionally, despite the limited number of wells, the experimental design allowed a first look to the groundwater table behavior under different LCLU (pasture and wooded Cerrado) and a crosscheck with the surface water balance outcomes.

2.5 Data analysis

The normality assumption was tested using the Shapiro-Wilk test using a 95% confidence interval for rainfall, evapotranspiration, surface runoff and ~~soil~~ water ~~storage~~balance residual datasets. The one-way analysis of variance (ANOVA) was applied to test the null and alternative hypothesis, that is, equality of surface runoff, evapotranspiration and ~~soil~~ water ~~storage~~balance residual distribution functions between the four treatments (LCLU) versus the difference in distribution functions between at least two treatments. Additionally, the multiple comparisons between treatments were performed using the Tukey test (Montgomery, 2008). The rainfall, evapotranspiration, surface runoff, water balance residual and soil moisture graphs were plotted using a daily basis timescale. The groundwater table fluctuation was plotted using a monthly timescale due to the noise typically found in this kind of measurement. In order to present the order of magnitude along the years, the data was also resumed annually in tables and figures.

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2.6 Data uncertainties

Data uncertainties are flaws found in the available information used to represent the reality and basically depend on the knowledge of the observed data (Refsgaard et al., 2007). The water balance uncertainty can be given by the standard error propagated from its components. Thus, the ~~soil~~ water ~~storage~~balance residual (d*S*/d*t*) standard error was propagated (Eq. 8).

$$\sigma_{dS/dt} = \left[\sigma_P^2 + \sigma_Q^2 + \sigma_{ET}^2\right]^{0.5} \quad \sigma_{\mathrm{ds/dt}} = \left(\sigma_{\mathrm{P}}^2 + \sigma_{\mathrm{O_F}}^2 + \sigma_{\mathrm{E_T}}^2\right)^{0.5} \tag{8}$$

Where: σ is the standard error (mm yr^{-1}); d*S*/d*t* is the ~~soil~~ water ~~storage~~balance residual; *P* is rainfall; ~~Q~~O_F is surface runoff; E_T is evapotranspiration.

The absolute error of the rainfall estimations was calculated using Eq. 9 based on the instrument accuracy informed by the manufacturer. Considering the used tipping bucket rain gauge (TB4), the error may reach up to ±3%.

$$\sigma_P = \overline{P} \cdot \varepsilon_p \quad \sigma_{\mathrm{P}} = \bar{P} \cdot \varepsilon_{\mathrm{P}} \tag{9}$$

Where: ~~σ_P~~σ_{P} is the standard error for rainfall (mm yr^{-1}); ~~$\overline{P}$~~ $\overline{P}$ is the annual average rainfall (mm yr^{-1}); ~~ε_P~~ε_{P} is the relative error from the tipping bucket rain gauge informed by the manufacturer.

The surface runoff may vary due to the heterogeneities found between plots' replicates (Wendt et al., 1986; Nearing et al., 1999; Gómez et al., 2001; Sadeghi et al., 2013). Thus, the standard error for surface runoff is given by the standard deviation of the replicated plots (Eq. 10).

$$\sigma_Q = \left[\frac{1}{N-1}\sum_{i=1}^{N}(Q_i - \overline{Q})^2\right]^{0.5} \quad \sigma_{\mathrm{O_F}} = \left[\frac{1}{N-1}\sum_{i=1}^{\mathrm{N}}\left(O_{\mathrm{F_i}} - \overline{O_F}\right)^2\right]^{0.5} \tag{10}$$

Where: ~~σ_Q~~$\sigma_{\mathrm{O_F}}$ is the standard error for surface runoff (mm yr^{-1}); N is the number of observations; ~~Q_i~~$O_{\mathrm{F_i}}$ is the surface runoff observed in plot *i* (mm yr^{-1}); ~~$\overline{Q}$~~ $\overline{O_F}$ is the average surface runoff between plots (mm yr^{-1}).

As previously mentioned, the evapotranspiration was estimated using the FAO 56 methodology (Allen et al., 1998) for pasture and sugarcane, and Priestley and Taylor (1972) for wooded Cerrado and bare soil. However, this study does not have evapotranspiration observations to evaluate how well this variable was estimated in the study sites. Consequently, the

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uncertainties for evapotranspiration estimates were calculated by combining all input variable uncertainties (Eq. 11) which were measured in the field for the FAO 56 method (temperature, relative humidity, solar radiation, barometric pressure and soil moisture) and the Priestley and Taylor method (temperature, net radiation and soil heat flux).

$$\sigma_{ET} = \left[\sum_{i=1}^{N} \left(\frac{\partial \, \mathrm{var}\, i}{\partial ET} \cdot u_{\mathrm{var}\, i} \right)^2 \right]^{0.5} \sigma_{E_T} = \left[\sum_{i=1}^{N} \left(\frac{\partial_{\mathrm{var}_i}}{\partial_{E_T}} - u_{\mathrm{var}_i} \right)^2 \right]^{0.5} \quad (11)$$

Where: σ_{ET} σ_{E_T} is the standard error for evapotranspiration (mm d^{-1}); var i var_i is the measured input variable *i*; *u* is the uncertainty of variable *i*.

3 Results and discussion

3.1 Water balance

The water balance components show different patterns according to the LCLU (Table 43 and Fig. 3). We verified this using a multiple comparison test (Tukey) in which the soil water storagebalance residual variation (d*S*/d*t*) in the wooded Cerrado was statistically different from the other LCLU (pasture, sugarcane and bare soil), which presented similar means. The annual evapotranspiration in the wooded Cerrado was the highest among the analyzed LCLU. The pasture presented similar annual evapotranspiration values to those found in the sugarcane and bare soil. However, sugarcane and bare soil had different means for evapotranspiration among them. Concerning the surface runoff, bare soil and pasture presented significant differences from the other LCLU. Hence, the results agree with previous studies, where the land use presented regulatory functions in the water balance (Krishnaswamy et al., 2013; Nobrega et al., 2017). Daily data of the water balance components and average soil moisture (first meter of soil) from allthe analyzed LCLU are available as supplement (S1).

Insert Table 4

Insert Table 3

Insert Fig. 3

The average annual rainfall in the study site was 1388 mm yr^{-1} between 2012 and 2016 (Fig. 3A). It was approximately 100 mm yr^{-1} lower than the average observed during the last 37 years (Cabrera et al., 2016) due to a drought in 2014 (Getirana, 2015; Melo et al., 2016). Additionally, precipitation (P) and soil water storagebalance residual (d*S*/d*t*) were the water balance components that had the largest variations throughout the monitoring period. We observed that sugarcane and pasture were similar considering the water balance components' patterns and orders of magnitude. However, wooded Cerrado and bare soil presented different characteristics from the other LCLU.

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The evapotranspiration estimates (Fig. 3B) were different between the considered land covers (Table ~~4~~3). We observed that the wooded Cerrado evapotranspiration presented the highest rates among all analyzed LCLU and also the smallest variability throughout the year. However, there is no agreement between the measurements and estimates performed in wooded Cerrado areas and the present study (Table ~~5).~~4), due to the diverse rainfall patterns among the study sites and the different methods used to measure or estimate the evapotranspiration. Thus, this study shows evidence of the need for reference values of evapotranspiration in undisturbed areas for a better understanding of their role in the water cycle. In addition, the rainfall is different for the studies compared in Table ~~5~~4.

