University of São Paulo
“Luiz de Queiroz” College of Agriculture
Center of Nuclear Energy in Agriculture

Effects of climate change and land use change on the water balance components
of the Xingu river basin, southeastern Amazon

Rodnei Rizzo

Thesis presented to obtain the degree of Doctor in
Science. Area: Applied Ecology

Piracicaba
2018

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Effects of climate change and land use change on the water balance components of the
Xingu river basin, southeastern Amazon

versão revisada de acordo com a resolução CoPGr 6018 de 2011

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balanço hídrico 4. Séries temporais 5. Análise de Mann-Kendall I. Título

I dedicate:

To my parents Roberto and Raquel,
for all their love and dedication.

I wouldn't have been able to get to this stage without them.

To Thais, the best gift life could ever give me.
I wouldn't have gotten through this doctorate if it wasn't for her.

To my grandparents Adair and Athur,
who taught me the meaning of unconditional love.

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RESUMO

Efeitos das mudanças climáticas e do uso da terra nos componentes do balanço hídrico da bacia do rio Xingu, sudeste amazônico

O desmatamento em larga escala na região sul da bacia amazônica brasileira, associado às mudanças climáticas globais, tem impactado o ciclo hidrológico regional. Previsões futuras indicam uma pressão ainda maior sobre os recursos hídricos regionais. O objetivo deste estudo foi realizar uma avaliação detalhada das possíveis alterações nos recursos hídricos da bacia do Alto Xingu, uma região extremamente representativa do sul da Amazônia. Para tanto, foram empregadas séries temporais de longa e média duração, correspondentes à precipitação (P), vazão (Q), evapotranspiração (ET) e variação do armazenamento de água (TWS). O estudo empregou medições *in situ*, bem como dados de sensoriamento remoto (SR). As estimativas de sensoriamento remoto foram empregadas na avaliação do balanço hídrico regional. As séries temporais de treze anos derivadas de produtos de SR foram submetidas a uma análise de tendência, com o objetivo de detectar variações significativas nos componentes do balanço hídrico. Além disso, as incertezas em cada produto foram obtidas comparando-se medições *in situ* com as estimativas de SR. Com o objetivo de descrever as limitações de tais produtos para a realização do balanço hídrico regional, a vazão do rio Xingu foi estimada com base na fórmula do balanço hídrico. Posteriormente, tal estimativa foi comparada com as medições *in situ*, gerando um indicativo da incerteza no fechamento do balanço hídrico. Já a análise das alterações a longo prazo considerou as medidas *in situ* da precipitação e vazão, no período de 1976-2015. Neste caso, um grupo de indicadores hidro-climatológicos foi calculado e posteriormente submetido aos testes de Mann-Kendall e Pettit. Devido à relevância das florestas na regulação da vazão dos rios, as mudanças no uso e ocupação da terra foram mapeadas a cada cinco anos, durante 1985-2015. Os resultados foram comparados aos dados hidro-climatológicos, buscando assim semelhanças nos padrões de alteração. Os produtos de sensoriamento remoto descreveram razoavelmente bem a variabilidade espacial dos componentes do balanço hídrico. As incertezas nas estimativas de P, ET e TWS corresponderam a 41, 25 e 18 mm mês⁻¹. Devido a incertezas nos produtos de SR, não foi possível realizar o fechamento do balanço hídrico. Com relação as séries temporais derivadas dos dados de SR, nenhuma mudança significativa foi observada. Por outro lado, a avaliação das séries temporais de longa duração, apresentaram diminuição de 245 mm na precipitação, com as chuvas tendo intensidade e número de eventos reduzidos. Este fenômeno é provavelmente resultante de dois processos, sendo um deles a redução na ciclagem da água devido ao desmatamento. O segundo corresponde a oscilação decadal na temperatura da superfície do Oceano Pacífico, a qual influencia a circulação atmosférica em grande escala. Embora o desmatamento cause aumento na vazão do rio, a redução da precipitação na Bacia do Alto Xingu foi suficientemente alta para mascarar esse efeito. Os dados aqui apresentados não só apresentam um diagnóstico sobre os recursos hídricos do Alto Xingu, como também são extremamente relevantes para a compreensão da interação entre a paisagem e os componentes do balanço hídrico.

Palavras-chave: Bacia do alto rio Xingu; Componentes do balanço hídrico; Produtos de sensoriamento remoto; Séries temporais de longa duração; Análise de Mann-Kendall

ABSTRACT

Effects of climate change and land use change in water balance components of the Xingu river basin, southeastern Amazon

In the southern of the Amazon basin, extensive deforestation associated with global climate change have impacted the regional water cycle. Predictions indicate that future alteration might cause even higher pressure over regional water resources. The goal of this study was to perform a detailed evaluation of past changes in the water resources of the upper Xingu basin, a region which is broadly representative of southern Amazon. The evaluation consisted of characterizing alterations in medium and long-term time series of rainfall, river discharge, evapotranspiration and total water storage change. The study employed not only in situ measurements, but also remotely sensed data. Remote sensing products including rainfall, evapotranspiration and water storage change were employed in the evaluation of the regional water balance. A thirteen years' time series derived from RS products was submitted to a trend analysis, to detect significant variations in the water balance. Furthermore, uncertainties in each remote sensing product were retrieved, mostly comparing in situ measurements with RS estimates. To describe limitations of such products to evaluate the regional water balance, river discharge was calculated as the residual of the water balance. Later on, the estimated river discharge was compared to in situ measurements and uncertainties in the water balance were defined. The analysis of long-term alterations considered in situ measurements of rainfall and river discharge, from the period of 1976-2015. In this case, a group of hydro-climatological indicators was derived and then submitted to Mann-Kendall and Petit test. Due to the relevance of forest cover on river flow regulation, land use changes (LUC) were mapped every five years from 1985 to 2015. LUC results were then compared to the hydro-climatological data, to identify similarities in changing patterns. The evaluation of water balance components based on remote sensing products described fairly well the spatial variability in the study site. The uncertainties in P, ET and TWSC products corresponded to 41, 25 and 18 mm month⁻¹, respectively. Due to these uncertainties, it was not possible to perform the water balance closure based on RS data. No significant changes were observed in the time series derived from these products. Contrastingly, the evaluation of a 40-years' time series presented a decrease of 245 mm in rainfall, with intensity and number of rainy events being reduced. This phenomenon is most likely resultant from two process, the reduction in water recycling due to deforestation, as well as the Pacific Ocean decadal oscillation, which influences the large-scale atmospheric circulation. Although deforestation tends to increase river discharge, the reduction in rainfall in the Upper Xingu Basin was high enough to mask this effect.

Keywords: Upper Xingu basin; Water balance components; Remote sensing products; Long-term time series; Mann-Kendall analysis

1. INTRODUCTION

The southern Amazon provides important ecosystem services at local, regional and continental scales. Some of them, such as food and energy production, are easily recognized at local and regional levels. Other essential services, provided by the large and contiguous rainforest existent in the area, such as the carbon sequestration from the atmosphere, air chemistry and climate regulation, as well as water balance and flows (Foley et al., 2007), are still not so clearly identified by the majority of the population. However, in the last decades, the increasing concern of climate change has raised attention to land use changes in Amazon and therefore the impacts on the services provided by the region.

Climate changes associated with increasing atmospheric greenhouse gas concentrations are expected to lead to significant changes in the Amazon energy and water balance, thus impacting ecosystem services related to regional water resources. There is a generally high confidence that, by the end of the century, increasing greenhouse gas concentrations will create a significantly warmer and drier climate in Amazon (Coe et al., 2016; Malhi et al., 2008). Most of the IPCCs (Intergovernmental Panel on Climate Change) models suggest not only a potentially severe decline in rainfall, but also more frequent and severe droughts in the southern and eastern Amazon (Coe et al., 2016).

Another aspect that has influenced the water and energy balances at the southern Amazon are the high deforestation rates. Decrease in forested areas reduces evapotranspiration, weakening moisture recycling and deep convection in the atmosphere (Costa and Foley, 2000). Such process has the potential to reduce convective clouds and consequently rainfall. In the last two decades, reductions in precipitation in this region have been found and related to a 10 cm decrease in regional water storage. At larger scales, lower rainfall caused by forest loss could result in lower river flows (Spracklen et al., 2012). On the other hand, in small watersheds, reduced evapotranspiration following deforestation increases runoff by 3 to 4 fold (Hayhoe et al., 2011).

One area of the southern Amazon that has been under intense land use changes since the early 1980's is the upper portion of the Xingu basin. In just 10 years (2001 – 2010), approximately 12 % (18 838 km²) of this basin forests were converted to croplands or pasturelands, resulting in expressive decreases in the region's natural vegetation cover (Silvério et al., 2015). Therefore, the main objective of this study was to perform a detailed evaluation of past changes in the water resources of the Xingu headwaters, by characterizing alterations in the medium and long-term time series of rainfall (P), river discharge (Q), evapotranspiration (ET)

and total water storage change (TWSC). Considering data collection restrictions imposed by isolated regions such as the Amazon basin, the study employs not only in situ measurements, but also remotely sensed data. A reliable set of remote sensing (RS) data is available for the period from 2001 to 2013. In situ measurements corresponded mostly to rainfall and river discharge data, which are used to analyze trends in the last four decades (1976-2015). Due to spatio-temporal differences in the datasets and therefore the environmental processes represented by each one, the study was performed in two steps, resulting in two chapters.

In the first chapter, the water balance components from the upper Xingu basin are characterized based on information from remote sensors, more specifically the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) rainfall estimates, ALEXI (Atmosphere-Land Exchange Inverse model) evapotranspiration and GRACE (Gravity Recovery Climate Experiment) equivalent water thickness anomalies. Later on, the thirteen years' time series derived from RS products were submitted to a trend analysis, to detect if there were significant variations in the water balance. Finally, uncertainties associated to each of the RS products were defined and the water balance closure performed. The time period evaluated in this specific study is considered of paramount changes in the region, not only due to high land use changes, but also because of expressive regional climate variations described in the literature (Brando et al., 2010; Hilker et al., 2014; Silvério et al., 2015). Such changes can result in alterations in the water balance, consequently impacting local and regional water resources. In the second chapter, attention is focused on rainfall and river discharge changes during 1976-2015. The analysis considers not only the overall fluxes, but also derive a group of hydro-climatological indicators that support the understanding of regional process. Due to forests relevance in river flow regulation and water recycling process, land use changes (LUC) were mapped every five years during 1985-2015. LUC results were then compared to the hydro-climatological data, looking for similarities in changing patterns. Furthermore, Mann-Kendall and Pettit analyses were employed to detect significant trends as well as abrupt changes in the time series. The two studies here presented provide useful insights on hydro-climatological alterations in an important region of the Amazon basin, and also describe how anthropization might have influenced water resources.

REFERENCES

- Brando, P.M., Goetz, S.J., Baccini, A., Nepstad, D.C., Beck, P.S.A., Christman, M.C., 2010. Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proc. Natl. Acad. Sci.* <https://doi.org/10.1073/pnas.0908741107>
- Coe, M.T., Macedo, M.N., Brando, P.M., Lefebvre, P., Panday, P., Silvrio, D., 2016. The Hydrology and Energy Balance of the Amazon Basin. Springer Berlin Heidelberg, pp. 35–53. https://doi.org/10.1007/978-3-662-49902-3_3
- Costa, M.H., Foley, J.A., 2000. Combined effects of deforestation and doubled atmospheric CO₂ concentrations on the climate of Amazonia. *J. Clim.* [https://doi.org/10.1175/1520-0442\(2000\)013<0018:CEODAD>2.0.CO;2](https://doi.org/10.1175/1520-0442(2000)013<0018:CEODAD>2.0.CO;2)
- Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., Defries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P., 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Front. Ecol. Environ.* 5, 25–32. [https://doi.org/10.1890/1540-9295\(2007\)5\[25:ARFDAL\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[25:ARFDAL]2.0.CO;2)
- Hayhoe, S.J., Neill, C., Porder, S., Mchorney, R., Lefebvre, P., Coe, M.T., Elsenbeer, H., Krusche, A. V., 2011. Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. *Glob. Chang. Biol.* 17, 1821–1833. <https://doi.org/10.1111/j.1365-2486.2011.02392.x>
- Hilker, T., Lyapustin, A.I., Tucker, C.J., Hall, F.G., Myneni, R.B., Wang, Y., Bi, J., 2014. Vegetation dynamics and rainfall sensitivity of the Amazon 1–6. <https://doi.org/10.1073/pnas.1404870111>
- Malhi, Y., Roberts, J.T., Betts, R.A., Killeen, T.J., Li, W., Nobre, C.A., 2008. Climate change, deforestation, and the fate of the Amazon. *Science* 319, 169–72. <https://doi.org/10.1126/science.1146961>
- Silvrio, D. V, Brando, P.M., Macedo, M.N., Beck, P.S.A., Bustamante, M., Coe, M.T., 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. *Environ. Res. Lett.* 10, 104015. <https://doi.org/10.1088/1748-9326/10/10/104015>
- Spracklen, D. V., Arnold, S.R., Taylor, C.M., 2012. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* 489, 282–285. <https://doi.org/10.1038/nature11390>

2. THE SOUTHEASTERN AMAZON WATER BALANCE CHARACTERIZATION, CHANGES AND UNCERTAINTIES: A REMOTE SENSING-BASED EVALUATION TO DESCRIBE WATER RESOURCES AT THE XINGU BASIN HEADWATERS

ABSTRACT

Changes in water resources of the southeastern Amazon are predicted for the near future. Therefore, the development and evaluation of methods for water basin monitoring are essential in climate change mitigation processes. The main goals of this study were: (a) employ remote sensing products to characterize the upper Xingu basin water balance (WB) components; (b) describe changes in the water balance components, based on remote sensing data and trend analyses, for the years of 2003-2013; (c) define the uncertainties in the remotely sensed data, as well as describe the capacity of these products to perform a water balance closure. Estimates of evapotranspiration, rainfall and water storage change were retrieved from the Atmosphere-Land Exchange Inverse (ALEXI), the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) and Gravity Recovery and Climate Experiment (GRACE) products, respectively. River discharge data was acquired from a gauge located in São José do Xingu, Pará state. ALEXI and CHIRPS uncertainties were defined based on in-situ measurements from flux towers and rainfall stations, respectively. GRACE uncertainties were defined based on pre-established measurement and leakage error. Later, these products and the respective uncertainties were used to characterize the water balance at the upper Xingu basin. Finally, the Mann-Kendall test was employed to define significant changes in the time series of the hydrological variables. ALEXI predictions underestimated the basin ET by 27 mm month⁻¹, while rainfall predictions tend to be 41 mm month⁻¹ overestimated. Average uncertainty associated to GRACE storage change corresponded to ~18 mm. Due to the considerable uncertainties observed, remote sensing products did not allow the basin water balance closure, with results tending to be overestimated by 50 mm month⁻¹. Although expressive land use changes are described in the study site, no significant alteration was detected in the water balance components. Due to climate high inter-annual variability, such variations masked the effects of land use changes over the WB components.

Keywords: Xingu basin; Remote sensing; Water balance closure; Time series; Mann-Kendall analysis

2.1. INTRODUCTION

The high production and exportation of commodities has established Brazil as an important player in the international food market. Meanwhile, in the Brazilian portion of Amazonia, clearing of forest and non-forest vegetation have reached 960,000 km² (Nogueira et al., 2018). Trade-offs related to changes from native vegetation to crops or pasturelands, in Amazonia, have been widely described in the literature (e.g. Andersen et al., 2002; Foley et al.,

2007). But a topic that is currently raising more attention is the impacts of land use changes (LUC) on regional water resources.