Insert Table 4

~~**Insert Table 5**~~

The sugarcane evapotranspiration rates were higher than pasture due to the higher crop water demand during the initial phase of its annual cycle, and both evapotranspiration estimates agree with measurements performed by previous studies (Sakai et al., 2004; Cabral et al., 2012; Nobrega et al., 2017). Both sugarcane and pastureland ceased the evapotranspiration during the dry season due to the decoupling condition, when the radiation is the only contributor to the evapotranspiration process (water stress condition) (Pereira, 2004). This happens due to the lack of water readily available for the plants along the root zone. This condition does not repeat in the wooded Cerrado as its root system is deeper (Canadell et al., 1996), and the plants may reach water in depths where sugarcane and pasture cannot do this. However, the root zone depth of an undisturbed vegetation such as the wooded Cerrado is uncertain and may vary according to the soil characteristics (Canadell et al., 1996) and the groundwater table level (Leite et al., 2018). It may influence the plants' transpiration (Rawitscher, 1948; Oliveira et al., 2005), and consequently the water balance residual.

The surface runoff (Fig. 3C) presented the lowest values among all water balance components and it was the most influenced variable by the land use. There was no surface runoff generation during August due to the non-occurrence of rainfall events. The bare soil was the most sensitive to the runoff generation throughout the dry season, when the occurrence of rainfall events was lower. The months of January, February and March registered the highest averages for rainfall due to the wet season. The runoff coefficients for wooded Cerrado, sugarcane, pasture, and bare soil were 0.001, 0.007, 0.029 and 0.063, respectively. These values are in compliance with a previous study performed by Oliveira et al. (2016) for similar conditions. Although a higher runoff coefficient for sugarcane in comparison with the pasture was expected, sugarcane presented runoff values significantly lower than pasture as the soil tillage increased water infiltration and, consequently, reduced the surface runoff. Additionally, there is an apparent inverse linear relationship between culture size and runoff coefficient.

The surface runoff in sugarcane plantations is not well understood by the scientific community despite the economic importance to the country. The monitored values agreed with previous studies in the same study area (Oliveira et al., 2016; Youlton et al., 2016b; Anache et al., 2018). The highest runoff rates were registered after planting and harvesting events, when the soil is more exposed to the rainfall.

In addition, the surface runoff in the pasture presented significantly higher rates in comparison with sugarcane and wooded Cerrado, due to the top soil compaction caused by grazing. The order of magnitude of the measured runoff in the pasture plots are similar to those previously published (Saraiva et al., 1981; Silva et al., 2011; Dedecek, 1989). The high runoff variability observed in this land use was due to the variable presence of animals, which were managed in an extensive approach and, consequently, heterogeneities may happen in soil compaction and vegetation conditions (Nacinovic et al., 2014). Additionally, the deforestation and agricultural land uses may increase soil compaction, as the LCLUC influence the hydrological patterns along the soil profile by evident modifications in the soil characteristics (bulk density, infiltration capacity, etc.) (Lamparter et al., 2016; Meister et al., 2017; de Almeida et al., 2018).

The wooded Cerrado presented the lowest runoff rates among all LCLU due to the higher soil protection, which avoided the overland flow generation. The order of magnitude of the surface runoff in the wooded Cerrado was similar to those found in shrublands and forested areas (Dedecek, 1989; Silva et al., 2011; Oliveira, 2012; Nacinovic et al., 2014; Oliveira et al., 2015). These reduced surface runoff rates in the wooded Cerrado increase soil water infiltration in comparison with pasture, sugarcane and bare soil. Thus, higher infiltration rates increase plant water availability (Krishnaswamy et al., 2013). Additionally, the organic matter layer above the soil (wooded Cerrado's forest floor litter) reduces the overland flow. In some cases, the litter removal may increase the surface runoff up to 50% (Gomyo and Kuraji, 2016).

The water balance residuals, which represent the soil water storage (Fig. 3D) showed the water surplus (positive values) and deficits (negative values), showing evidence ofevidencing the consumption of the soil water storage along the dry season (June – September). Such behavior is also evidenced by the average soil water storage. Onlycontent along the first meter of soil (Fig. 3E), as the soil moisture became lower in the wooded Cerrado in comparison with pasture and sugarcane observations during the dry season. This is because only the wooded Cerrado condition had negative values during the dry season, as the other land uses (sugarcane and pasture) had no conditions to remove water from deeper regions due to the shallow root system and their physiological characteristics. Thus, wooded Cerrado vegetation adapted to dry weather conditions, due to the plant water demand for evapotranspiration, which reduced gradually as long as the soil water storagebalance residual accumulated during the wet season was consumed (Oishi et al., 2010; Christoffersen et al., 2014; Cabral et al., 2015; Oliveira et al., 2015).. In addition, the structural quality of soil from undisturbed woodlands leads to a higher capacity to retain water than that pasture soil (Tseng et al., 2018).

3.2 Groundwater table fluctuation

The groundwater table fluctuation inside the wooded Cerrado area was lower compared to the pasture area considering the observations of the monitoring wells (Fig. 3E and Fig. 4). This variation in the wooded Cerrado was less than 1 meter per year due to the water deficit periods during the dry season.3F). This variation in the wooded Cerrado was less than 1 m per year due to the water deficit periods during the dry season. In addition, a similar study in a Cerrado area (Villalobos-Vega et al., 2014) verified that the groundwater table fluctuation tend to be lower where the unsaturated zone is thicker. In the well located in the pasture, the water table fluctuated negatively along 2014 and 2015 due to the drought that happened in 2014

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(Getirana, 2015). The water surplus of 2015-2016 happened due to the La Niña phenomena, that raised the rainfall pattern after the long dry season of 2014-2015 (Kakatkar et al., 2018). Consequently, the water table raised along 2016. The water scarcity periods that occurred in the wooded Cerrado area were due to the higher vegetation demand, as it is denser than the pasture and it has a deep root system. It is important to remember that both monitoring wells (pasture and wooded Cerrado) have the same non-saturated zone thickness (40 m) and similar hydraulic conductivities (approximately 10^{-3} m d^{-1}). The evapotranspiration and root zone depth controlled the soil water storagecharacteristics. However, in order to perform more complete evaluations of the hydrogeological processes in the study site, further measurements and additional monitoring wells may be necessary.

There are clear evidences that a time lapse between the water infiltration thought the soil and the aquifer recharge exists due to the huge non-saturated zone thickness (around 40 m) (Fig. 3F). For this reason, we cannot ignore that the evapotranspiration influences the aquifer recharge, as previously reported by other studies under similar and different conditions from the present study (Scanlon et al., 2005; Scott et al., 2014; Lucas et al., 2015; Oliveira et al., 2017; Lucas and Wendland, 2015). Changes in the LCLU, such as the potential conversion from wooded Cerrado to an agricultural LCLU (here we tested the pasture), may affect groundwater recharge, processes and availability. These effects tend to be non-linear and difficult to analyze as they result from complex interactions between LCLU and hydrological processes (Han et al., 2017). Thus, mathematical approaches (Archer and Fowler, 2018; Gómez et al., 2018) or natural tracers (Su et al., 2018) are useful tools to verify the response time of the groundwater table to the water balance from different LCLU. In further studies, such techniques may be part of a solution to investigate how responsive the aquifer is to the surface water partitioning in the conditions considered here along the time.

The evapotranspiration and root zone depth controlled the water balance residual and, consequently, the water percolation throughout the non-saturated zone and aquifer recharge (Finch, 1998; Gouvêa and Wendland, 2011; Krishnaswamy et al., 2013; Lucas and Wendland, 2015; Domínguez et al., 2016; Manzione et al., 2017).. In the pasture area (site 1), the soil water that was not consumed by the plants and neither evaporated, flowing down along the unsaturated zone. Consequently, the water uptake by the plants becomes unfeasible as the roots are more shallow (see Table 2) than in the wooded Cerrado. Furthermore, the aquifer recharge decreases as the vegetation density increases in undisturbed Cerrado areas (Oliveira et al., 2017), following the principle that the increased canopy cover of the wooded Cerrado found in the study area may occur due to the deep groundwater level (Leite et al., 2018).(Leite et al., 2018; Villalobos-Vega et al., 2014). However, the water balance analysis performed here focused on hillslope hydrology, and the monitoring wells depths reflects the aquifer behavior in a broader area covered by pasture and wooded Cerrado in comparison with the 100-m2 plots where we monitored the surface water partitioning. Thus, all assumptions made throughout this section are subject to further analysis, which may include the water balance calculation for a broader area (e. g. the whole 300 ha wooded Cerrado fragment where part of the present study plots were located to represent either LCLU). Nevertheless, the hillslope scale water balance outcomes are comparable to the groundwater table fluctuations, as the wells represent the plots' surroundings for the pasture and wooded Cerrado LCLU. Groundwater depth monthly datasets of the monitoring wells (wooded Cerrado and pasture) are available as supplement (S2).

~~**Insert Fig. 4**~~

3.3 Data uncertainties

The water balance components (*P*, ~~Q~~O_F, E_T, and d*S*/d*t*) uncertainties were calculated for each land cover (Table ~~6~~5) and the relative errors agreed with previous water balance studies in different scales (Graham et al., 2010; Oliveira et al., 2014). Concerning rainfall (P), which is the only water input, the same measured values were used for all LCLU. The surface runoff presented higher relative uncertainties in the pasture plots, followed by bare soil, wooded Cerrado, and later by sugarcane. Evapotranspiration (ET) can be a potential source of uncertainties in a water balance (da Paz et al., 2014), it was estimated adopting methods that use ground measured variables (e.g. temperature, relative humidity, solar radiation and soil moisture) and the relative uncertainties may reach up to ~~41~~63%. The pasture presented the higher relative error for ET due to the reduced average evapotranspiration compared to the other LCLU (sugarcane and wooded Cerrado~~).~~), and the wooded Cerrado presented the higher standard error for ET. Nevertheless, the water balance hypothesis mainly relies on minimizing uncertainties in the evapotranspiration estimates or measurements (Beven, 2006). The surface runoff (~~Q~~O_F) did not contribute significantly in the water balance error propagation due to its reduced order of magnitude compared to the other water balance components (E_T and *P*). However, runoff measurements produced relative errors that reached up to ~~51~~26% (pasture).

Insert Table 5

Insert Fig. 4

The ~~soil~~ water ~~storage~~balance residual (d*S*/d*t*) presented the accumulated uncertainties from rainfall, surface runoff and evapotranspiration (Fig. ~~5~~4). All LCLU presented ~~a relative error~~standard errors for d*S*/d*t* with similar orders of magnitudes, except the bare soil, which presented lower ~~than 50%.~~errors due to the reduced number of inputs to calculate the evaporation in an open-surface condition. The wooded Cerrado accumulated an error of ~~40%~~636 mm yr^{-1} for the water balance residual mainly due to its highest component: evapotranspiration. This suggests that efforts to minimize the uncertainties in measuring or estimating the evapotranspiration in the wooded Cerrado may significantly improve its water balance. Additionally, other land uses (pasture and sugarcane) also presented a high d*S*/d*t* uncertainty due to the standard error accumulated from the evapotranspiration estimates.

3.4 Water balance trade-offs due to the LCLUC

The Brazilian Cerrado is very important economically, as it is responsible for most of the agricultural production that supplies both external and internal markets (Klink and Machado, 2005). A better understanding of the trade-offs between the ecosystem and economical needs that govern the land cover and land use dynamics in the Cerrado biome is necessary (Marris, 2005). The undisturbed Cerrado area was reduced to 50% of its original extension due to intense land use (Lapola et

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al., 2013; Alkimim et al., 2015). The undisturbed vegetation helps to maintain the water cycle, with low surface runoff and high evapotranspiration rates.

This study show evidence that the suppression of the wooded Cerrado ~~by~~and the conversion to agricultural land uses, such as sugarcane and pasture, increased the surface runoff and decreased evapotranspiration, even considering measurements and estimation method uncertainties. Consequently, the ~~soil water storage (dS/dt), which was defined by the~~ water balance residual~~,~~, (dS/dt), increased significantly, suggesting that the infiltration also rose. However, the soil water was not available to the plants' roots in the agricultural land uses during the dry season (April – September), likewise the wooded Cerrado~~.~~, where the soil water content is (in average) higher than the agricultural LCLU (Fig. 3E). Thus, the percolation and aquifer recharge increased in the agricultural area (site 1) and this fact was explained by the water table fluctuations observed in the monitoring well located in the pasture that were not observed in the monitoring well located inside the wooded Cerrado area (site 2).

Previous studies show that native forests help to maintain aquifer recharge by the high infiltration rates, similarly to observations performed in tropical forests in south India and in mountainous areas in the Himalayas (Krishnaswamy et al., 2013; Ghimire et al., 2014). Nevertheless, evapotranspiration appears as a key component in the aquifer recharge control in the study site condition, which is located in a Guarani Aquifer System outcrop zone (Lucas et al., 2015; Lucas and Wendland, 2015). Therefore, the aquifer recharge rates, evidenced here by the groundwater table fluctuation (Fig. 3F), may be reduced in ~~undisturbed~~ forested areas in comparison with agricultural landscapes due to the atmospheric and vegetation water demands~~.~~, and the increased soil water retention capacity (Adane et al., 2018; Dias et al., 2015; Wang et al., 2018; Tseng et al., 2018). This validate the information that the LCLU significantly impacts groundwater recharge (Scanlon et al., 2005; Scott et al., 2014; Lucas et al., 2015; Dawes et al., 2012). This fact ~~suggests~~may suggest that the ecosystem services of native forests, such as the wooded Cerrado, is not the aquifer recharge maintenance, but rather the constant return of water to the atmosphere throughout the year.

Significant and non-significant changes in the water partitioning may be observed in the case of substituting the wooded Cerrado by bare soil, pasture or sugarcane (Fig. ~~6~~5). We highlight the E_T reduction (more than 400 mm yr^{-1}). The worst case scenario (bare soil condition) is generally the transition between the LCLU (fallow condition), increasing significantly surface runoff rates and impacting soil and water conservation (Pimentel et al., 1995).