The effects of Amazon's LUCs coupled with global climate changes, are likely to increase extreme events incidence, impacting plant health, amplifying economic losses and affecting human well-being (Chambers and Artaxo, 2017; Lawrence and Vandecar, 2015; Spera et al., 2016). Field observations and numerical models indicate that large-scale deforestation has decreased net surface radiation and evapotranspiration, increasing sensible heat flux, and stream runoff (Coe et al., 2016). Amazon mean rainfall has already decreased by $-12 \pm 11\%$ year⁻¹, and another $8.1 \pm 1.4\%$ year⁻¹ reduction is expected by 2050 (Spracklen and Garcia-Carreras, 2015). The resulting water deficit would have great impact in the Amazon (Boers et al., 2017). Decrease in precipitation is described as one of the major causes of the alteration in soil water storage in southeastern Amazon basin, which suffered a reduction of 10 cm between 2003 - 2014 (Hilker et al., 2014). In the Xingu River basin, an Amazon sub-basin, projections suggest that the reduction in evapotranspiration due to deforestation could inhibit rainfall and decrease river discharge by 36 % (Stickler et al., 2013).

Due to the expressive environmental changes recently observed, innovative intervention mechanisms (e.g. novel institutions and policies, incentives, information and technologies) have been developed. These mechanisms aim to support a more technical and scientific-based decision making process (Newton et al., 2013). Among them, the availability of standard sets of indicators based on transparent data collection procedures, is beneficial for water resources management and water policy decision making (Karimi et al., 2013). However, ground measurements of water resources are extremely limited in time and space, especially in the Amazon basin (Collischonn et al., 2008; Delahaye et al., 2015a). The adequate monitoring of vast areas requires a fairly dense network. Ground observations usually are not a cost-effective alternative for monitoring hydro-meteorological variables in large areas (Pelgrum and Bastiaanssen, 1996). On the other hand, satellite derived estimates are indicated as a useful tool in several applications, including operational hydrology, meteorology and agriculture (Collischonn et al., 2008). The Food and Agriculture Organization (FAO-UN), endorses the use of a remote sensing-based water accounting techniques for evaluating basin water resources and providing standardized indicators related to the water balance.

Quantifying the water balance changes and water balance closure, over large spatial scales, is essential to understand the availability of water resources (Penatti et al., 2015). The terrestrial water balance consists of four main terms: precipitation (P), evapotranspiration (ET), discharge (Q) and water storage change (TWSC). Retrievals from remote sensing have the

potential to provide spatially continuous estimates of components from the terrestrial water cycle over regional to global scales (Alsdorf, 2003).

A typical example of a southern Amazon region under intensive land use changes is the Xingu Basin. LUCs directly influence the water balance by reducing water recycling and consequently affecting rainfall, increasing river discharge and altering groundwater recharge. Considering future scenarios of land use and climate change, the Xingu regional water resources will most likely suffer further alterations. Evaluating the Xingu's water balance is an important step towards the development of mitigation and adaptation strategies. Furthermore, testing the available remote sensing products for water resources monitoring and management, is also key for a sustainable water use. Therefore, this study aims to (a) employ remote sensing products to characterize the upper Xingu basin water balance components; (b) describe changes in the water balance variables, based on remote sensing data and trend analyses; (c) define the uncertainties in the remotely sensed data, as well as describe the capacity of these products to perform a water balance closure.

2.2. MATERIALS AND METHODS

2.2.1. Study site

The Xingu River is one of the main Amazon River tributaries, it drains an area of 510,000 km² in Mato Grosso and Pará states, within the southeastern Amazon's "arc of deforestation". Our study site is located at the Xingu headwaters (hereafter called upper Xingu basin) and correspond to an area of ~210,000 km². The site encompasses two different biomes, the Cerrado (a Brazilian savanna) and transitional tropical forests (Figure 1). Precipitation is heterogeneously distributed through the year, with average value corresponding to 1900 mm yr⁻¹ (Hayhoe et al., 2011). A dry season typically spans from May to August and a wet season from October to March (Panday et al., 2015). The most expressive land use changes occurred between

1995 - 2015, and such process is characterized by three different moments (Garcia et al., 2018). Initially, the forest and cerrado at eastern and southeastern basin were converted to pasturelands (between 1995 and 2000). Later, similar changes occurred in the western portion (mostly between 2000 – 2005). Finally, between 2005-2015 an expressive land use intensification is observed, with pasturelands being converted to croplands, and agricultural areas adopting the double cropping system.

Figure 1. The study site, land use in the year of 2015 and location of rainfall stations, river gauge and flux towers. Land use map was adapted from MAPBIOMAS (2018).

2.2.2. River discharge and Rainfall measurement

Monthly river discharge was retrieved from a gauge of the Brazilian National Water Agency (ANA), which is located at the municipality of São Jose do Xingu, Pará (Figure 1). Daily precipitation was acquired from rainfall stations located along the entire Xingu basin and surroundings (Figure 1). Although this study focuses only in the upper Xingu, stations from the entire basin were used due to the limited number of rain gauges over the study site and the time coverage of such stations. Data were filtered to eliminate time series with incomplete records or anomalies. Information from the 248 rainfall stations was organized according to water years (12 months ranging from September to August of the following year). Years with more than 36 days, or more than 10 consecutive days, of missing data were removed from the analysis. Then, a data quality control (QC) was performed to reduce errors from technical sources. The QC procedure works in an annual time step comparing each station to its neighbors, looking for abnormal differences. The comparison radius was defined based on a variogram analysis (Delahaye et al., 2015). For each station, 14 indicators were calculated and used to remove years with suspicious data. At the end of QC procedure, the number of stations was reduced to an average of 150 per month.

2.2.3. Micrometeorological measurements

Daily energy fluxes were acquired from flux tower K83 (da Rocha et al., 2004) of the Large-Scale Biosphere-Atmosphere Experiment (LBA). The K83 is located at the Floresta Nacional do Tapajos (Pará state), in a tropical humid forest on a broad and flat plateau. Measurements were performed during 2000 - 2004 using an eddy covariance system. The equipment included a three-axis sonic anemometer (Campbell Scientific instrument - CSI, Logan, UT, USA), two infrared gas analyzers (open-path Li-Cor 7500 and a closed-path Li-Cor 6262 - Li-Cor, Lincoln, Nebraska, USA), five soil heat flux plates at 2 cm depth in five locations (REBS HFT3.1, Seattle, Washington, USA), net radiometer (Q*7.1 ventilated net radiometer; REBS) and rain gauge (TE525, Texas Electronics, Dallas, Texas).

Data distribution, as well as description of quality control procedures are provided by Oak Ridge National Laboratory Distributed Active Archive Center (Saleska et al., 2013). A common approach to avoid expressive errors in eddy covariance data is to maintain a constant Bowen-ratio (H/LE) when closing the energy balance. Therefore, the daily energy balance closure (EBC) was evaluated in both datasets and only days with EBC greater than 0.8 were considered in the analysis (Numata et al., 2017; Wilson et al., 2002). Errors in balance closure

were distributed between H and LE by applying the constant Bowen-ratio approach (Twine et al., 2000). This is a common approach to rectify the error and has been used in studies considering flux data from the Amazon basin (Khand et al., 2017; Numata et al., 2017). Later, missing daily data were gap filled based on the respective monthly average and aggregated to monthly scale, following Ruhoff et al., (2013) and Saleska et al. (2013) procedures.

2.2.4. Acquisition and evaluation of remote sensing data

2.2.4.1. Rainfall - CHIRPS

The Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) is a satellite-gauge based product, which provide monthly precipitation data at a spatial resolution of 0.05° (Funk et al., 2015). Briefly, Cold Cloud Duration (CCD) (developed with thermal infrared data from Climate Prediction Center -CPC- and the National Oceanic and Atmospheric Administration -NOAA) and TMPA 3B42 (TRMM Multi-Satellite Precipitation Analysis) product are used to predict 5-days accumulated precipitation. To reduce prediction bias, the 5-days rainfall is converted to fractions of the long-term averaged estimates and multiplied by CHPclim data (monthly precipitation). Using a modified Inverse Distance Weighting (IDW) algorithm (Funk et al., 2015), the estimates are combined with rainfall stations measurements. Then, the data is adjusted to daily and monthly intervals using daily information from CCD, NOAA Climate Forecast System (CFS) rainfall and stations data.

Before establishing a comparison between CHIRPS estimates and gauges measurements, the scale mismatch between these two data sources must be adjusted (Duan et al., 2016). Monthly data from gauges was upscaled to a 0.05° spatial resolution using the IDW method (Hu et al., 2014; Yong et al., 2010). Furthermore, an adequate uncertainty analysis requires estimates to be compared with an independent set of rainfall measurements. Considering that CHIRPS is a satellite-gauge product, the rainfall validation set (previously described) had to first be compared with the CHIRPS control stations. The comparison procedure was performed monthly and matching stations were removed from the validation set. Finally, validation is performed calculating the coefficient of determination (r^2), mean absolute error (MAE) and root mean square error (RMSE).

2.2.4.2. Water Storage Change - GRACE

GRACE products measure monthly variations in Earth's gravity field since 2003, at 1° spatial resolution. The product provides the equivalent water thickness anomalies (WTA), which

are directly related to terrestrial water storage change (TWSC) (Oliveira et al., 2014; Tapley et al., 2004). There are different solutions available for GRACE WTA, including the ones from the Center for Space Research (CSR), Geoforschungs Zentrum Potsdam (GFZ) and Jet Propulsion Laboratory (JPL). These three products were averaged (Sakumura et al., 2014; Swenson and Wahr, 2006) following Landerer and Swenson (2012) and the monthly basin WTA was defined as the area-weighted average of GRACE values over the upper Xingu. The change in water storage for each month was calculated by differentiation of WTA. Initially, WTA values were interpolated in a daily scale using a spline function and then, TWSC was calculated by WTA backward difference (Swann and Koven, 2017). Uncertainty values of TWSC are required to calculate water balance uncertainties. GRACE basin-estimated uncertainty is derived from the combination of measurement error and leakage error, taking into account the covariance as described by Landerer and Swenson (2012). The basin wide error in water storage was estimated to our study site and corresponded to 18 mm. This is the best approximation available, once there are no reliable methods to define GRACE error at each individual month (Swann and Koven, 2017).

2.2.4.3. Evapotranspiration - ALEXI

The Atmosphere-Land Exchange Inverse (ALEXI) model is driven primarily by a diagnostic measurement of the morning rate of surface temperature rise, which can be acquired from satellites. The method uses a time-differential land surface temperature (LST) measurement, rather than absolute instantaneous measurements of LST, reducing model sensitivity to errors in temperature retrieval due to atmospheric and emissivity correction (Anderson et al., 1997). This is analogous to the use of within-scene temperature scaling in algorithms like SEBAL or METRIC, but in ALEXI the scaling is in time rather than in the space domain.

ALEXI is based on the Two-Source Energy Balance (TSEB) model (Norman et al., 1995), with improved parameterizations (Kustas & Norman, 1999). TSEB considers the radiometric temperature (TRAD) as the average of soil (T_s) and vegetation (T_c) temperature components weighted by fractional vegetation cover (f_c). These components temperatures are used to solve the energy balance for soil, canopy and combined system (soil and canopy), i.e. mixed pixel:

$$Rn_s + Rn_c - G = (H_s + H_c) + (\lambda E_s + \lambda E_c)$$

where Rn_s and Rn_c are net radiation in soil and canopy; G is the soil heat flux, H is sensible heat, λE is latent heat.. Canopy transpiration (λE_c) is estimated using a modified Priestley Taylor approach. The soil evaporation λE_s is computed as a residual to eq. (1). To support regional applications, ALEXI couples TSEB with an atmospheric boundary layer (ABL) model to simulate changes in near-surface

air temperature (T_a) that are consistent with TSEB modeled surface fluxes (Anderson et al, 1997; Anderson et al., 2007). Maps of daily actual ET are retrieved over a 5 km resolution analysis grid using a polar orbiter-based version (ALEXI_POLAR) of ALEXI (Anderson et al, 2007; Anderson et al., 2015). ALEXI_POLAR is forced with measurements of day–night LST difference generated using the MODIS-Aqua instantaneous swath product (MYD11_L2), along with insolation from Clouds and the Earth's Radiant Energy System (CERES) (Wielicki et al., 1996) and meteorological data from Climate Forecast System Reanalysis (CFSR) (Saha et al., 2010). A Leaf Area Index (LAI) time series (retrieved from MODIS images) is used to the partitioning of surface temperature and fluxes between the soil and canopy components in pixels with partial vegetation cover (Kustas et al., 2009). Eventually, there were gaps in the ET spatial predictions, due to persistent cloud cover and consequently lack of input data for ALEXI. In these cases, the gaps were filled with potential ET. We considered that in cloudy periods (wet season) there are no water deficit and therefore filling gaps with potential evapotranspiration would be a suitable option.

Considering that in situ measurements of ET fluxes are not available for the study site, comparisons between flux tower data and ET predictions were performed outside the basin, at site with similar vegetation. These comparisons aim to aid the discussion and indicate the capacity of predictions to correctly describe the seasonality and magnitude of evapotranspiration at locations as close as possible to the study site. ALEXI estimates were compared to monthly ET from a flux tower and the determination coefficient (r^2), RMSE and MAE were calculated.

2.2.5. Water Balance Closure and Uncertainty Analysis

The water balance evaluation and the uncertainty analysis were performed considering the monthly data and the period of 2003-2014. To evaluate the capacity of remote sensing products to perform the basin closure, the river discharge was calculated as the residual of the water balance by applying the following equation:

$$Q_{wb} = P - ET - TWSC$$

where, Q_{wb} is the monthly river discharge calculated as the water balance residual; P is the precipitation estimates derived from CHIRPS; ET is the evapotranspiration from ALEXI model; and $TWSC$ is the water storage change derived from GRACE. The basin water closure was assessed by two different methods. The first one was by calculating the imbalance (difference between estimated and measured discharge time series). The second one was the method of moments derived from a first order approximation of the Taylor series expansion (Rodell et al., 2011, 2004), which is described as:

$$\sigma_{wb} = \sqrt{\sigma_P^2 + \sigma_{ET}^2 + \sigma_{TWS}^2}$$

where, σ is the error for each component. The method employed the MAE values derived from rainfall and ET, while TWS error was derived following Landerer and Swenson (2012). The 95% confidence limits on the residual (river discharge) are calculated as $\pm 2\sigma_{Q_{wb}}$ (Oliveira et al., 2014). Furthermore, it was also calculated the ratio between the square error from each of the three components $\sigma_P^2, \sigma_{ET}^2, \sigma_{TWS}^2$ and the square error of the estimated discharge $\sigma_{Q_{wb}}^2$. This calculus indicates the relative contribution of each components to the uncertainty in the estimated discharge $\sigma_{Q_{wb}}^2$. The method of moments has been used in many hydrological studies, where water balance was computed from remote sensing data (Long et al., 2014; Maeda et al., 2017; Oliveira et al., 2014; Rodell et al., 2004).

2.2.6. Non-parametric trend analysis

Monthly data from each water balance component were organized according to water years (12 months ranging from September to August of the following year), and later aggregated to the annual time scale. Annual time series of the basin average rainfall, discharge, water storage change and evapotranspiration were submitted to Mann-Kendal trend test (MK). We used annual instead of monthly data to avoid the serial correlation in the time series, which can affect the trend analyses generating false positives. The technique defines if a variable consistently changes through time, therefore indicating an upward or downward trend. The test allows trend evaluation in normally and non-normally distributed data, which makes it a robust method for hydroclimatic time series (Jiang et al., 2016; Yue et al., 2002).