Insert Fig. ~~6~~5

Sugarcane and pasture presented trade-offs that were equal, as non-significant changes occurred among each other's water balance components. However, the sugarcane plantation presented a higher potential to maintain the evapotranspiration rates closer to the undisturbed Cerrado conditions than the pasture, agreeing with previous estimates (Loarie et al., 2011). In addition, it is suggested that sugarcane has increased evapotranspiration rates in comparison with other annual crops (Guarenghi and Walter, 2016; Hernandes et al., 2018b, a).

~~**Insert Table 6**~~

~~**Insert Fig. 5**~~

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4 Conclusions

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This paper presented an experimental approach at the hillslope scale concerning the possible water partitioning trade-offs due to the LCLUC dynamics. We monitored the water balance components over 5-years in different land covers: wooded Cerrado, pasture, sugarcane and bare soil. These land covers are subjected to the current LCLUC dynamics in southeastern Brazil. The water partitioning observations in different LCLU confirm that ~~changes~~modifications in the land surface conditions may significantly change the ~~soil water storage (up to 584 mm yr^{-1}), which is the~~ water balance residual~~.~~ (up to 584 mm yr^{-1}). The decrease in evapotranspiration and increase in surface runoff are common patterns when the wooded Cerrado is replaced by agricultural land uses. The water balance outcomes evidences that the undisturbed Cerrado vegetation consumes the soil water storage along the dry season (June – September). By contrast, the agricultural LCLU (pasture and sugarcane) reduce or even stop the water consumption along either season. The probable main reason for that is the reduced water retention capacity commonly found in disturbed soils.

Higher water consumption by dense and native vegetation, such as the wooded Cerrado, also happens due to the higher infiltration rates, increasing the plant water availability. In general, the root systems are deeper than pasturelands and sugarcane plantations, and have the capacity of reaching water for transpiration deeper in the soil profile. This maintains evapotranspiration throughout the year, even during the dry season. Hence, less water becomes available for the aquifer recharge in areas where the canopy layer is higher and denser. However, reference values for evapotranspiration in undisturbed land covers, such as the wooded Cerrado, are still needed in order to reduce uncertainties from the current approximations and validate the water balance hypothesis. Particularly the ~~wooded~~undisturbed Cerrado and agricultural LCLU should be investigated concerning its potential to maintain the aquifer recharge and groundwater availability, as well as answering how responsive the aquifer is to the surface water partitioning in different LCLU along the time.

Data availability

The datasets underlying this research are available as supplements (S1 and S2) of this paper and they are accessible from the following data repository link: http://www.hydroshare.org/resource/a1c032dbb78d48748b673c876c20b21c.

Author contribution

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JAAA, EW, PTSO and CY designed the experiments and JAAA, LMPR, PTSO and CY carried them out. JAAA, LMPR and EW analysed the experiments' outcomes and discussed the results. JAAA and EW prepared the manuscript with contributions from all co-authors.

Competing interests

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The authors declare that they have no conflict of interest.

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Tables

Table 1: Monitoring site instrumentation~~.~~ characteristics.

Variable	Sensor	Height or depth (m)	Measurement range	Maximum error	Site no.
Temperature (°C) and relative humidity (%)	HMP45C	2.0	-39.2 to +60°C and 0.8% to 100%	±0.5°C and ±3%	1
	HC2S3	9.5 and 11.0		±0.1°C and ±0.8%	2
Rainfall (mm)	Hydrological Services TB4	1.5 and 11.0	0 to 700 mm h^{-1}	±3%	1 and 2
Atmospheric pressure (mbar)	Vaisala CS106	1.0	500 to 1100 mBar	±1.5 mBar	1
Wind direction (°) and velocity (m.s^{-1})	Young 05103	2.0 and 11.0	0 to 360° and 0 to 100 m s^{-1}	±3° and ±0.3 m s^{-1}	1 and 2
Solar radiation (MJ.m^{-2})	Kipp & Zonen CMP3	2.0	0 to 2000 W m^{-2}	±5%	1
Soil moisture (%)	FDR	-0.3; -0.6 and -0.9	0 to ~65%	±3%	1*
	Environscan Sentek	-0.1; -0.5; -0.7; -1.0 and -1.5			2
Net solar radiation (W.m^{-2})	Kipp & Zonen NR-LITE2	11.0	±2000 W m^{-2}	±5%	2
Soil heat flux (W.m^{-2})	Hukseflux HFP01	-0.1	±2000 W m^{-2}	-15% to +5%	2
~~Water~~Groundwater table (~~groundwater) (~~m)	Diver Schlumberger	-40.0 and -39.2	0 to 10 m	± 2.5 cm	1 and 2

*At site 1, the bare soil did not have soil moisture probes.

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Table 2: Variables used to calculate evapotranspiration for sugarcane and pasture.

Variable	Sugarcane	Pasture	Source
Z_f (m)	1.2 – 2.0	0.5 – 1.5	Allen et al. (1998)
p	0.65	0.60	
θ_{fc}	0.14	0.14	Values obtained from laboratory essays (Oliveira, 2014)
θ_{wp}	0.09	0.09	
Kc K_C	Plant (1): 0.5050[a]; 0.80; 09580[b]; 095[c]; 1.1010[d]; 1.1818[e]; 0.9292[f]; 0.6868[g] Ratoon (2): 0.5555[a]; 0.80; 09080[b]; 090[c]; 1.0000[d]; 1.0505[e]; 0.8080[f]; 0.6060[g]	0.75 (3)	(1) Doorenbos et al. (1975) (2) Doorenbos et al. (1979) (3) Allen et al. (1998)

Approximate sugarcane age (days): a (0-30); b (30-60); c (60-75); d (75-120); e (120-300); f (300-330), g (330-360).

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Table 3: Priestley and Taylor coefficients (α) calculated for a wooded Cerrado area.

Season	Priestley and Taylor coefficients (α)
Summer (December – March)	1.09
Fall (March – June)	1.00
Winter (June – September)	0.77
Spring (September – December)	0.98

~~Table 4~~Table 3: **Mean and standard deviation of the annual water balance components for 2012-2016 period.**

Land use	Water balance components (mm yr^{-1})			
	P	dS/dt	E_T	~~Q~~Q_F
Wooded Cerrado	1388±188	185±182b	1201±49a	2±2c
Pasture		689±135a	654±137bc	45±26b
Sugarcane		571±100a	801±212b	16±18c
Bare soil		769±96a	482±40c	137±62a
Data source	observations	residuals	estimations	observations

dS/dt: ~~soil~~ water ~~storage~~balance residual; P: precipitation; E_T: evapotranspiration; ~~Q~~Q_F: surface runoff; identical lower case letters indicate no significant difference between means in the same column by the Tukey means comparison test (P value > 0.05).

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Table ~~5~~4: Evapotranspiration and rainfall from studies developed in Brazil under similar LCLU of the present study.