The MK test starts by applying an indicator function (sgn) on the difference between all possible pairs of measurements. The value measured in time j (x_j) is subtracted from the values previously observed (x_i), considering that time $j > i$. Then, these differences are used to define Kendall's statistics S :

$$sgn(\theta) = \begin{cases} +1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n sgn(x_j - x_i),$$

where, n is the length of the dataset. Based on S , the variance $V(S)$ and the normalized test statistics Z are calculated:

$$V(S) = \frac{1}{18} [n(n-1)(2n+5)],$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0, \\ \frac{S+1}{\sqrt{V(S)}} & \text{if } S < 0 \end{cases}$$

where, the null hypothesis of no trend is rejected, if the absolute Z value is higher than the theoretical $Z(1-\alpha/2)$ value (at 0.05 level of significance). A positive S value indicates an upward trend while a negative S indicates a downward trend. The magnitude of the trend is represented by the Sen's slope (Sen, 1968) calculated over the time period, i.e. the slope of trend lines in variable quantity by a time unit.

2.3. RESULTS AND DISCUSSION

2.3.1. *Spatio-Temporal variation of the remotely sensed water balance components*

2.3.1.1. Rainfall

The seasonal cycle of Amazon basin is associated with either monsoon reversals in the land–ocean temperature gradient or north–south migration of the Intertropical Convergence Zone (ITCZ), which are driven by changes in solar radiation distribution over the year (Wright et al., 2017). Due to the reasonably wide extension of our study site, slightly different seasonality is observed in the northern and southern portions of the area (Figure 2). Rainfall onset tends to be earlier in the northern portion of the basin, with reasonable precipitation rates being already observed in September, and end dates occurring between May and June (Figure 2). At the southern of Xingu basin, the wet season is shorter, corresponding to the period between October to March. The wider rainy season observed in the northern results in considerably higher annual precipitations, with values corresponding to $2200 \text{ mm year}^{-1}$, while at the south of the study site rainfall average is $1600 \text{ mm year}^{-1}$.

Figure 2. Upper Xingu basin spatially explicit monthly rainfall derived from CHIRPS, for the months of January to December.

The basin average time series (Figure 3a) showed an extremely high interannual variability, with the highest monthly rainfall ranging from 300 to 500 mm. Higher values were observed especially in 2004 and 2014, which were associated to the warm condition in the western Pacific-Indian Ocean and warm Subtropical South Atlantic (Marengo et al., 2011). Monthly average rainfall ranged from 200 to 340 mm yr⁻¹ in the wet season, dropping to values lower than 20 mm in dry season (Figure 3b). These results agree with previous studies, which described monthly precipitation reaching 300 mm between February-March and decreasing to less than 50 mm in June-August (Hayhoe et al., 2011; Panday et al., 2015).

(a)

(b)

Figure 3. Basin average time series (a) and monthly means (b) of the precipitation (P), terrestrial water storage change (TWSC), evapotranspiration (ET) and discharge (Q), for the period between 2003-2013.

2.3.1.2. Total water storage change

Once that rainy season has started, a great share of water inflow is destined to recharge water storage over the Xingu basin. This fact is related to the soil column, which is deeper than 8 meters, and the high infiltrability observed in the regional soils (Hayhoe et al., 2011). As a result of such moisture storage capacity, the movement of water through the soil column results in a delay of seasonal river flow. This is observed by evaluating the correlation between the river discharge and TWSC at different time lags, where the best agreement was observed at a 2 months lag (Figure 4a). These findings agree with hydrological simulations performed at the entire Xingu basin (Panday et al., 2015), which indicated lower discharge during the first half of the wet season, followed by increasing discharge in the subsequent months and dry season. The comparison between TWSC and precipitation resulted in a better correlation, with no time lag ($r=0.9$) (Figure 4b), indicating that TWSC temporal variability presents an immediate response to rainfall variations.

Figure 4. Comparison between the basin average TWSC, discharge (a) and precipitation (b, at the Xingu river basin. The relation between Q and TWSC considered a 2 months time lag.

Water storage change and precipitation also presented similarities in terms of spatial variability (Figure 5a, b). At the northern portion of the basin (Point 1, Figure 5), TWSC presented a lower variation throughout the year, with values ranging from -100 to 100 mm month⁻¹ (Figure 5a). On the other hand, the southern basin's (Point 3, Figure 5) TWSC ranged from -130 to 150 mm month⁻¹. Such difference is related to the shorter rainy season in the south (Figure 5b), combined to the high forest evaporative demand and consequently high extraction of soil moisture by trees, which results in a more expressive decline of water storage (Coe et al., 2016; Dias et al., 2015). Furthermore, the southern region of the basin presents a faster increase

and higher precipitation during November and December, which results in higher TWSC during these two months (Figure 5a, b).

Figure 5. Monthly average TWSC (a) and rainfall (b) at three spots located in the northern (P1), central (P2) and southern (P3) portion of the upper Xingu basin (c). The TWSC map correspond to GRACE estimates in June 2003.

2.3.1.3. Evapotranspiration

The estimates of basin average evapotranspiration show small variability throughout the year (Figure 3a), with ET ranging from 99 mm month⁻¹ in the dry season and 125 mm month⁻¹ in the wet season. Considering that the forest still is the predominant land use in the basin (> 70%), these considerably small differences in seasonal ET were already expected. The Amazon forest is a deep-rooted vegetation with high leaf area index, located in a region with generally abundant soil moisture and high rates of incoming radiation during the dry season (Coe et al., 2016). According to Maeda et al. (2017), in such forested landscapes ET averages should range from 75 to 110 mm month⁻¹, with a relative constancy throughout the year (Maeda et al., 2017). According to Christoffersen et al. (2014), there is a reasonably flat seasonal cycle or a slight dry season decrease in ET at transitional southern forests, while equatorial forest present ET peaking with

net radiation during the dry season. Such difference between northern and southern forests evapotranspiration is observed in our study site (Figure 6). At the extreme north of the basin the highest ET values are observed between June-July, while in the south evapotranspiration maxima and minima follow the same temporal pattern of precipitation.

Figure 6. Upper Xingu average monthly ET maps calculated from the ALEXI estimates, considering the years 2003-2014.

2.3.1.4. Changes in the water balance time series

In the last 20 years, alterations in the water balance components of Amazon basin and sub-basins have been observed (Brando et al., 2014; Hilker et al., 2014; Silvério et al., 2015). Studies suggest that these alterations are related to more frequent sea-surface temperature anomalies and consequently changes in atmospheric circulation patterns, as well as the extensive deforestation of the Amazon forest (Brando et al., 2010; Marengo, 2009). Among the impacts caused by deforestation, ET reduction is probably one of the most immediate effects. Conversion of natural vegetation to agricultural lands reduces the local ET by 39% (Dias et al., 2015). The same patterns were observed in areas converted from savanna (cerrado) to pasture, in which a 36% decrease in ET was found (Oliveira et al., 2014). In the period of 2003 to 2014, approximately 10% of our study site ($\sim 20,000 \text{ km}^2$) was deforested (Garcia et al., 2018), but the Mann-Kendall test indicated a non-significant upward change ($S = 0.24$ and $p = 0.12$) (Table 1). These facts might be associated to the natural climate oscillation, which causes considerable

alterations in evapotranspiration from one year to another and might have masked the ET decrease.

Evaluating MOD16 ET estimates during 2003-2010, Oliveira et al. (2014) described significant upward changes in the Cerrado biome, including the transitional areas encompassed by the Xingu basin. According to the authors, this upward pattern is related to the multiple occurrence of El Nino Southern Oscillation (ENSO) phenomena during the last decade, which resulted in droughts during early 2000s and high precipitation rates during 2013-2014. This extreme oscillations on rainfall could directly influence ET and consequently mask the effects of land use changes in evapotranspiration signal. On the other hand, Swan et al. (2017) tested several ET products during the period of 2003-2015 and indicated that MOD16 and P-LSH (Process-Based Land Surface Evapotranspiration/Heat Fluxes algorithm; Zhang et al. (2015)) were the only ones presenting trends over the Amazon basin.

Table 1. Mann-Kendall trend test of the basin average water balance components from the study site

	Annual Avg. (mm)	Standard dev	Annual Min. (mm)	Annual Max. (mm)	S ¹	p ²	Sen's slope	Period
ET	1323.6	31.6	1265.6	1370.6	0.24	0.12	8.96	2003-2013
Q	526.9	71.5	378.4	645	0.27	0.11	9.45	2003-2013
P	1955	193	1729.7	2378	0.27	0.18	17.08	2003-2013
TWSC	-0.51	62.3	-119.1	104.1	-0.28	0.2	-7.42	2003-2013

¹Kendall's statistic S; ²p value.

Analyzing the MK from the rainfall time series, we observed a non-significant positive change in the basin average P ($S = 0.27$, $p = 0.18$) (Table 1). Hilker et al. (2014), evaluating the rainfall over the Amazon basin (between 2000-2012) based on TMPA estimates, indicated a net decline across much of the eastern and southeastern portion of the basin, where precipitation was reduced by up to 25%. Based on data from 280 meteorological stations distributed across the Amazon, Brando et al. (2010) found that annual wet-season rainfall decreased at a rate of 5.31 mm yr⁻¹ between 1995 - 2005. On the other hand, Oliveira et al. (2014), evaluating changes in the TMPA's precipitation of the transition Cerrado-Amazon forest, during 2003-2010, found no significant changes. Many studies have described a long-term decrease in rainfall over the southern Amazon (Butt et al., 2011; Debortoli et al., 2017; Marengo, 2009; Spracklen et al., 2012), which is associated not only to widespread deforestation at Amazon but also to long-term variations in the Pacific Ocean surface temperature. In our study, the shorter period evaluated and the occurrence of extremely severe ENSOs, most likely masked the trend described in the

literature. Alterations in the Xingu's water storage are primarily related to the alterations in rainfall pattern and evapotranspiration (Panday et al., 2015). The MK analyses did not detect any significant alteration in the TWSC ($p = 0.2$) and annual average presented value close to 0, indicating that water storage is negligible over the long-term (Table 1). Considering that no alterations were observed in rainfall or ET, it was already expected that no significant changes wouldn't be observed in TWSC. Hilker et al (2014) found a decline in TWSC of 10 cm in some regions of the eastern and southeastern Amazon basin during 2003-2012 and related this change to expressive reductions in rainfall.

Although the MK analysis indicated an increase in the river discharge ($S = 0.27$), these results were considered not significant ($p = 0.11$) (Table 1). Studies conducted at small catchments in the upper Xingu, indicated that deforestation-induced reductions in ET have an immediate effect in river discharge, resulting in increased volumes of water to be exported through stream conduits (Hayhoe et al., 2011; Riskin et al., 2017). At forested sites, vegetation can easily access shallow soil water during the wet season and deep-rooted trees are able to access deep soil water during dry periods (Nepstad et al., 1994; Canadell et al., 1996; von Randow et al., 2004). Consequently, ET rates may remain relatively constant over time. In agricultural and pastures lands, only shallow soil water above 2 m is available to plants (von Randow et al., 2004) and, in the absence of crops, no water will be taken up by vegetation, leaving a larger volume of water to move through and be exported from the watersheds (Hayhoe et al., 2011). Although the effects of deforestation have already been observed in small streams, at large scales alterations in discharge signal might be difficult to identify due to natural climate variability, which can have a larger magnitude than the changing patterns (Rodriguez et al., 2010).

2.3.2. Uncertainties in RS products and water balance closure

2.3.2.1. Rainfall

The comparison of the RS estimates and rain-gauge interpolated values indicated a good fit of CHIRPS predictions (Figure 7). The r^2 , RMSE and MAE values corresponded to 0.82, 60 and 41 mm (Figure 7a), and predictions are usually overestimated by 20-50 mm month⁻¹ (Figure 7c). Furthermore, CHIRPS uncertainty is not homogeneously distributed over the study site. There are two locations with high errors, one at north of the site and other at the southern portion of the basin, over the Xingu National park (Figure 7b). The high uncertainty at these two places could be related to the bias correction procedure employed by CHIRPS. This technique uses control stations (rain-gauges) to adjust the estimates biases, but in locations where there are

no stations, the bias correction is limited. Another possibility is that the gauges network's poor coverage results in a limited representation of the actual rainfall spatial occurrence (interpolated rainfall maps) and consequently indicates as error any variability that is not capable of been described by the in-situ measurements and the respective interpolated map (Berg et al., 2006; Franchito et al., 2009; Melo et al., 2015).

Figure 7. Comparison between monthly rainfall measurements from all available stations and CHIRPS estimates (a), spatially explicit representation of monthly average MAE in mm (b) and the basin average error.

In the literature, there are many studies describing overestimation of rainfall by remote sensing products (Arvor et al., 2017; Oliveira et al., 2014; Sahoo et al., 2011). The TMPA product, which is used in CHIRPS calibration, also indicated overestimated predictions at southeast of the Upper Xingu, with RMSE ranging from 90 to 160 mm yr⁻¹ (Oliveira et al., 2014).

Overestimated rainfall rates are observed not only in TMPA and derived products (such as CHIRPS), but also in PERSIANN (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks) and CMORPH (CPC MORPHing technique). At the southern Amazon, PERSIANN-CDR predictions presented positive bias and RMSE value of 72 mm month⁻¹ (Arvor et al., 2017). A comparison over the Amazon basin indicated that TMPA, PERSIANN-CDR and CMORPH overestimate wet season and annual rainfall, while dry season is underestimated (Sahoo et al., 2011). Furthermore, PERSIANN-CDR and CMORPH present slightly higher errors than TMPA product (Sahoo et al., 2011).

2.3.2.2. Evapotranspiration

In our study site, the magnitude of average ET values is generally overestimated. The comparison between flux tower data and RS predictions (Figure 8) indicated that the RMSE and MAE corresponded to 31.2 and 27.9 mm month⁻¹ (approx. 28% of the mean monthly average). This is the first time the ALEXI global algorithm is used to retrieve ET estimates from an Amazon sub-basin, and the results are similar to other ET algorithms, such as the MOD16. Swan & Koven (2017), compared the estimates from 6 models (FLUXNET-MTE, MOD16, ET-M, PLSH, BESS, JF-ET) and indicated that ET monthly predictions of the Amazon Basin might reach an uncertainty of 27%, depending on the evaluated month. Loarie et al. (2011) used data from 10 eddy covariance flux towers to validate ET estimates from MOD16 for the Brazilian Amazon forest and Brazilian savannah (between 2000 and 2006). These authors indicated that MOD16 annual error corresponded to approximately 5% (or approximately 50 mm yr⁻¹).

The errors observed, as well as the discrepancies observed between different studies can be related to several factors, including the different parametrization of models, the input variables, as well as the flux tower measurement errors (Mu et al., 2007). Sensitivity analyses are required to identify the variables which influence the ET output the most and to define the level of agreement between input and output errors, but this is beyond the scope of this study.

Figure 8. Comparison between ET measurements from a flux tower and predictions from ALEXI algorithm.

Although a considerable error was detected in ALEXI estimates, the product presented similarities with hydrological simulations performed at the Xingu basin (Panday et al., 2015), which indicated average ET fluxes in the Xingu basin varying between 75 mm month⁻¹ to 110 mm month⁻¹ (Dias et al., 2015; Panday et al., 2015). The authors also indicated that higher ET values were observed in wet season (November–April) and lower ET in dry season (May–October).

2.3.2.3. Water balance closure

The balance closure is often evaluated by deriving the discharge as the residual from the water balance equation and later comparing these results to in situ measurements (Oliveira et al., 2014; Sahoo et al., 2011). The estimated discharge from the Xingu basin detected fairly well the river seasonal patterns, but fluxes were usually overestimated in wet season and underestimated in dry season (Figure 9a, b). The basin average errors correspond to approximately 50 mm (Figure 9a). This result is mainly influenced by three aspects: the overestimated evapotranspiration and rainfall, as well as the presence of considerable noise in the time series. During wet periods the CHIRPS estimates presented higher errors, having great influence in the water balance and resulting in estimated discharges higher than the measured values. Considering that P and ET have opposite influence in the water balance equation, the overestimated P was

partially masked by the positive errors in ET. On the other hand, in periods with no precipitation, the error in estimated Q were mostly associated to ET. Consequently, the overestimated ET resulted in extremely low Q (Figure 9a).

Figure 9. Difference between estimated and measured discharge (a), the comparison between estimated and measured discharge (b), contribution of each component to the total uncertainty in the predicted Q (c) and the estimated time series of Q (d). The 1:1 line is represented in blue in graph (b). The grey envelope in graph (d) correspond to the 95% confidence limits on the predicted river discharge.

Rainfall and ET are the variables that most contributed to overall uncertainty, corresponding to 47% and 31% (Figure 9c), respectively. Discharge uncertainties defined by the

method of moments varied between 61 - 113 mm month⁻¹ and presented an overall value of 101 mm month⁻¹ (Figure 9d). Uncertainties of this magnitude are described in other studies that also estimated discharge as a residual from remote sensing data (Armanios and Fisher, 2014; Oliveira et al., 2014; Sheffield et al., 2009). In the Amazon basin, rainfall estimates were considered the variable that most contributed to uncertainties, particularly during the wet season (Maeda et al., 2017; Sahoo et al., 2011). The closure imbalance in such region vary between -70 and 50 mm month⁻¹, and most of non-closure error are assigned to P (40%) and ET (38%) components (Sahoo et al., 2011).

2.4. CONCLUSIONS

The correct management of water resources require a set of reliable information, which are able to describe the spatio-temporal variation in the evaluated water basin. In our study site, the precipitation and water storage change acquired from remote sensing datasets correctly described the variability, but ALEXI overestimated the evapotranspiration, especially in the dry season. Comparing CHIRPS and ALEXI estimates against in situ data resulted in a mean absolute error of 47 and 31 mm month⁻¹, respectively. Such errors impacted the water balance closure, resulting in expressive bias along the entire time series of estimated discharge.

The Mann-Kendall analysis of the water balance components indicated no significant change over the period of 2003-2013. Temporal variations in water balance components are influenced by several factors, e.g. land use change, ENSO and climate change. These factors usually have opposite effects and consequently mask changes in variables such as river discharge or evapotranspiration.

Considering the water balance closure based on remote sensing techniques, the estimated discharge from the Xingu basin detected fairly well the river seasonal patterns, but fluxes were usually overestimated in wet season and underestimated in dry season. The basin average errors correspond to 50 mm, which were mostly influenced by the overestimated evapotranspiration and rainfall. Although remote sensing techniques still present some limitations, these products have the potential to aid in the evaluation water resources, especially in basins with limited in situ information.

REFERENCES

- Alsdorf, D.E., 2003. GEOPHYSICS: Tracking Fresh Water from Space. *Science* (80-.).
<https://doi.org/10.1126/science.1089802>
- Andersen, L.E., Granger, C.W.J., Reis, E.J., Weinhold, D., Wunder, S., Lykke, C., Andersen, E., 2002. The Dynamics of Deforestation and Economic Growth in the Brazilian Amazon.
- Anderson, M.C., Gao, F., Knipper, K., Hain, C., Dulaney, W., Baldocchi, D.D., Eichelmann, E., Hemes, K.S., Yang, Y., Medellín-Azuara, J., & Kustas, W.P. (2018). Field-scale assessment of land and water use change over the California Delta using remote sensing. *Remote Sens.*, 10, 889
- Anderson, M. C.; Norman, J. M.; Diak, G. R.; Kustas, W. P.; Mecikalski, J. R. A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. *Remote Sens. Environ.* 1997, 60, 195–216, doi:10.1016/s0034-4257(96)00215-5.
- Anderson, M. C.; Norman, J. M.; Diak, G. R.; Kustas, W. P. A two-source time-integrated model for estimating surface fluxes using thermal infrared remote sensing. *Remote Sens.* ... 1997.
- Anderson, M. C.; Kustas, W. P.; Norman, J. M. Upscaling flux observations from local to continental scales using thermal remote sensing. In *Agronomy Journal*; 2007.
- Anderson, M. C.; Zolin, C. A.; Hain, C. R.; Semmens, K.; Tugrul Yilmaz, M.; Gao, F. Comparison of satellite-derived LAI and precipitation anomalies over Brazil with a thermal infrared-based Evaporative Stress Index for 2003-2013; 2015; Vol. 526; ISBN 3015046616.
- Armanios, D.E., Fisher, J.B., 2014. Measuring water availability with limited ground data: Assessing the feasibility of an entirely remote-sensing-based hydrologic budget of the Rufiji Basin, Tanzania, using TRMM, GRACE, MODIS, SRB, and AIRS. *Hydrol. Process.*
<https://doi.org/10.1002/hyp.9611>
- Arvor, D., Funatsu, B.M., Michot, V., Dubreui, V., 2017. Monitoring rainfall patterns in the southern amazon with PERSIANN-CDR data: Long-term characteristics and trends. *Remote Sens.* 9. <https://doi.org/10.3390/rs9090889>
- Berg, W., L'Ecuyer, T., Kummerow, C., 2006. Rainfall climate regimes: The relationship of regional TRMM rainfall biases to the environment. *J. Appl. Meteorol. Climatol.*
<https://doi.org/10.1175/JAM2331.1>
- Boers, N., Marwan, N., Barbosa, H.M.J., Kurths, J., 2017. A deforestation-induced tipping point for the South American monsoon system. *Sci. Rep.* 7, 41489.
<https://doi.org/10.1038/srep41489>

- Borma, L.S., Rocha, H.R., Cabral, O.M., Randow, C. Von, Collicchio, E., Kurzatkowski, D., Brugger, P.J., Freitas, H., Tannus, R., Oliveira, L., Renno, C.D., 2009. Atmosphere and hydrological controls of the evapotranspiration over a floodplain forest in the Bananal Island region, Amazonia 114, 1–12. <https://doi.org/10.1029/2007JG000641>
- Brando, P.M., Balch, J.K., Nepstad, D.C., Morton, D.C., Putz, F.E., Coe, M.T., Silverio, D., Macedo, M.N., Davidson, E.A., Nobrega, C.C., Alencar, A., Soares-Filho, B.S., 2014. Abrupt increases in Amazonian tree mortality due to drought-fire interactions. *Proc. Natl. Acad. Sci.* <https://doi.org/10.1073/pnas.1305499111>
- Brando, P.M., Goetz, S.J., Baccini, A., Nepstad, D.C., Beck, P.S.A., Christman, M.C., 2010. Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proc. Natl. Acad. Sci.* <https://doi.org/10.1073/pnas.0908741107>
- Butt, N., De Oliveira, P.A., Costa, M.H., 2011. Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *J. Geophys. Res. Atmos.* 116, 2–9. <https://doi.org/10.1029/2010JD015174>
- Chambers, J.Q., Artaxo, P., 2017. Biosphere-atmosphere interactions: Deforestation size influences rainfall. *Nat. Clim. Chang.* <https://doi.org/10.1038/nclimate3238>
- Chen, X., Alimohammadi, N. and Wang, D. Modelling interannual variability of seasonal evaporation and storage change based on the extended Budyko framework. *Water Resour. Res.*, 49, 6067-6078.
- Christoffersen, B.O., Restrepo-Coupe, N., Arain, M.A., Baker, I.T., Cestaro, B.P., Ciais, P., Fisher, J.B., Galbraith, D., Guan, X., Gulden, L., van den Hurk, B., Ichii, K., Imbuzeiro, H., Jain, A., Levine, N., Miguez-Macho, G., Poulter, B., Roberti, D.R., Sakaguchi, K., Sahoo, A., Schaefer, K., Shi, M., Verbeeck, H., Yang, Z.L., Araújo, A.C., Kruijt, B., Manzi, A.O., da Rocha, H.R., von Randow, C., Muza, M.N., Borak, J., Costa, M.H., Gonçalves de Gonçalves, L.G., Zeng, X., Saleska, S.R., 2014. Mechanisms of water supply and vegetation demand govern the seasonality and magnitude of evapotranspiration in Amazonia and Cerrado. *Agric. For. Meteorol.* <https://doi.org/10.1016/j.agrformet.2014.02.008>
- Coe, M.T., Macedo, M.N., Brando, P.M., Lefebvre, P., Panday, P., Silvério, D., 2016. The Hydrology and Energy Balance of the Amazon Basin. Springer Berlin Heidelberg, pp. 35–53. https://doi.org/10.1007/978-3-662-49902-3_3
- Collischonn, B., Collischonn, W., Tucci, C.E.M., 2008. Daily hydrological modeling in the Amazon basin using TRMM rainfall estimates. *J. Hydrol.* <https://doi.org/10.1016/j.jhydrol.2008.07.032>

- da Rocha, H., Goulden, M., Miller, S.D., Menton, M.C., Pinto, L.D.V.O., de Freitas, H.C., Silva-Figueira, A.M.E., 2004. Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. *Ecol. Appl.* 14, S22–S32. <https://doi.org/10.1890/02-6001>
- Debortoli, N.S., Dubreuil, V., Hirota, M., Filho, S.R., Lindoso, D.P., Nabucet, J., 2017. Detecting deforestation impacts in Southern Amazonia rainfall using rain gauges. *Int. J. Climatol.* 37, 2889–2900. <https://doi.org/10.1002/joc.4886>
- Delahaye, F., Kirstetter, P.E., Dubreuil, V., Machado, L.A.T., Vila, D.A., Clark, R., 2015a. A consistent gauge database for daily rainfall analysis over the Legal Brazilian Amazon. *J. Hydrol.* <https://doi.org/10.1016/j.jhydrol.2015.04.012>
- Delahaye, F., Kirstetter, P.E., Dubreuil, V., Machado, L.A.T., Vila, D.A., Clark, R., 2015b. A consistent gauge database for daily rainfall analysis over the Legal Brazilian Amazon. *J. Hydrol.* 527, 292–304. <https://doi.org/10.1016/j.jhydrol.2015.04.012>
- Dias, L.C.P., Macedo, M.N., Costa, M.H., Coe, M.T., Neill, C., 2015. Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil. *J. Hydrol. Reg. Stud.* 4, 108–122. <https://doi.org/10.1016/j.ejrh.2015.05.010>
- Du, C.; Sun, F.; Yu, J.; Liu, X.; and Chen, Y. New interpretation of the role of water balance in an extended Budyko hypothesis in arid regions. *Hydrol. Earth Syst. Sci.*, 20, 393–409, 2016.
- Duan, Z., Liu, J., Tuo, Y., Chiogna, G., Disse, M., 2016. Evaluation of eight high spatial resolution gridded precipitation products in Adige Basin (Italy) at multiple temporal and spatial scales. *Sci. Total Environ.* 573, 1536–1553. <https://doi.org/10.1016/j.scitotenv.2016.08.213>
- Foley, J.A., Asner, G.P., Costa, M.H., Coe, M.T., Defries, R., Gibbs, H.K., Howard, E.A., Olson, S., Patz, J., Ramankutty, N., Snyder, P., 2007. Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Front. Ecol. Environ.* 5, 25–32. [https://doi.org/10.1890/1540-9295\(2007\)5\[25:ARFDAL\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[25:ARFDAL]2.0.CO;2)
- Franchito, S.H., Rao, V.B., Vasques, A.C., Santo, C.M.E., Conforte, J.C., 2009. Validation of TRMM precipitation radar monthly rainfall estimates over Brazil. *J. Geophys. Res. Atmos.* 114. <https://doi.org/10.1029/2007JD009580>
- Friedl, M.A., Sulla-Menashe, D., Tan, B., Schneider, A., Ramankutty, N., Sibley, A., Huang, X., 2010. MODIS Collection 5 global land cover: Algorithm refinements and characterization of new datasets. *Remote Sens. Environ.* <https://doi.org/10.1016/j.rse.2009.08.016>

- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes. *Sci. Data*. <https://doi.org/10.1038/sdata.2015.66>
- Gao, F., Masek, J., Schwaller, M., & Hall, F.G. (2006). On the blending of the Landsat and MODIS surface reflectance: predicting daily Landsat surface reflectance. *IEE Trans. Geosci. Remote. Sens.*, 44, 2207-2218
- Garcia A S, Vilela VMFN, Rizzo R , Ballester MVR (2018) Improving land use and land cover classification with multi-sensor metrics and decision trees. Manuscript in preparation
- Hayhoe, S.J., Neill, C., Porder, S., Mchorney, R., Lefebvre, P., Coe, M.T., Elsenbeer, H., Krusche, A. V., 2011. Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. *Glob. Chang. Biol.* 17, 1821–1833. <https://doi.org/10.1111/j.1365-2486.2011.02392.x>
- Hilker, T., Lyapustin, A.I., Tucker, C.J., Hall, F.G., Myneni, R.B., Wang, Y., Bi, J., 2014. Vegetation dynamics and rainfall sensitivity of the Amazon 1–6. <https://doi.org/10.1073/pnas.1404870111>
- Hu, Q., Yang, D., Li, Z., Mishra, A.K., Wang, Y., Yang, H., 2014. Multi-scale evaluation of six high-resolution satellite monthly rainfall estimates over a humid region in China with dense rain gauges. *Int. J. Remote Sens.* <https://doi.org/10.1080/01431161.2013.876118>
- Jiang, C., Li, D., Gao, Y., Liu, W., Zhang, L., 2016. Impact of climate variability and anthropogenic activity on streamflow in the Three Rivers Headwater Region , Tibetan Plateau , China. *Theor. Appl. Climatol.* <https://doi.org/10.1007/s00704-016-1833-7>
- Karimi, P., Bastiaanssen, W.G.M., Molden, D., 2013. Water Accounting Plus (WA+) - A water accounting procedure for complex river basins based on satellite measurements. *Hydrol. Earth Syst. Sci.* 17, 2459–2472. <https://doi.org/10.5194/hess-17-2459-2013>
- Khan, M.S., Liaqat, U.W., Baik, J., Choi, M., 2018. Stand-alone uncertainty characterization of GLEAM, GLDAS and MOD16 evapotranspiration products using an extended triple collocation approach. *Agric. For. Meteorol.* 252, 256–268. <https://doi.org/10.1016/j.agrformet.2018.01.022>
- Khand, K., Numata, I., Kjaersgaard, J., Vourlitis, G.L., 2017. Dry season evapotranspiration dynamics over human-impacted landscapes in the southern Amazon using the landsat-based METRIC model. *Remote Sens.* 9. <https://doi.org/10.3390/rs9070706>