Land use	Lat	Long	Method	E_T (mm yr^{-1})	P	References
Sugarcane[1]	-21.63	-47.78	EC	892	1194	Cabral et al. (2012)
Sugarcane[2]	-21.63	-47.78	EC	685	1353	Cabral et al. (2012)
Sugarcane[1]	-22.18	-47.85	FAO 56	930	1535	Present study
Sugarcane[2]	-22.18	-47.85	FAO 56	715	1290	Present study
Wooded Cerrado	-21.62	-47.65	EC	811	1498	da Rocha et al. (2009)
Wooded Cerrado	-21.62	-47.65	EC	1228	1448	Cabral et al. (2015)
Wooded Cerrado	-15.93	-47.88	EC	821	1440	Giambelluca et al. (2009)
Wooded Cerrado	-15.80	-55.33	PM RS	1004	1696	Nobrega et al. (2017)
Wooded Cerrado	-22.18	-47.85	PM RS	823	1194	Oliveira et al. (2015)
Wooded Cerrado	-22.18	-47.85	PT	1201	1388	Present study
Pasture	-3.01	-54.53	EC	647	1597	Sakai et al. (2004)
Pasture	-15.81	-55.34	PM RS	639	1780	Nobrega et al. (2017)
Pasture	-22.18	-47.85	FAO 56	654	1388	Present study
Cerrado and Amazon transition	-11.41	-55.33	EC	1005	2000	Vourlitis et al. (2002)

Lat: Latitude; Long: Longitude; E_T: Evapotranspiration; P: Rainfall; EC: Eddy covariance; PM RS: Penman-Monteith and remote sensing; FAO 56: Allen et al. (1998); PT: Priestley and Taylor (1972); 1: Plant; 2: Ratoon.

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Table 65: Water balance uncertainties.

Variables		LCLU			
		Wooded Cerrado	Pasture	Sugarcane	Bare soil
P (observed)	Average (mm yr^{-1})	1388			
	Standard error (σ) (mm yr^{-1})	42			
	Relative error (ε) (%)	3%			
QO_F (observed)	Average (mm yr^{-1})	2	45	16	137
	Standard error (σ) (mm yr^{-1})	0.2	12	1	27
	Relative error (ε) (%)	10%	26%	5%	19%
E_T (estimated)	Average (mm yr^{-1})	1201	654	801	482
	Standard error (σ) (mm yr^{-1})	60634	268412	273361	2439
	Relative error (ε) (%)	553%	4163%	3445%	58%
d*S*/d*t* (residual)	Average (mm yr^{-1})	185	689	571	769
	Standard error (σ) (mm yr^{-1})	73636	271415	276363	5563
	Relative error (ε) (%)	40344%	3960%	4864%	78%

d*S*/d*t*: water balance residual; *P*: precipitation; E_T: evapotranspiration; O_F: surface runoff.

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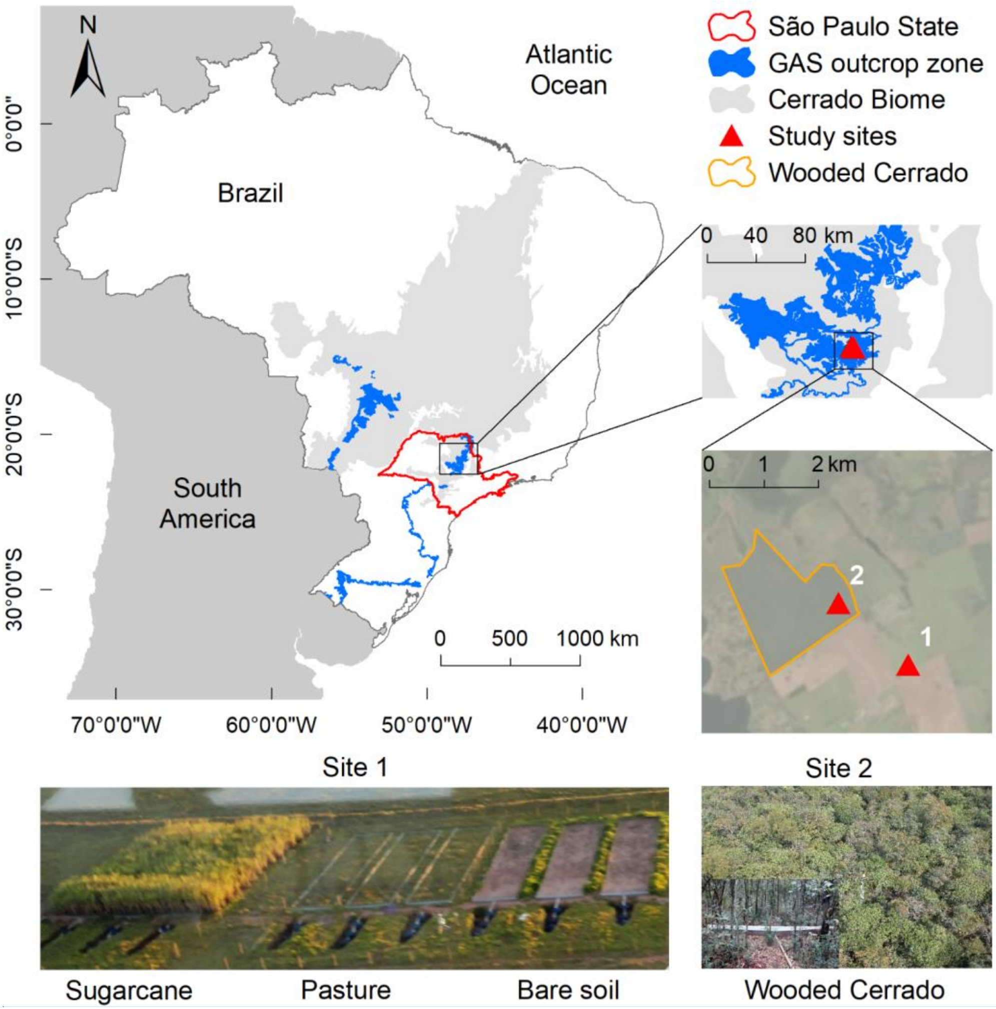
Figures



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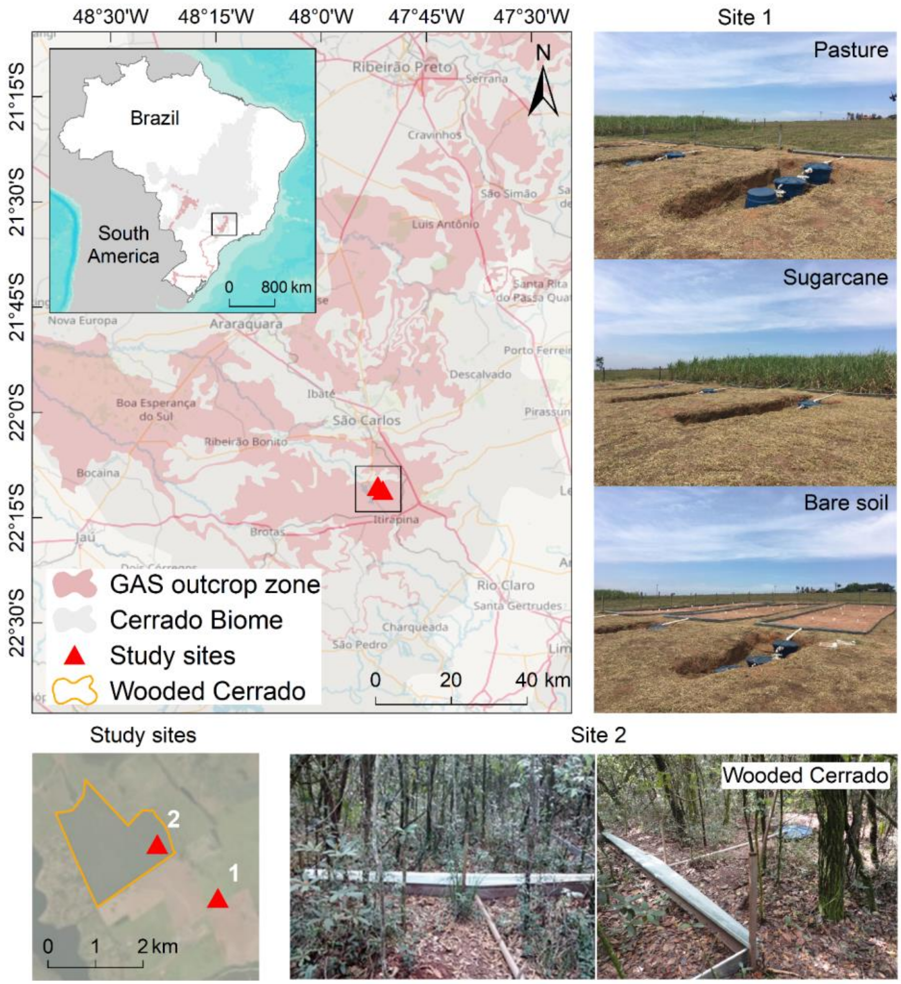
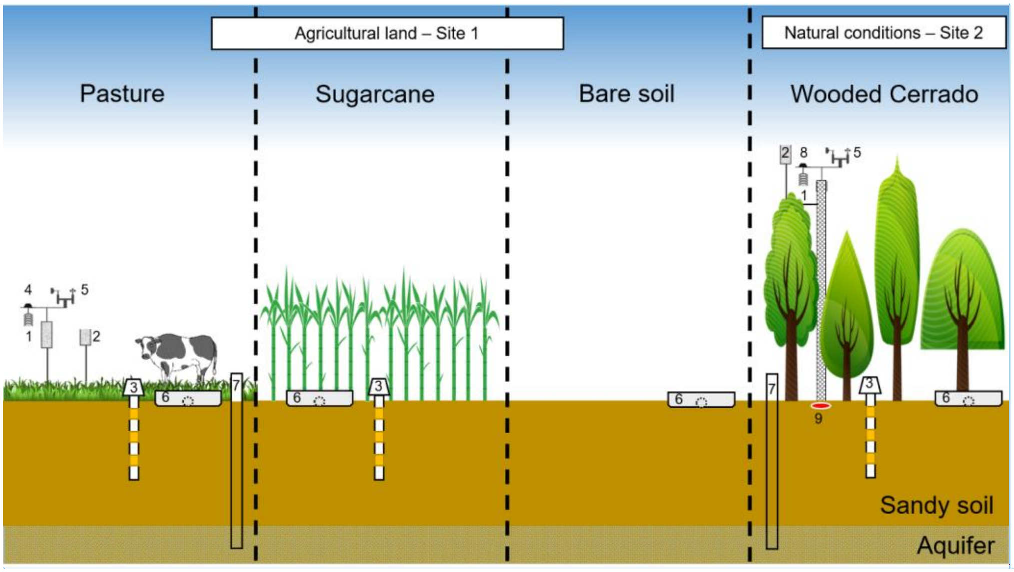


Figure 1: Location of study sites, Cerrado biome borders, Guarani Aquifer System (GAS) outcrop zone distribution in Brazil, and experimental design, where site 1 contains the plots with agricultural land uses (pasture, sugarcane and bare soil) and site 2 contains the plots with wooded Cerrado.



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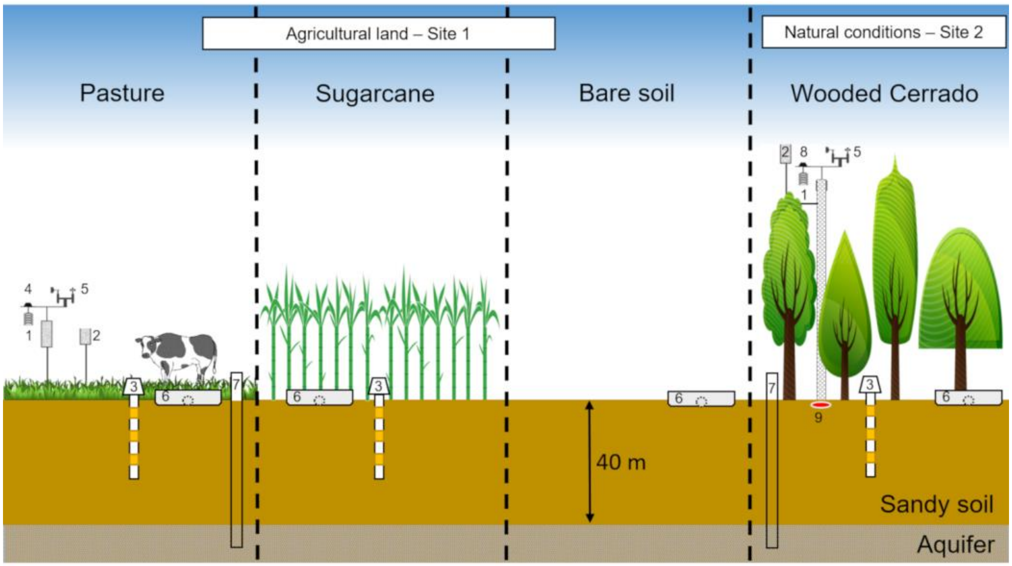
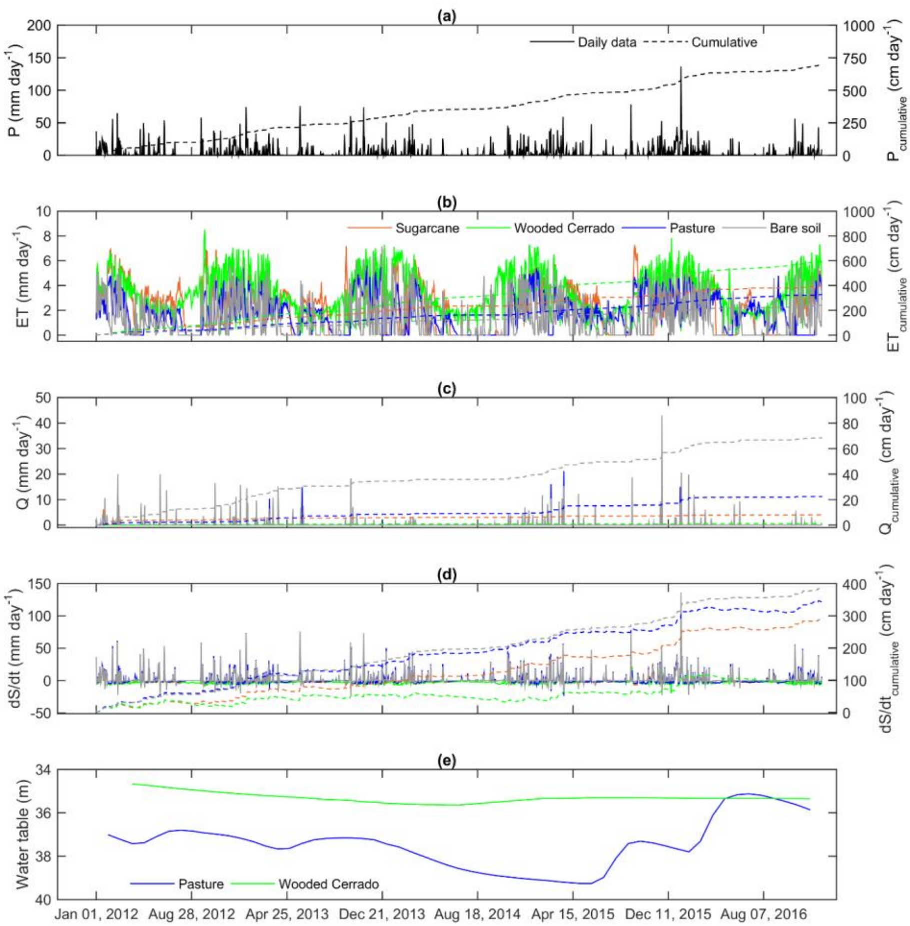