- Kustas, W. P.; Norman, J. M. Evaluation of soil and vegetation heat flux predictions using a simple two-source model with radiometric temperatures for partial canopy cover. *Agric. For. Meteorol.* 1999, doi:10.1016/S0168-1923(99)00005-2.
- Kustas, W.; Anderson, M. Advances in thermal infrared remote sensing for land surface modeling. *Agric. For. Meteorol.* 2009, doi:10.1016/j.agrformet.2009.05.016.
- Landerer, F.W., Swenson, S.C., 2012a. Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resour. Res.* 48, 1–11. <https://doi.org/10.1029/2011WR011453>
- Landerer, F.W., Swenson, S.C., 2012b. Accuracy of scaled GRACE terrestrial water storage estimates. *Water Resour. Res.* <https://doi.org/10.1029/2011WR011453>
- Lawrence, D., Vandecar, K., 2015. Effects of tropical deforestation on climate and agriculture. *Nat. Clim. Chang.* 5, 27–36. <https://doi.org/10.1038/nclimate2430>
- Loarie, S.R., Lobell, D.B., Asner, G.P., Mu, Q., Field, C.B., 2011. Direct impacts on local climate of sugar-cane expansion in Brazil. *Nat. Clim. Chang.* 1, 105–109. <https://doi.org/10.1038/nclimate1067>
- Long, D., Longuevergne, L., Scanlon, B.R., 2014. Uncertainty in evapotranspiration from land surface modeling, remote sensing, and GRACE satellites. *Water Resour. Res.* 50, 1131–1151. <https://doi.org/10.1002/2013WR014581>. Received
- Maeda, E.E., Ma, X., Wagner, F.H., Kim, H., Oki, T., Eamus, D., Huete, A., 2017. Evapotranspiration seasonality across the Amazon Basin 439–454.
- MapBiomas (2018) Collection **2.3** of Brazilian Land Cover & Use Map Series, accessed on **06/02/2018** through the link: <http://mapbiomas.org/>
- Marengo, J.A., 2009. Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s. *Hydrol. Process.* <https://doi.org/10.1002/hyp.7396>
- Marengo, J.A., Rusticucci, M., Penalba, O., Renom, M., 2010. An intercomparison of observed and simulated extreme rainfall and temperature events during the last half of the twentieth century: Part 2: Historical trends. *Clim. Change* 98, 509–529. <https://doi.org/10.1007/s10584-009-9743-7>
- Marengo, J.A., Tomasella, J., Alves, L.M., Soares, W.R., Rodriguez, D.A., 2011. The drought of 2010 in the context of historical droughts in the Amazon region. *Geophys. Res. Lett.* 38. <https://doi.org/10.1029/2011GL047436>
- Melo, D.D.C.D., Xavier, A.C., Bianchi, T., Oliveira, P.T.S., Scanlon, B.R., Lucas, M.C., Wendland, E., 2015. *Journal of Geophysical Research: Atmospheres* 9426–9436. <https://doi.org/10.1002/2015JD023797>. Received

- Mu, Q., Heinsch, F.A., Zhao, M., Running, S.W., 2007. Development of a global evapotranspiration algorithm based on MODIS and global meteorology data. *Remote Sens. Environ.* <https://doi.org/10.1016/j.rse.2007.04.015>
- Nepstad, D. C., De Carvalho, C. R., Davidson, E. A., Jipp, P. H., Lefebvre, P. A., Negreiros, G. H., ... Vieira, S. (1994). The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature*. <https://doi.org/10.1038/372666a0>
- Newton, P., Agrawal, A., Wollenberg, L., 2013. Enhancing the sustainability of commodity supply chains in tropical forest and agricultural landscapes. *Glob. Environ. Chang.* 23, 1761–1772. <https://doi.org/10.1016/j.gloenvcha.2013.08.004>
- Nogueira, E.M., Yanai, A.M., de Vasconcelos, S.S., de Alencastro Graça, P.M.L., Fearnside, P.M., 2018. Carbon stocks and losses to deforestation in protected areas in Brazilian Amazonia. *Reg. Environ. Chang.* <https://doi.org/10.1007/s10113-017-1198-1>
- Norman, J. M.; Kustas, W. P.; Humes, K. S. Source approach for estimating soil and vegetation energy fluxes in observations of directional radiometric surface temperature. *Agric. For. Meteorol.* 1995, 77, 263–293, doi:10.1016/0168-1923(95)02265-Y.
- Numata, I., Khand, K., Kjaersgaard, J., Cochrane, M.A., Silva, S.S., 2017. Evaluation of landsat-based metric modeling to provide high-spatial resolution evapotranspiration estimates for amazonian forests. *Remote Sens.* 9. <https://doi.org/10.3390/rs9010046>
- Oliveira, P.T.S., Nearing, M.A., Moran, M.S., Goodrich, D.C., Wendland, E., Gupta, H. V., 2014. Trends in water balance components across the Brazilian Cerrado. *Water Resour. Res.* 50. <https://doi.org/10.1002/2013WR015202>
- Panday, P.K., Coe, M.T., Macedo, M.N., Lefebvre, P., Castanho, A.D. de A., 2015a. Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. *J. Hydrol.* 523, 822–829. <https://doi.org/10.1016/j.jhydrol.2015.02.018>
- Panday, P.K., Coe, M.T., Macedo, M.N., Lefebvre, P., Castanho, A.D. de A., 2015b. Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. *J. Hydrol.* 523, 822–829. <https://doi.org/10.1016/j.jhydrol.2015.02.018>
- Pelgrum, H., Bastiaanssen, W.G.M., 1996. An intercomparison of techniques to determine the area-averaged latent heat flux from individual in situ observations: A remote sensing approach using the European Field Experiment in a Desertification-Threatened Area data. *Water Resour. Res.* <https://doi.org/10.1029/96WR01396>
- Penatti, N.C., Almeida, T.I.R. de, Ferreira, L.G., Arantes, A.E., Coe, M.T., 2015. Satellite-based hydrological dynamics of the world's largest continuous wetland. *Remote Sens. Environ.* 170, 1–13. <https://doi.org/10.1016/j.rse.2015.08.031>

- Ramoelo, A., Majozi, N., Mathieu, R., Jovanovic, N., Nickless, A., Dzikiti, S., 2014. Validation of global evapotranspiration product (MOD16) using flux tower data in the African savanna, South Africa. *Remote Sens.* 6, 7406–7423. <https://doi.org/10.3390/rs6087406>
- Randow, C. Von, Manzi, A. O., Kruijt, B., Oliveira, P. J. De, & Zanchi, F. B. (2004). Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia, 26, 5–26. <https://doi.org/10.1007/s00704-004-0041-z>
- Riskin, S.H., Neill, C., Jankowski, K., Krusche, A. V., McHorney, R., Elsenbeer, H., Macedo, M.N., Nunes, D., Porder, S., 2017. Solute and sediment export from Amazon forest and soybean headwater streams: *Ecol. Appl.* 27, 193–207. <https://doi.org/10.1002/eap.1428>
- Rodell, M., Famiglietti, J.S., Chen, J., Seneviratne, S.I., Viterbo, P., Holl, S., Wilson, C.R., 2004. Basin scale estimates of evapotranspiration using GRACE and other observations. *Geophys. Res. Lett.* 31, 10–13. <https://doi.org/10.1029/2004GL020873>
- Rodell, M., McWilliams, E.B., Famiglietti, J.S., Beaudoin, H.K., Nigro, J., 2011. Estimating evapotranspiration using an observation based terrestrial water budget. *Hydrol. Process.* <https://doi.org/10.1002/hyp.8369>
- Rodriguez, D.A., Tomasella, J., Linhares, C., 2010. Is the forest conversion to pasture affecting the hydrological response of Amazonian catchments? Signals in the Ji-Paraná Basin. *Hydrol. Process.* <https://doi.org/10.1002/hyp.7586>
- Ruhoff, A.L., Paz, A.R., Aragao, L.E.O.C., Mu, Q., Malhi, Y., Collischonn, W., Running, S.W., 2013. Assessment of the MODIS global evapotranspiration algorithm using eddy covariance measurements and hydrological modelling in the Rio Grande basin Assessment of the MODIS global evapotranspiration algorithm using eddy covariance measurements and hydrologic 6667. <https://doi.org/10.1080/02626667.2013.837578>
- Saha, S.; Moorthi, S.; Pan, H. L.; Wu, X.; Wang, J.; Nadiga, S.; Tripp, P.; Kistler, R.; Woollen, J.; Behringer, D.; Liu, H.; Stokes, D.; Grumbine, R.; Gayno, G.; Wang, J.; Hou, Y. T.; Chuang, H. Y.; Juang, H. M. H.; Sela, J.; Iredell, M.; Treadon, R.; Kleist, D.; Van Delst, P.; Keyser, D.; Derber, J.; Ek, M.; Meng, J.; Wei, H.; Yang, R.; Lord, S.; Van Den Dool, H.; Kumar, A.; Wang, W.; Long, C.; Chelliah, M.; Xue, Y.; Huang, B.; Schemm, J. K.; Ebisuzaki, W.; Lin, R.; Xie, P.; Chen, M.; Zhou, S.; Higgins, W.; Zou, C. Z.; Liu, Q.; Chen, Y.; Han, Y.; Cucurull, L.; Reynolds, R. W.; Rutledge, G.; Goldberg, M. The NCEP climate forecast system reanalysis. *Bull. Am. Meteorol. Soc.* 2010, 91, 1015–1057, doi:10.1175/2010BAMS3001.1.

- Sahoo, A.K., Pan, M., Troy, T.J., Vinukollu, R.K., Sheffield, J., Wood, E.F., 2011. Reconciling the global terrestrial water budget using satellite remote sensing. *Remote Sens. Environ.* 115, 1850–1865. <https://doi.org/10.1016/j.rse.2011.03.009>
- Sakumura, C., Bettadpur, S., Bruinsma, S., 2014. Ensemble prediction and intercomparison analysis of GRACE time-variable gravity field models. *Geophys. Res. Lett.* <https://doi.org/10.1002/2013GL058632>
- Saleska, S.R., H.R. da Rocha, A.R. Huete, A.D. Nobre, P. Artaxo, and Y.E. Shimabukuro. 2013. LBA-ECO CD-32 Flux Tower Network Data Compilation, Brazilian Amazon: 1999-2006. Data set. Available on-line [<http://daac.ornl.gov>] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA <http://dx.doi.org/10.3334/ORNLDAAAC/1174>
- Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's Tau. *J. Am. Stat. Assoc.* 63, 1379–1389.
- Sheffield, J., Ferguson, C.R., Troy, T.J., Wood, E.F., McCabe, M.F., 2009. Closing the terrestrial water budget from satellite remote sensing. *Geophys. Res. Lett.* <https://doi.org/10.1029/2009GL037338>
- Silvério, D. V., Brando, P.M., Macedo, M.N., Beck, P.S.A., Bustamante, M., Coe, M.T., 2015. Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. *Environ. Res. Lett.* 10, 104015. <https://doi.org/10.1088/1748-9326/10/10/104015>
- Spera, S.A., Galford, G.L., Coe, M.T., Macedo, M.N., Mustard, J.F., 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. *Glob. Chang. Biol.* 22, 3405–3413. <https://doi.org/10.1111/gcb.13298>
- Spracklen, D. V., Arnold, S.R., Taylor, C.M., 2012. Observations of increased tropical rainfall preceded by air passage over forests. *Nature* 489, 282–285. <https://doi.org/10.1038/nature11390>
- Spracklen, D. V., Garcia-Carreras, L., 2015. The impact of Amazonian deforestation on Amazon basin rainfall. *Geophys. Res. Lett.* <https://doi.org/10.1002/2015GL066063>
- Stickler, C.M., Coe, M.T., Costa, M.H., Nepstad, D.C., McGrath, D.G., Dias, L.C.P., Rodrigues, H.O., Soares-Filho, B.S., 2013. Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales. *Proc. Natl. Acad. Sci. U. S. A.* 110, 9601–6. <https://doi.org/10.1073/pnas.1215331110>

- Swann, A.L.S., Koven, C.D., 2017. A Direct Estimate of the Seasonal Cycle of Evapotranspiration over the Amazon Basin. *J. Hydrometeorol.* 18, 2173–2185. <https://doi.org/10.1175/JHM-D-17-0004.1>
- Swenson, S., Wahr, J., 2006. Post-processing removal of correlated errors in GRACE data. *Geophys. Res. Lett.* <https://doi.org/10.1029/2005GL025285>
- Tapley, B.D., Bettadpur, S., Ries, J.C., Thompson, P.F., Watkins, M.M., 2004. GRACE measurements of mass variability in the Earth system. *Science* (80-.). <https://doi.org/10.1126/science.1099192>
- Turner, D. P., Urbanski, S., Bremer, D., Wofsy, S. C., Meyers, T., Gower, S. T., & Gregory, M. (2003). A cross-biome comparison of daily light use efficiency for gross primary production. *Global Change Biology*. <https://doi.org/10.1046/j.1365-2486.2003.00573.x>
- Twine, T.E., Kustas, W.P., Norman, J.M., Cook, D.R., Houser, P.R., 2000. Correcting eddy-covariance flux underestimates over a grassland.
- Velpuri, N.M., Senay, G.B., Singh, R.K., Bohms, S., Verdin, J.P., 2013. A comprehensive evaluation of two MODIS evapotranspiration products over the conterminous United States: Using point and gridded FLUXNET and water balance ET. *Remote Sens. Environ.* <https://doi.org/10.1016/j.rse.2013.07.013>
- Wielicki, B. A.; Barkstrom, B. R.; Harrison, E. F.; Lee, R. B.; Smith, G. L.; Cooper, J. E. Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment. *Bull. Am. Meteorol. Soc.* 1996, doi:10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2.
- Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at FLUXNET sites 113, 223–243.
- Wright, J.S., Fu, R., Worden, J.R., Chakraborty, S., Clinton, N.E., Risi, C., Sun, Y., Yin, L., 2017. Rainforest-initiated wet season onset over the southern Amazon. *Proc. Natl. Acad. Sci.* 114, 8481–8486. <https://doi.org/10.1073/pnas.1621516114>
- Yong, B., Ren, L.L., Hong, Y., Wang, J.H., Gourley, J.J., Jiang, S.H., Chen, X., Wang, W., 2010. Hydrologic evaluation of Multisatellite Precipitation Analysis standard precipitation products in basins beyond its inclined latitude band: A case study in Laohahe basin, China. *Water Resour. Res.* <https://doi.org/10.1029/2009WR008965>

- Yang, Y; Anderson, M.C.; Feng, G.; Hain, C.; Semmens, K.A.; Kustas, W.P.; Noormets, A.; Wynne, R.H.; Thomas, V.A.; Sun, G. Daily Landsat-scale evapotranspiration estimation over a forested landscape in North Carolina USA using multi-satellite data fusion. *Hydrol. Earth Syst. Sci.* 21, 1017-1037, 2017.
- Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.* 259, 254–271.
- Zhang, K., Kimball, J.S., Nemani, R.R., Running, S.W., Hong, Y., Gourley, J.J., Yu, Z., 2015. Vegetation Greening and Climate Change Promote Multidecadal Rises of Global Land Evapotranspiration. *Sci. Rep.* <https://doi.org/10.1038/srep15956>

3. LAND USE CHANGES IN SOUTHEASTERN AMAZON AND TRENDS IN RAINFALL AND RIVER DISCHARGE SINCE 1976

ABSTRACT

Since the early 1970s, the agricultural frontier of southeastern Amazon has undergone extensive land use changes and conversion of natural vegetation to pasture or cropland. These alterations, combined with regional climate changes, have the potential to influence the hydrologic cycle at small to large scales. We evaluated a 40-year time series (1976 to 2015) of rainfall and river discharge and related them to land use changes in the Upper Xingu River Basin (UX). We acquired data from six rainfall stations and four river gauges and mapped land use changes from Landsat images at five-year intervals. Mann-Kendall trend analysis and Pettit's change point detection were employed to describe annual and seasonal changes in the time series. Monthly discharge from Xingu River was used to derive annual, seasonal and monthly discharges, as well as runoff coefficient. The largest changes in land use occurred in the last two decades and approximately 60,900 km² in the Upper Xingu Basin were deforested between 1985 and 2015. Rainfall in the Xingu Basin decreased by about 245 mm over the period but there was no trend in river discharge. The number of rainy days and intensity of events also decreased, but the length of the rainy season and seasonal and annual discharges did not change.