Figure 2: Hydrological monitoring performed on the four treatments: (1) relative humidity and air temperature probes at 2 m (site 1) and 11 m (site 2); (2) rainfall gauges; (3) soil moisture sensors; (4) solar radiation sensor; (5) wind speed and direction (anemometers) at 2 m (site 1) and at 11 m (site 2); (6) surface runoff collectors; (7) monitoring wells equipped with water table pressure transducers; (8) net radiation sensor; (9) soil heat flux plate.



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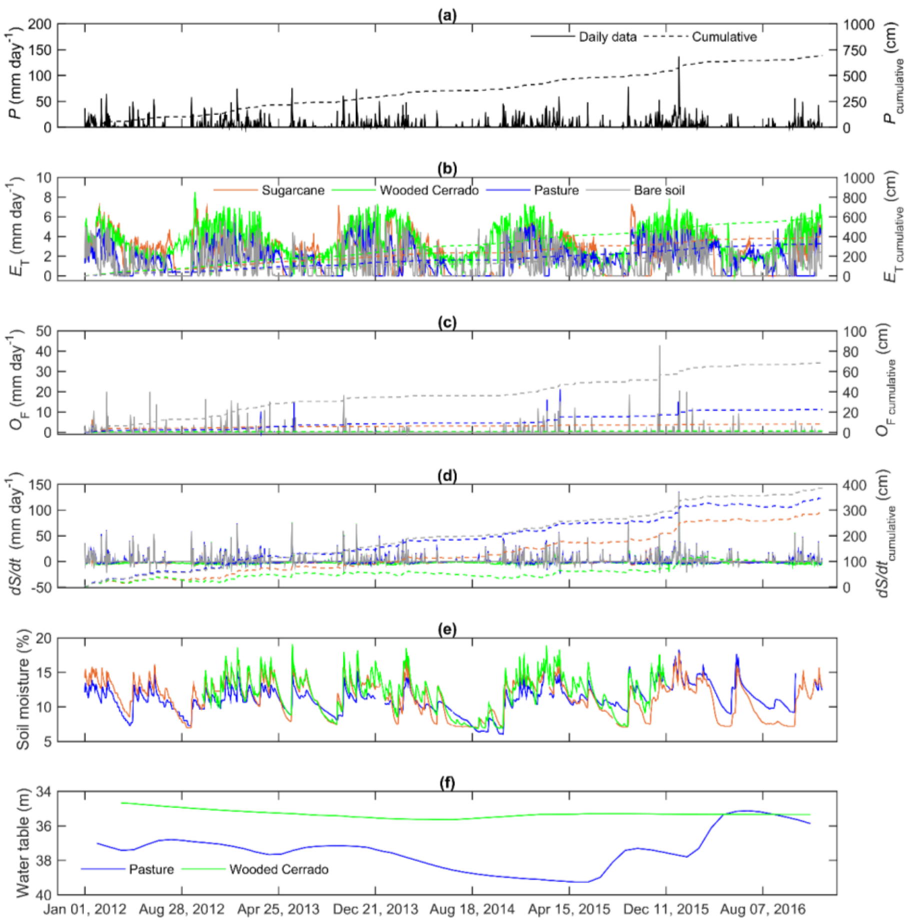

Figure 3: Water balance components for different LCLU rainfall, P (a); evapotranspiration, E_T (b); surface runoff, ~~Q~~O_F (c); ~~soil~~ water ~~storage~~balance residual, dS/dt (d); Right axes present the cumulative sum of the variables represented by graphs (a), (b), (c) and (d). ~~The water table (e~~Soil moisture in the first meter of soil (e) for pasture, sugarcane and wooded Cerrado; and water table (f) depth of the monitoring wells located in site 1 (pasture) and site 2 (wooded Cerrado).

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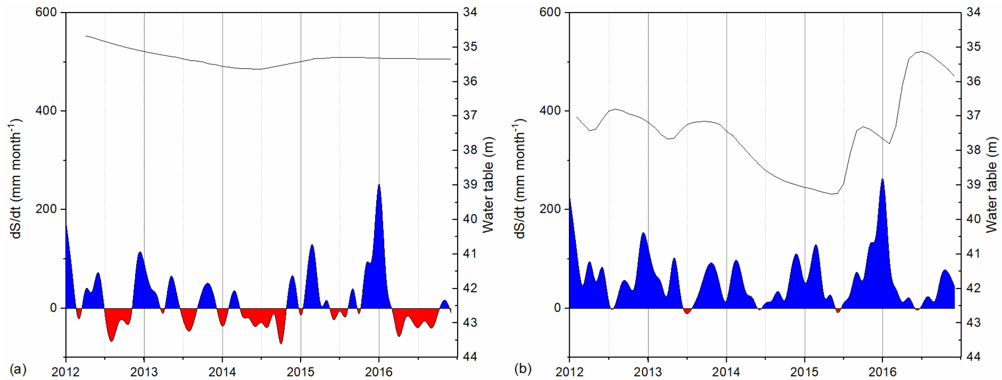

Figure 4: Water balance residual in the wooded Cerrado (a) and in the pasture (b), where the blue areas represent water surplus and red areas represent water deficit; the solid black lines represent the aquifer water table fluctuation.