Keywords: Amazônia; Upper Xingu basin; Deforestation; Land use changes; Climate change; Mann-Kendall analysis; Hydro-climatological indicators

3.1. INTRODUCTION

Since the early 1970s, large portions of Amazon have experienced rapid and widespread deforestation associated with the expansion of the agricultural frontier (Morton et al., 2006; DeFries et al., 2010; Ballester et al., 2003; Garcia et al., 2017). During 1970s and 1980s, deforestation was driven primarily by governmental policies that promoted settlement, speculation and infrastructure development (Alves et al., 2009; Pfaff et al., 2009; Walker et al., 2009; Sawakuchi et al., 2013). However, in the 1990s increasing food demands from international markets have become a main driver of forest change. Recent land use change in southern Amazônia have been characterized by expansion of both croplands and pastures, a shift to expansion of croplands into pasturelands (Morton et al. 2006, Macedo et al. 2012) and intensification and double-cropping on croplands (Spera et al. 2014, 2016).

Agricultural expansion plays an important role in economic growth of the Brazilian Legal Amazônia but trade-offs between deforestation and economic growth have been observed across the Amazon basin (Foley et al., 2007). These trade-offs usually imply negative environmental impacts, such as landscape biophysical changes. The combined effects of forest

loss and climate changes have altered the energy and water balances (Lathuillière et al., 2012; Silvério et al., 2015, Panday et al., 2015). The Amazon forest plays a critical role in the water and energy cycles. Trees can draw on water from eight meters or more in the soil, which supplies water even during intense dry seasons (Panday et al., 2015). High year-round evapotranspiration (ET) returns a large volume of water to the atmosphere. Forest cover loss reduces ET and increases sensible heat flux (Silvério et al., 2015), thus reducing humidity, cloud formation and rainfall (Wright et al., 2017). At the scale of small watersheds, reduced evapotranspiration following deforestation increases runoff in small streams by three to four fold (Hayhoe et al., 2011). At larger scales discharge has been increased by as much as 20% (Costa et al., 2003, Coe et al., 2011). However, lower rainfall caused by forest loss could result in lower river flows (Spracklen et al., 2012). Stickler et al. (2013) found that business-as-usual projections of forest loss to 2050 in the Xingu Basin would decrease river discharge by 36% and reduce the energy produced by the new Belo Monte dam on the Lower Xingu River to 25% of maximum output. These feedbacks among changes to land-cover, water balance and climate have the potential to reduce precipitation, increase precipitation variability and threaten agricultural production, energy production, and regional communities whose livelihood depend on freshwater resources.

The Xingu River is a large, southern Amazon River tributary. The upper Xingu region lies within a zone of highly seasonal rainfall and is dominated by soils suitable for crop agriculture. The area experienced large alterations on land cover between 2000 and 2010. Approximately 12% of the basin (or 19,000 km²) were deforested since 2000, despite the presence of large forest protected area in the central basin (Silvério et al., 2015). The Xingu basin is now one of Brazil's most important agricultural regions and produces 13% of Brazil's soybeans, most of which is exported to Asia and Europe (Lathuillière et al., 2014). In addition to threatening these new investments in agriculture, lower rainfall and more severe droughts also increase the likelihood of forest fires and degrade areas of existing forest (Brando et al. 2014).

Because of large and recent changes in land cover within the time frame of historical rainfall and river flow instrument records, the upper Xingu basin provides an opportunity to evaluate relationships between land cover and changes to the hydrologic cycle. Evaluating changes to rainfall and river discharge is essential to understand how the combined effect of anthropogenic activities and global climate change have altered freshwater resources and how these changes might affect other important areas of current or future agricultural expansion. This study addresses the following questions: (a) How has rainfall in the upper Xingu changed during the last 40 years (1976 to 2015)? and (b) how have the combined changes of rainfall and forest cover influenced the discharge in the Xingu River and its tributaries?

3.2. MATERIALS AND METHODS

3.2.1. Study site and datasets

The Xingu Basin lies in the states of Mato Grosso and Pará, within the southern Amazon's "arc of deforestation". The 210,000 km² basin includes the highly altered headwaters region and a less altered lower central Xingu Basin. Originally covered by transitional forests (about 80 % of the area), the area encompasses the central Brazil Cerrado (savanna) and more humid forests to the north. Most of the soils are Oxisols, with medium to clay texture, that are nutrient poor but physically well structured. Precipitation is heterogeneously distributed through the year, with average value corresponding to 1900 mm yr⁻¹ (Hayhoe et al., 2011). A dry season typically lasts from May to August and a wet season from September to April (Marengo et al., 2011).

To examine changes to river flows at the scale of the upper Xingu Basin, we compiled data of monthly river discharge from two gauges from the Brazilian National Water Agency (ANA) database (Table 1). Gauge 1 is located in the municipality of São Jose do Xingu (Fig. 1, gauge 1) and measures the discharge generated by the entire study basin. The discharge record for this station was from 1976 to 2015. We also compiled data from a tributary in the Upper Xingu Basin, the Ronuro River, that had a long and consistent discharge record, (Fig. 1, gauge 2). Because the Ronuro gauge was discontinued, discharge records corresponded only to 1976 to 2007. To evaluate how the land use change influenced streams discharge at the scale of small watersheds with nearly homogeneous land use, we compiled hourly discharge measurements for the last 10 years (2007 to 2017) (Table 1), from one small forest watershed and one small cropland watershed at Tanguro Ranch using a record that was initiated by Hayhoe et al. (2011) (Fig. 1, gauges 3 and 4).

Figure 1. The study site, agricultural areas by year of conversion and location of rainfall stations and river gauges.

To evaluate changes to precipitation, we compiled daily precipitation from 59 stations and then filtered these data to eliminate stations with incomplete records or data anomalies. Data from each rainfall station were organized according to water years (12 months ranging from September to August of the following year). Years with more than 36 total days of missing data or more than 10 consecutive days of missing data were removed from the analysis. Then, a data quality control (QC) was performed to reduce errors from technical sources. The QC procedure worked in an annual time step and compared each station and its neighbors, looking for

abnormal differences. The comparison radius was defined based on a variogram analysis (Delahaye et al., 2015). For each station, 14 indicators were calculated and used to identify years with suspicious data. Cases in which data inconsistencies were confirmed, the information for that year was removed from the dataset. We restricted our analysis to stations that covered 1976 to 2015 with less than 11 non-consecutive missing years. Six stations met the QC's criteria and were selected for further analysis. Finally, precipitation data was averaged to create a 40-year time series of daily rainfall.

Table 1. Description of rainfall stations, river gauges and the results of trend analysis for annual data

Id	Station	Long	Lat.	Period	Catchment Area (km ²)
		o			
Rainfall station					
1	S.J.do Xingu	-52.75	-10.81	1976-2011	-
2	Cajabi	-54.55	-10.75	1976-2015	-
3	Rio Ferro	-54.19	-12.51	1976-2013	-
4	Agrochapada	-54.28	-13.45	1976-2011	-
5	Paranatinga	-54.05	-14.42	1976-2015	-
6	BR-309	-53.99	-14.61	1976-2015	-
River gauges					
1	Xingu River	-51.99	-6.73	1976-2015	210,359
2	Ronuro River	-54.44	-13.14	1976-2007	3,845
3	Stream Forest	-52.33	-12.83	2007-2017	6.73
4	Stream Soy	-52.43	-12.54	2007-2017	27.53

3.2.2. Land use change

We used Landsat images acquired from USGS/Landsat Higher Level Science Data Products for the years 1985, 1990, 1995, 2000, 2005, 2010, 2015. All images corresponded to the dry season and ranged from Julian day 154 to 220. Preference was given to data with no cloud interference or other atmospheric errors. For each year, 30 m spatial resolution images of either LANDSAT 5 (sensor TM) or LANDSAT 7 (sensor ETM+) were classified. Additionally, croplands were defined with a smoothed satellite time series of MODIS Vegetation Indices, from the Institute of Surveying, Remote Sensing and Land Information (University of Natural Resources and Life Science, Vienna). The temporal and spatial scales of this product were eight days and 250 m, respectively.

Images were projected to South American Datum 1969/Albers equal-area conic, then mosaicked and geometrically corrected based on images from 2015 Landsat 8 taken as reference, with root mean square error (RMSE) lower than 0.5. Mosaics were classified with a combination of remote sensing products and classification processes, developed by Garcia et al (2018). First,

natural or semi-natural areas were extracted by an ISODATA algorithm, in which each resulting class was reclassified into forest, woody vegetation, grassland, secondary complex, agriculture, water surface, bare soil and burned land. Then, MODIS temporal profiles were used to identify managed areas and classify them into pasturelands or croplands (Arvor et al., 2011).

3.2.3. Hydro-climatological indicators

To examine patterns in the long-term datasets, we derived a group of annual hydro-climatological indicators from the precipitation and river discharge data. The wet season onset and end dates were defined according to Arvor et al. (2014) and Liebmann et al. (2007):

$$AA(t) = \sum_{n=1}^t (R(n) - \bar{R}) \quad (\text{Eq. 1}),$$

where, $AA(t)$ represents the Anomalous Accumulation at day t , $\bar{R}$ is the average daily rainfall and $R(n)$ is the daily rainfall at day n . The rainy season onset and end were then determined by the minimum and maximum of AA . We also derived the average period of consecutive days without precipitation (DMEAN), average period of consecutive days with precipitation (WMEAN), percentage of rain events higher than 1 mm (NB1P), 10 mm (NB10P), 20 mm (NB20P) and 50 mm (NB50P).

We used the following indicators to describe variations in river discharge: annual discharge (AD), dry season (Jun-Sep) discharge (DD), wet season (Oct-May) discharge (WSD), lowest monthly discharge (LM), highest monthly discharge (HM) and the ratio between annual discharge and annual rainfall, or runoff coefficient (RC).

3.2.4. Trend analysis and change point detection

We submitted time series of rainfall, discharge and the derived indexes to Mann-Kendal trend test (MK) (Mann, 1945; Kendall, 1975). The technique defines if a variable consistently changes through time or has an increasing or decreasing trend. The test allows trend evaluation in normally and non-normally distributed data, which makes it a robust method for hydroclimatic time series (Jiang, Li, Gao, Liu, & Zhang, 2016; Yue, Pilon, & Cavadias, 2002). Before applying the MK test, we evaluated the serial correlation of the datasets and, if necessary, employed a trend-free pre-whitening (TFPW) method to eliminate adverse effects (Yue et al., 2002).

The MK test starts by applying an indicator function (sgn) on the difference between all possible pairs of measurements (Eq. 2). The value measured in time j (x_j) is subtracted from the values previously observed (x_i), considering that time $j > i$. Then, these differences are used to define Kendall's statistics S (Eq. 3):

$$\text{sgn}(\theta) = \begin{cases} +1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases}, \text{ (Eq. 2)}$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i), \text{ (Eq. 3)}$$

where, n is the length of the dataset. Based on S , the variance $V(S)$ (Eq. 4) and the normalized test statistics Z (Eq. 5) are calculated:

$$V(S) = \frac{1}{18} [n(n-1)(2n+5)], \text{ (Eq. 4)}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{if } S < 0 \end{cases}, \text{ (Eq. 5)}$$

where, the null hypothesis of no trend is rejected, if the absolute value of Z is higher than the theoretical value of $Z(1-\alpha/2)$ (at 0.05 level of significance). A positive S value indicates an increasing trend while a negative S indicates a decreasing trend. The magnitude of the trend is represented by the Sen's slope (Sen, 1968) calculated over the time period.

We used the Pettitt test (Pettitt, 1979), a nonparametric method, capable of detecting changes in the time series mean, to identify abrupt changes in the time series. This test repeatedly splits the time series $X(n)$ into two subsets, alternating the date τ . The test performs a rank-based comparison between the subsets $k(\tau)$ (Pettitt, 1979; Zhang, Zheng, Wang, & Yao, 2015):

$$k(\tau) = \sum_{i=1}^{\tau} \sum_{j=\tau+1}^n \text{sgn}(x_j - x_i), \text{ (Eq. 6)}$$

where, sgn corresponds to Eq. 2. The abrupt change is defined as the date τ where the absolute value of $k(\tau)$ is the maximum. The p value of the statistical test is then computed using the approximated limiting distribution by Pettitt (1979).

3.3. RESULTS

3.3.1. Land use change

The Xingu Basin experienced high rates of deforestation and conversion to agriculture from 1985 to 2015 (Fig. 1). In 1985, native forests and Cerrado covered 199,500 km², approximately 95% of the Basin (Fig. 2a). From 1985 to 2015, 60,900 km² (29% of the Basin) were converted into pastures and croplands. The highest conversion rates occurred between 1995 and 2005, when 36,000 km² of native vegetation were converted (Fig. 2a). Land use changes were most concentrated in the central east and southern regions of the Basin, while a large area of intact tropical forest, in the Xingu Indigenous Park, remains in the central portion of the Basin (Fig. 1). Conversion of forest to pastures occurred much earlier than forest clearing for croplands, or pasture conversion to croplands. Pasture area increased three-fold between 1985 and 2015, covering about 32,000 km² in 2015. In contrast, croplands were nearly nonexistent in 1985 but covered about 23,000 km² in 2015. Highest rates of native vegetation conversion to pastures took place between 1995 and 2000 (about 17,000 km²), while cropland expansion was greater between 2000-2015 (about 21,000 km²). The pattern of land use change in the Ronuro River Basin was nearly identical to that in the entire Basin (Fig. 2b).

Figure 2. Land use changes in Xingu Basin (a) and in the catchment at Ronuro River (b), for the period of 1985 - 2015.

3.3.2. Rainfall trends

The Mann-Kendall test of each rainfall station showed significant downward trends for four stations, negative S in all cases, and p values ranging from 0.001 to 0.35 (Table 2). Sen's slope indicated rainfall reductions of 10 to 25 mm yr⁻¹. Although not significant, the trend from Rio Ferro and Cajabi stations were also downward (Table 2).

Table 2. Trend analysis for annual data of each rainfall station

Id	Station	S	Sen's slope (mm yr ⁻¹)	p value	Available data (%)
Rainfall stations					
1	S.J.do Xingu	-0.31	-15.19	0.01	81
2	Cajabi	-0.12	-7.33	0.35	73
3	Rio Ferro	-0.23	-11.03	0.08	74
4	Agrochapada	-0.26	-9.74	0.04	84
5	Paranatinga	-0.40	-9.56	0.001	73
6	BR-309	-0.43	-25.91	0.001	78
River gauges					
1	Xingu River	-0.17	-1.60	0.11	97
2	Ronuro River	-0.32	-0.07	0.003	100
3	Stream Forest	-	-	-	97
4	Stream Soy	-	-	-	86

Average annual rainfall over the study site decreased 12.7 mm yr⁻¹ (Fig. 3a). Rainy season rainfall decreased by 10.4 mm yr⁻¹ (Fig. 3b) and dry season rainfall decreased 1.2 mm yr⁻¹ (Fig. 3c). Both seasonal and annual values changed abruptly about 1996. Before 1996, the average annual rainfall was 1900 mm in the wet season and 85 mm in the dry season. After 1996 these values were 1700 mm and 40 mm. The difference in annual rainfall averages, before and after the abrupt change, was 245 mm (Fig. 3). The change coincided with an abrupt increase in deforested area in the Xingu Basin (Fig. 2 and Fig. 3).

Figure 3. Annual (a), wet (b) and dry season (c) rainfall and the corresponding parameters of the Mann-Kendall trend analysis. Dotted lines represent the averaged rainfall of periods before and after abrupt change.

The indexes representing the percentage of rainy days with rain $> 1, 10, 20$ and 50 mm (NB1P, NB10P, NB20P, NB50P) all decreased. There was an average decrease of 16 days ($0.11 \% \text{ yr}^{-1}$) in the number of days with events $> 1 \text{ mm}$ during the rainy seasons from 1976 to 2015, and gaps between two rain events increased on average 1 day. Events in the dry season also changed. NB1P decreased 3 days ($0.06 \% \text{ yr}^{-1}$) and NB10P decreased 1 day ($0.02 \% \text{ yr}^{-1}$). Although rainfall amounts changed over time, there were no changes to the total length of the wet and dry seasons (Table 3). There was also no significant change ($p > 0.05$, Table 3) to the average rainy

season onset date (October 20th, day 50 of the hydrologic year) or end date (March 20th, day 230 of the hydrological year) (Fig. 4).

Table 3. Trend analysis of rainfall indicators derived from averaged annual and seasonal data from Xingu basin

MK analysis	Onset (days)	End (days)	DMEAN ¹ (days)	WMEAN ² (days)	NB1P ³ (%)	NB10P ⁴ (%)	NB20P ⁵ (%)	NB50P ⁶ (%)
Annual								
S	0.10	0.13	0.18	-0.28	-0.24	-0.36	-0.31	-0.25
Sen's slope	0.16	0.24	0.13	-0.01	-0.11	-0.10	-0.06	-0.019
p	0.365	0.187	0.10	0.010	0.029	0.001	0.004	0.021
Wet season								
S	-	-	0.24	-0.29	-0.21	-0.33	-0.30	-0.23
Sen's slope	-	-	0.027	-0.01	-0.12	-0.14	-0.09	-0.02
p	-	-	0.027	0.007	0.051	0.002	0.006	0.036
Dry season								
S	-	-	0.16	-0.21	-0.28	-0.24	-0.13	-
Sen's slope	-	-	0.24	-0.004	-0.06	-0.02	-0.009	-
p	-	-	0.133	0.050	0.011	0.03	0.22	-

¹Average period of consecutive days without precipitation; ²Average period of consecutive days with precipitation; ³ Percentage of rain events > than 1 mm; ⁴> than 10 mm; ⁵> than 20 mm; ⁶> than 50 mm.

3.3.3. River discharge trends

The longest available time series from small (7 to 28 km²) single land-use catchments in forest or cropland, showed that monthly and annual discharge was approximately four times greater in the cropland catchment (Fig. 5). In addition to higher discharge, flow varied more in the cropland catchment (Fig. 5).

Figure 4. Average daily rainfall in millimeters, onset (▲) and end (▼) dates derived from the time series.

In the Ronuro River, annual discharge decreased 4.2 mm yr^{-1} (Table 4). Highest monthly discharge decreased by 0.75 mm/yr^{-1} (Table 4) and lowest monthly discharge decreased by -0.1 mm yr^{-1} (Table 4). Decreases in discharge of 3.5 mm/yr^{-1} were observed in the dry season (Table 4) but not in the wet season. Because the most extensive changes in land use took place between 2000 and 2005, over a relatively short period of the 1976 to 2007 hydrological data record, changes in discharge were most likely primarily related to changes to rainfall.

Figure 5. Monthly discharge in forested and soybean cropland catchments located at Tanguro Ranch in the southeastern Xingu Basin.

In the Xingu Basin, a decrease in lowest monthly discharge of 0.07 mm mo^{-1} (24%) was the only metric that changed significantly over time (Table 4). Lowest monthly discharge also appeared to change abruptly in 1997, with an average value 12.64 mm yr^{-1} before and 10.44 mm yr^{-1} after this date. Because higher rates of deforestation should lead to higher streamflow if rainfall does not change, we expected an increase in the highest monthly discharge and runoff coefficient.

Table 4. Trend and abrupt change analyses derived from hydrological indexes

Index	S	Sen's slope (mm yr^{-1})	p	Pettit test	p
Ronuro River					
AD ¹	-0.31	-4.25	0.01	1995	0.05
LM ²	-0.24	-0.1	0.05	1997	0.05
DD ³	-0.28	-3.46	0.02	1997	0.02
HM ⁴	-0.23	-0.75	0.06	1985	0.14
WD ⁵	-0.15	-0.74	0.23	1985	0.08
RC ⁶	-0.12	-0.11	0.32	1996	0.36
Xingu River					
AD ¹	-0.17	-1.6	0.11	1995	0.03
LM ²	-0.32	-0.07	0.003	1997	<0.0001
DS ³	-0.13	-0.5	0.22	1997	0.16
HM ⁴	-0.1	-0.28	0.35	1983	0.66
WS ⁵	-0.17	-1.28	0.12	1995	0.1
RC ⁶	0.15	0.12	0.17	2003	0.058

¹Annual discharge; ²Lowest month discharge; ³Dry season discharge; ⁴Highest month discharge; ⁵Wet season discharge; ⁶Runoff coefficient.

3.4. DISCUSSION

The 245 mm yr^{-1} reduction in annual rainfall after 1995 and a reduction in the number of days with rain in basin coincided with high rates of deforestation across the entire southeast Amazon during the 1990s (Pfaff et al., 2007). Abrupt decreases in rainfall in the late 1990s were also found in other locations in the southern Amazon (Debortoli et al., 2015). Reduced rainfall associated with deforestation have also been documented in northwest Rondônia, Brazil (Butt et al. 2011; Spracklen et al., 2012) as well as over the entire Amazon basin (Marengo et al., 2001).

Reduced rainfall is linked to deforestation by several mechanisms, which operate at different spatio-temporal scales (Butt et al., 2011; Debortoli et al., 2017). Tropical forest has high capacity to absorb solar radiation and convert this energy in latent heat (da Rocha et al., 2004). Croplands and pasturelands have reduced root systems (exploring only a superficial portion of

the soil profile), lower leaf area index and higher surface albedo during fallow periods compared with forests (Coe et al., 2016). When forests are converted to another land use, there is a reduction in net radiation (R_n) and higher proportion of R_n is dissipated as sensible heat (Bruijnzeel, 2004; Coe et al., 2016; Costa & Foley, 1997). Large-scale and complex feedbacks between land cover and climate have the potential to reduce precipitation and increase rainfall variability (Nobre et al. 1991, Spracklen et al. 2012, Lee et al. 2012, Lawrence and Vandecar 2014, Knox et al. 2015). For the Xingu Basin, Stickler et al. (2013) estimated that current and future deforestation and the corresponding decrease in ET would reduce rainfall by 6 to 15% by 2050 and reduce hydropower output of the Belo Monte Dam on the lower Xingu River.

At smaller spatial scales, decreases in precipitation are associated with deforestation because the land cover heterogeneity of edges, between forest and cleared areas, creates centers of strong atmospheric divergence, and affects precipitation (Butt et al., 2011; Knox et al., 2011; Saad et al., 2010; Spracklen et al., 2012). The precipitation is altered through changes in the thermodynamic profile and the development of surface induced mesoscale circulation (Spracklen et al. 2012). According to Knox et al. (2011), the upwelling air generated at the deforested edge carries moisture, resulting in the formation of deep convective clouds. Consequently, higher rainfall is observed along forest edges, while in the interior of deforested areas rainfall is slightly lower.

The loss of forest cover has been linked to a delay of the onset of the rainy season in Amazon (Costa and Pires, 2010; Fu et al., 2013). Analysis of daily rainfall from Rondônia suggested that deforestation since the 1970s caused an 18-day delay in the onset of the rainy season (Butt et al., 2011). The mechanism for the effect is that latent heat flux over the land surface is an important source of atmospheric humidity during the initial stages of transition between wet and dry seasons (Fu and Li, 2004) and deforestation reduces latent heat flux, creates drier conditions in the troposphere, and delays the rainy season's onset (Schubert et al., 2004).

Our finding that rainy season onset and end dates in the Xingu Basin have not changed despite high deforestation likely occurred because changes in rainy season length are not exclusively related to deforestation (Makarieva et al., 2013). Rainy season duration is the result of interactions between convective activity from South Atlantic Convergence Zone, large-scale atmospheric circulation, and local circulation (Negri et al. 2000; Siqueira et al., 2004; Debortoli et al. 2015). Rainfall alterations are also related to long-term changes in sea surface temperature, sea-level pressure gradients between tropical and subtropical Atlantic and the Pacific decadal oscillation (Fernandes et al., 2011; Zeng et al., 2008). These factors likely confounded detection of any change in rainy season length based on land cover change alone.

These large-scale circulation patterns also induce cycles of wet and dry periods of 20 to 30 years duration in Amazon (Marengo, 2009). The mid-1950s to late-1970s were a dry period in southern Amazon and was followed by higher rainfall rates until the end of the 1990s (Marengo, 2009). The abrupt change in rainfall in Xingu Basin that we observed after 1996 cannot be related exclusively to higher deforestation rates in Southern Amazon but likely is also related to this shift from a wet to dry periods. It is likely that global climate change will intensify these alterations in the future (Coe et al., 2013). Atmospheric greenhouse gases will raise temperatures and likely drought frequency and intensity (Malhi et al., 2008). Although climate projections for precipitation are highly variable (Almeida et al., 2016), for the Xingu Basin several models indicate higher temperatures (Lewis et al., 2011; Vourlitis and da Rocha, 2010) in the Xingu Basin as well as a decline in dry season rainfall and recurrent droughts (Zelazowski et al., 2011; Coe et al., 2013).

The maintenance of high-quality and long-term rainfall and stream gauging stations distributed over large areas in the relatively remote Amazon Basin remains an important barrier to detecting land use-induced changes to the hydrological cycle and validating changes projected by earth system models. For the Xingu Basin, despite the existence of distributed rainfall measurement stations, a small proportion (6 out of 59) met rigorous criteria for data quality and completeness.

At the small scale of headwater watersheds, the approximately four times greater discharge from cropland catchments over multiple years caused by elimination of forest cover was similar to the patterns found by others in the Upper Xingu (Hayhoe et al., 2011; Riskin et al., 2017). In small watersheds, conversion of forest to croplands resulted in higher flows in both wet and dry season. Although seasonal variations in flow were greater in croplands, the overall magnitude of annual flow variation was small. This is because surface infiltrability and subsurface hydraulic conductivity are high in the deep and weathered Oxisols on which most cropping takes place (Scheffler et al. 2011). This generates deep and groundwater-dominated water flowpaths that do not produce overland flows and that stabilize streamflows across wet and dry seasons (Neill et al. 2013). In addition, the presence of more than 10,000 small impoundments constructed for roads and water supply to cattle when ranching dominated the Upper Xingu Basin (Macedo et al., 2013) likely decrease flow velocity and increase ET from water surfaces (Lehner et al., 2011). The relationship between land cover and stream flow and runoff in small watersheds in the upper Xingu basin likely differs from that in other parts of the Amazon Basin on other soils. Small catchments in the Ji-Paraná Basin in Rondônia had a decreased capacity to regulate flows after deforestation, and exhibited a greater difference between extreme flows,

including both lower flows in dry season and higher flows in the rainy season (Rodriguez et al., 2010). Similar increases in rapid discharge from deforested small watersheds have been found on soils with lower infiltrability and hydraulic conductivity in other parts of the Amazon (Biggs et al. 2006, Germer et al. 2010). Although soils play a very large role in controlling runoff processes (Bruijnzeel, 2004) and much of the Xingu Basin is underlain by permeable Oxisols (Neill et al. 2017), extrapolating results from a small number of headwater watersheds to the entire Xingu Basin is confounded by the presence of both less permeable soils and higher relief in the southern portion of the Basin where the headwaters of many Xingu tributaries are located, and large area of wetlands and flooded forest along the central floodplain but upstream of the river gauge at São Jose do Xingu.

At the intermediate scale of the Ronuro Basin, lower rainfall was accompanied by a reduction in annual discharge from ~750 mm in the mid-1970s to ~650 mm after mid-1990s. Relatively low rates of deforestation that occurred in the Ronuro Basin during most of measurement period suggested that this trend was caused primarily by changes to climate and not by deforestation. Lack of discharge measurements of the Ronuro River after 2007 prevented further analysis after the period of high deforestation.

At the scale of the Xingu Basin, alterations in the Xingu River discharge caused by reduced rainfall were offset by the increased discharge by deforestation in the late-2000s. Panday et al. (2015) reached a similar conclusion for the Xingu Basin based on a modeling analysis. The current level of deforestation in the Xingu Basin has influenced river flow regulation at the local scale, resulting in increased river runoff and greater differences between dry and wet season discharge. At the larger scale, increased deforestation and reductions in rainfall had opposite effects on discharge, so decreased river discharge caused by rainfall reduction was counteracted by increased discharge induced by deforestation. These trends can now be detected from existing long-term measurements. The consequences of changes to rainfall for the region could be profound because decreased rainfall and increased drought can degrade and transform remaining forest and because vast areas of recently-created cropland rely on adequate and predictable rainfall.

3.5. CONCLUSIONS

In the last decades the Xingu basin suffered great changes in land use, with more than 30% of the basin being deforested. An abrupt decrease in rainfall was observed at the period of most intense land use changes. Along the last 40 years, reduction in annual rainfall corresponded to 500 mm yr⁻¹, most of which happened after 1995. A reduction in the number of days with rain

coincided with high rates of deforestation across the entire southeast Amazon, during the 1990s. Although there are clear evidences linking rainfall patterns and the land use changes, alterations cannot be associated exclusively to deforestation. Rainfall alterations are also related to decadal oscillations in sea surface temperature between tropical and subtropical Atlantic and the Pacific oceans. The Xingu river discharge had no significative change in the period evaluated. This is related to the discharge four times higher in deforested catchments, which offset reductions related to rainfall. Considering the evidences presented in this study, as well as future projections of global climate change, it is essential the development of mitigation strategies to attenuate the alterations in the Xingu's water resources.