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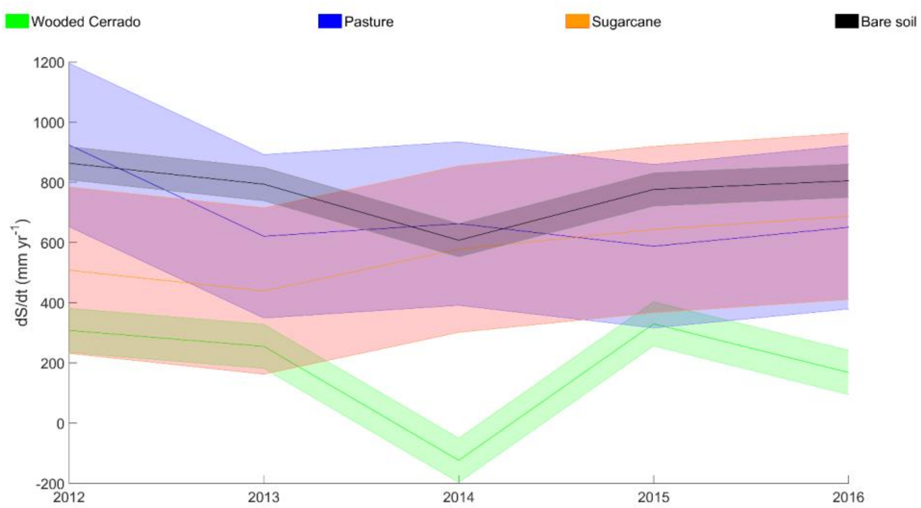

Figure 5: Annual soil water storage

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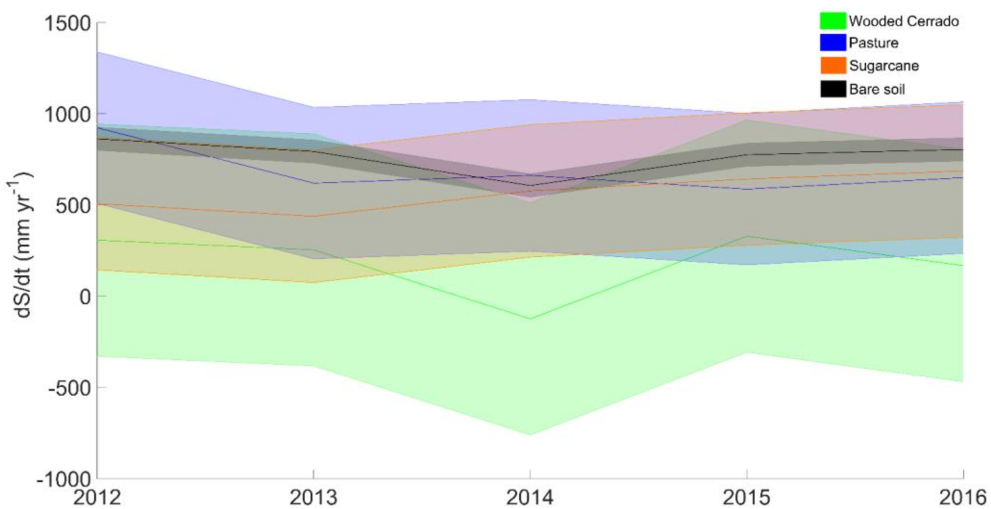

Figure 4: Annual water balance residual (d*S*/d*t*) for different LCLU during 2012-2016 period; shaded areas indicate the standard error (uncertainties) of d*S*/d*t* estimates.

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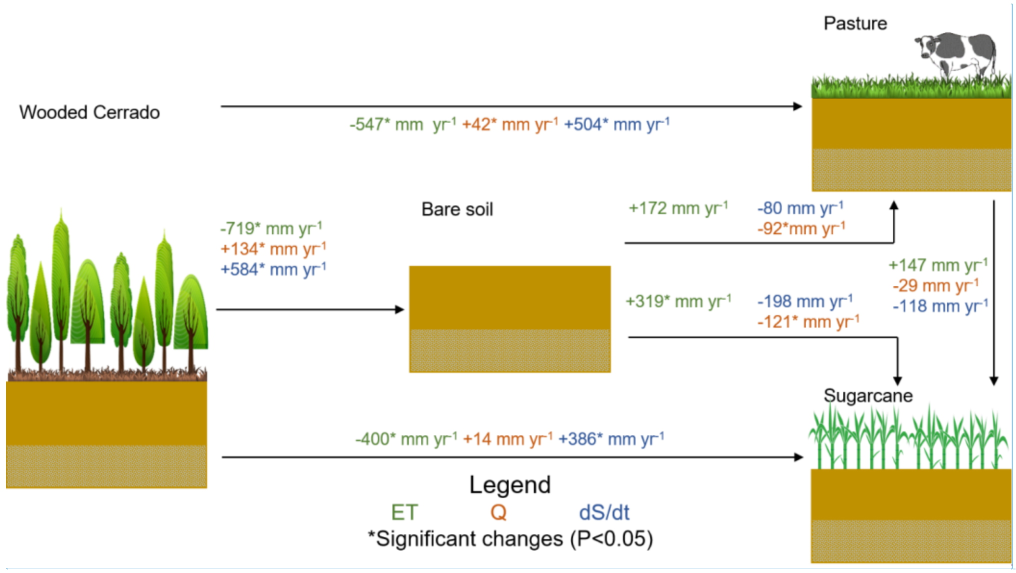

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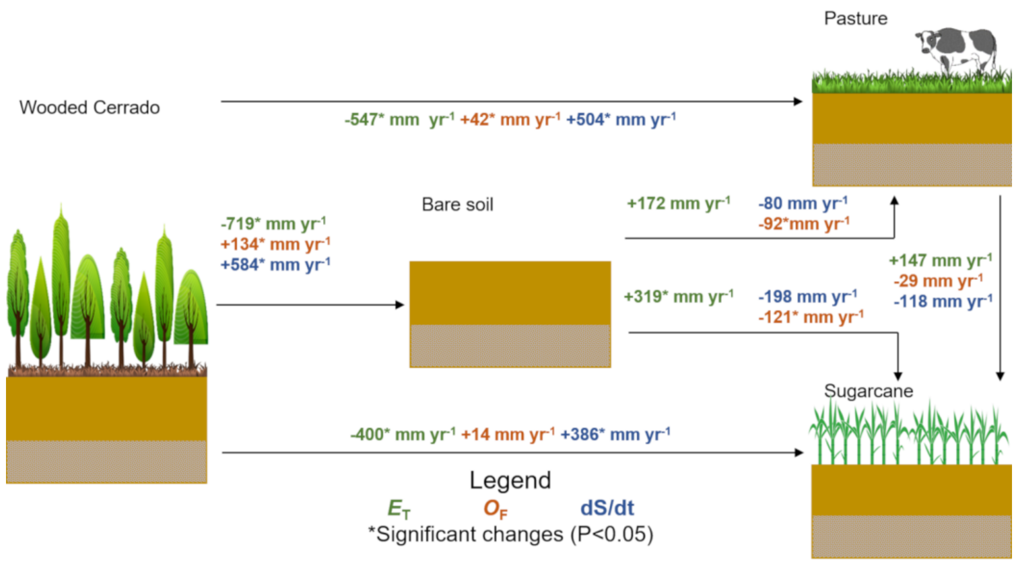

Figure 65: Annual observed means (2012-2016) of hydrological trade-offs related to evapotranspiration (E_T), surface runoff (Q), soilO_F), water storagebalance residual (dS/dt) due to potential LCLUC found in southeastern Brazil.

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