References

- Almeida CT, Oliveira-Júnior JF, Delgado RC, Cubo P, Ramos MC (2016) Spatiotemporal rainfall and temperature trends throughout the Brazilian Legal Amazon, 1973-2013. *International Journal of Climatology*, 37, 2013-2026.
- Alves DS, Morton DC, Batistella M, Roberts DA, Souza C (2009) The Changing Rates and Patterns of Deforestation and Land Use in Brazilian Amazonia. In: *Amazonia and Global Change* (eds Keller M, Bustamante M, Gash J, Dias PS), pp. 11-24. American Geophysical Union, Washington.
- Arvor D, Jonathan M, Meirelles MSP, Dubreuil V, Durieux L (2011) Classification of MODIS EVI time series for crop mapping in the state of Mato Grosso, Brazil. *International Journal of Remote Sensing*, 32, 7847–7871.
- Arvor D, Dubreuil V, Ronchail J, Simões M, Funatsu BM (2014) Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil). *International Journal of Climatology*, 34, 2622–2633.
- Ballester MVR, Victoria DC, Krusche AV, Coburn R, Victoria RL, Richey JE, Matricardi E (2003) A remote sensing/GIS-based physical template to understand the biogeochemistry of the Ji-Parana river basin (Western Amazonia). *Remote Sensing of Environment*, 87, 429–445.
- Brando PM, Balch, JK, Nepstad DC, Morton DC, Putz, FE, Coe, MT, Soares-Filho, BS (2014) Abrupt increases in Amazonian tree mortality due to drought–fire interactions. *Proceedings of the National Academy of Sciences of the United States of America*, 111, 6347–6352.
- Bruijnzeel LA (2004) Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agriculture, Ecosystems & Environment*, 104, 185-228.
- Butt N, de Oliveira PA, Costa MH (2011) Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil. *Journal of Geophysical Research*, 116, D11120.

- Coe, M. T., Latrubesse, E. M., Ferreira, M. E., & Amsler, M. L. (2011). The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. *Biogeochemistry*. <https://doi.org/10.1007/s10533-011-9582-2>
- Coe MT, Marthews TR, Costa MH, Galbraith DR, Greenglass NL, Imbuzeiro HMA et al. (2013) Deforestation and climate feedbacks threaten the ecological integrity of south-southeastern Amazonia. *Philosophical transactions of the Royal Society*, B368, 20120155.
- Coe MT, Macedo MN, Brando PM, Lefebvre P, Panday P, Silvrio D (2016) The hydrology and energy balance of the Amazon Basin. In: *Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin* (eds Nagy L, Forsberg BR, Artaxo P), pp. 35–53. Springer, Heidelberg
- Costa MH, Foley JA (1997) Water balance of the Amazon Basin: Dependence on vegetation cover and canopy conductance. *Journal of Geophysical Research: Atmospheres*, 102, 23973–23989.
- Costa, M. H., Botta, A., & Cardille, J. A. (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. *Journal of Hydrology*, 283(1–4), 206–217. [https://doi.org/10.1016/S0022-1694\(03\)00267-1](https://doi.org/10.1016/S0022-1694(03)00267-1)
- Costa MH, Pires GF (2010) Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. *International Journal of Climatology*, 30, 1970–1979.
- da Rocha HR, Goulden ML, Miller SD, Menton MC, Pinto LDVO, de Freitas HC, Silva Figueira AM (2004) Seasonality of water and heat fluxes over a tropical forest in eastern Amazonia. *Ecological Applications*, 14, 22–32.
- Debortoli NS, Dubreuil V, Funatsu B, Delahaye F, Oliveira CH, Rodrigues-Filho S, Fetter R (2015) Rainfall patterns in the Southern Amazon: a chronological perspective (1971-2010). *Climatic Change*, 132, 251–264.
- Debortoli, N. S., Dubreuil, V., Hirota, M., Filho, S. R., Lindoso, D. P., & Nabucet, J. (2017). Detecting deforestation impacts in Southern Amazonia rainfall using rain gauges. *International Journal of Climatology*, 37(6), 2889–2900. <https://doi.org/10.1002/joc.4886>
- DeFries RS, Rudel T, Uriarte M, Hansen M (2010) Deforestation driven by urban population growth and agricultural trade in the twenty-first century. *Nature Geoscience*, 3, 178–181.
- Delahaye, F, Kirstetter, P E, Dubreuil, V, Machado, L A T, Vila, D A, Clark, R (2015) A consistent gauge database for daily rainfall analysis over the Legal Brazilian Amazon. *Journal of Hydrology*, 527, 292–304.

- Dias LCP, Macedo MN, Costa MH, Coe MT, Neill C (2015) Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin Central Brazil. *Journal of Hydrology: Regional Studies*, 4, 108–122.
- Fernandes K, Baethgen W, Bernardes S, DeFries RS, DeWitt DG, Goddard LM, Uriarte M (2011) North Tropical Atlantic influence on western Amazon fire season variability. *Geophysical Research Letters*, 38, L12701.
- Foley, J. A., Asner, G. P., Costa, M. H., Coe, M. T., Defries, R., Gibbs, H. K., ... Snyder, P. (2007). Amazonia revealed: forest degradation and loss of ecosystem goods and services in the Amazon Basin. *Frontiers in Ecology and the Environment*, 5(1), 25–32. [https://doi.org/10.1890/1540-9295\(2007\)](https://doi.org/10.1890/1540-9295(2007))
- Fu R, Li W (2004) The influence of the land surface on the transition from dry to wet season in Amazonia. *Theoretical and Applied Climatology*, 78, 97–110.
- Fu R, Yin L, Li W, Arias PA, Dickinson RE, Huang L, et al. (2013) Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proceedings of the National Academy of Sciences of the United States of America*, 110, 18110–18115.
- Garcia AS, Sawakuchi HO, Ferreira ME, Ballester MVR (2017) Landscape changes in a neotropical forest-savanna ecotone zone in central Brazil: The role of protected areas in the maintenance of native vegetation. *Journal of Environmental Management*, 187, 16–23.
- Garcia A S, Vilela VMFN, Rizzo R , Ballester MVR (2018) Improving land use and land cover classification with multi-sensor metrics and decision trees. Manuscript in preparation
- Hayhoe SJ, Neill C, Porder S, Mchorney R, Lefebvre P, Coe MT, et al. (2011) Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. *Global Change Biology*, 17, 1821–1833.
- Jiang C, Li D, Gao Y, Liu W, Zhang L (2016) Impact of climate variability and anthropogenic activity on streamflow in the Three Rivers Headwater Region, Tibetan Plateau, China. *Theoretical and Applied Climatology*, 129, 667–681.
- Knox R, Bisht G, Wang J, Bras R (2011) Precipitation variability over the forest-to-nonforest transition in southwestern Amazonia. *Journal of Climate*, 24, 2368–2377.
- Knox, R. G., Longo, M., Swann, A. L. S., Zhang, K., Levine, N. M., Moorcroft, P. R., & Bras, R. L. (2015). Hydrometeorological effects of historical land-conversion in an ecosystem-atmosphere model of Northern South America. *Hydrology and Earth System Sciences*. <https://doi.org/10.5194/hess-19-241-2015>

- Lathuillière MJ, Johnson MS, Donner SD (2012) Water use by terrestrial ecosystems: temporal variability in rainforest and agricultural contributions to evapotranspiration in Mato Grosso, Brazil. *Environmental Research Letters*, 7, 24024.
- Lathuillière MJ, Johnson MS, Galford GL, Couto EG (2014) Environmental footprints show China and Europe's evolving resource appropriation for soybean production in Mato Grosso, Brazil. *Environmental Research Letters*, 9, 74001.
- Lawrence D, Vandecar K (2014) Effects of tropical deforestation on climate and agriculture. *Nature Climate Change*, 5, 27-36.
- Lee JE, Lintner BR, Neelin JD, Jiang X, Gentine P, Boyce CK, et al. (2012) Reduction of tropical land region precipitation variability via transpiration. *Geophysical Research Letters*, 39, L19704.
- Lehner B, Liermann C R, Revenga C, Vörösmarty C, Fekete B, Crouzet P, et al. (2011) High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, 9, 494–502.
- Lewis SL, Brando PM, Phillips OL, van der Heijden GMF, Nepstad D (2011) The 2010 Amazon drought. *Science*, 331, 554.
- Liebmann B, Camargo S J, Seth A, Marengo JA, Carvalho LMV, Allured D, et al. (2007) Onset and end of the rainy season in south America in observations and the echam 45 atmospheric general circulation model. *Journal of Climate*, 20, 2037-2050.
- Macedo, M. N., DeFries, R. S., Morton, D. C., Stickler, C. M., Galford, G. L., & Shimabukuro, Y. E. (2012). Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proceedings of the National Academy of Sciences*, 109(4), 1341–1346. <https://doi.org/10.1073/pnas.1111374109>
- Macedo MN, Coe MT, DeFries R, Uriarte M, Brando PM, Neill C, Walker W S (2013) Land-use-driven stream warming in southeastern Amazonia. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 368, 20120153.
- Makarieva AM, Gorshkov VG, Sheil D, Nobre AD, Li BL (2013) Where do winds come from? A new theory on how water vapor condensation influences atmospheric pressure and dynamics. *Atmospheric Chemistry and Physics*, 13, 1039–1056.
- Malhi Y, Roberts JT, Betts RA, Killeen TJ, Li W, Nobre CA (2008) Climate change, deforestation, and the fate of the Amazon. *Science*, 319, 169–72.
- Marengo JA, Liebmann B, Kousky VE, Filizola NP, Wainer IC (2001) onset and end of the rainy season in the Brazilian Amazon Basin. *Journal of Climate*, 14, 833–852.

- Marengo JA (2009) Long-term trends and cycles in the hydrometeorology of the Amazon basin since the late 1920s. *Hydrological Processes*, 23, 3236-3244.
- Marengo JA, Tomasella J, Alves LM, Soares WR, Rodriguez DA (2011) The drought of 2010 in the context of historical droughts in the Amazon region. *Geophysical Research Letters*, 38, L12703.
- Morton DC, DeFries RS, Shimabukuro YE, Anderson LO, Arai E, Espirito- Santo FB, et al. (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, 103, 14637-14641.
- Negri AJ, Anagnostou EN, Adler RF, Negri AJ, Anagnostou EN, Adler RF (2000) A 10-yr climatology of Amazonian rainfall derived from passive microwave satellite observations. *Journal of Applied Meteorology*, 39, 42–56.
- Neill C, Coe MT, Riskin SH, Krusche AV, Elsenbeer H, Macedo M N, et al. (2013) Small watershed responses to Amazon soybean cropland expansion and intensification. *Philosophical Transactions of the Royal Society B*, 368, 20120425.
- Neill C, Jankowski K, Brando PM, Coe MT, Deegan LA, Macedo MN, et al. (2017) Surprisingly modest water quality impacts from expansion and intensification of large-scale commercial agriculture in the Brazilian Amazon-Cerrado region. *Tropical Conservation Science*, 10, 1-5.
- Nobre CA, Sellers PJ, Shukla J (1991) Amazonia deforestation and regional climate change. *Journal of Climate*, 4, 957-988.
- Panday PK, Coe MT, Macedo MN, Lefebvre P, Castanho ADA (2015) Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. *Journal of Hydrology*, 523, 822–829.
- Pettitt (1979) A Non-parametric to the Approach Problem. *Applied Statistics*, 28, 126–135.
- Pfaff A, Barbieri A, Ludewigs T, Merry F, Perz S, Reis E (2009) Road impacts in Brazilian Amazonia, In: *Amazonia and Global Change* (eds Keller M, Bustamante M, Gash J, Dias PS), American Geophysical Union, Washington.
- Riskin SH, Neill C, Jankowski K, Krusche AV, McHorney, R, Elsenbeer, H, et al. (2017) Solute and sediment export from Amazon forest and soybean headwater streams. *Ecological Applications*, 27, 193–207.
- Rodriguez DA, Tomasella J, Linhares C (2010) Is the forest conversion to pasture affecting the hydrological response of Amazonian catchments? Signals in the Ji-Paraná?? Basin *Hydrological Processes*, 24, 1254–1269.

- Saad S I, da Rocha HR, Silva Dias MAF, Rosolem R (2010) Can the deforestation breeze change the rainfall in Amazonia? A case study for the BR-163 highway region. *Earth Interactions*, 14, 1–25.
- Sawakuchi HO, Ballester MRV, Ferreira ME (2013) The role of physical and political factors on the conservation of native vegetation in the Brazilian forest-savanna ecotone. *Open Journal of Forestry*, 3, 49–56.
- Scheffler R, Neill C, Krusche AV, Elsenbeer H (2011) Soil hydraulic responses to land-use change associated with the recent soybean expansion at the Amazon cropland frontier. *Agriculture, Ecosystems & Environment*, 144, 281–289.
- Schubert SD, Suarez MJ, Pegion PJ, Koster R D, Bacmeister J T (2004) Causes of long-term drought in the US great plains. *Journal of Climate*, 17, 485–503.
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's Tau. *Journal of the American Statistical Association*, 63, 1379–1389.
- Silvério DV, Brando PM, Macedo MN, Beck PSA, Bustamante M, Coe M T (2015) Agricultural expansion dominates climate changes in southeastern Amazonia: the overlooked non-GHG forcing. *Environmental Research Letters*, 10, 104015.
- Siqueira JR, Toledo Machado LA, Siqueira JR, Machado LAT (2004) Influence of the frontal systems on the day-to-day convection variability over South America. *Journal of Climate*, 17, 1754–1766.
- Spera, S. A., Cohn, A. S., Vanwey, L. K., Mustard, J. F., Rudorff, B. F., Risso, J., & Adami, M. (2014). Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. *Environmental Research Letters*. <https://doi.org/10.1088/1748-9326/9/6/064010>
- Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., & Mustard, J. F. (2016). Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology*, 22(10), 3405–3413. <https://doi.org/10.1111/gcb.13298>
- Spracklen DV, Arnold SR, Taylor CM (2012) Observations of increased tropical rainfall preceded by air passage over forests. *Nature*, 489, 282–285.
- Stickler CM, Coe MT, Costa MH, Nepstad DC, McGrath DG, Dias LC, Soares-Filho BS (2013) Dependence of hydropower energy generation on forests in the Amazon Basin at local and regional scales. *Proceedings of the National Academy of Sciences of the United States of America*, 110, 9601–6.

- Vourlitis G, da Rocha H (2010) Flux Dynamics in the Cerrado and Cerrado–Forest Transition of Brazil. In: *Ecosystem Function in Savannas* (eds Hill MJ, Hanan NP), pp. 97–116. CRC Press, Boca Raton.
- Walker R, Defries R, Vera-Diaz MC, Shimabukuro Y, Venturieri A (2009) The Expansion of Intensive Agriculture and Ranching in Brazilian Amazonia. In: *Amazonia and Global Change* (eds Keller M, Bustamante M, Gash J and Dias PS), pp. 61–81. American Geophysical Union, Washington.
- Wang J, Chagnon FJF, Williams ER, Betts AK, Renno N, Machado, LAT, Bisht G, Knox R, Bras RL (2009) Impact of deforestation in the Amazon basin on cloud climatology. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 3670–3674.
- Wright JS, Fu R, Worden JR, Chakraborty S, Clinton NE, Risi C, Sun Y, Yin L (2017) Rainforest-initiated wet season onset over the southern Amazon. *Proceedings of the National Academy of Sciences of the United States of America*, 114, 8481–8486.
- Yue S, Pilon P, Cavadias G (2002) Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, 259, 254–271.
- Zelazowski P, Malhi Y, Huntingford C, Sitch S, Fisher J B (2011) Changes in the potential distribution of humid tropical forests on a warmer planet. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 369, 137–160.
- Zeng N, Yoon JH, Marengo J, Subramaniam A, Nobre C, Mariotti A, Neelin JD (2008) Causes and impacts of the 2005 Amazon drought. *Environmental Research Letters*, 3, 014002.
- Zhang A, Zheng C, Wang S, Yao, Y (2015) Analysis of streamflow variations in the Heihe River Basin, northwest China: Trends, abrupt changes, driving factors and ecological influences. *Journal of Hydrology: Regional Studies*, 3, 106–124.