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The influence of water table depth on evapotranspiration in the Amazon arc of deforestation

Authors: John O'Connor[1], Maria J. Santos[2], Karin T. Rebel[1] and Stefan C. Dekker[1,3]

[1]Copernicus Institute of Sustainable Development, Department Environmental Sciences, Utrecht University, The Netherlands
[2]University Research Priority Program in Global Change and Biodiversity and Department of Geography, University of Zürich, Switzerland
[3]Faculty of Management, Science and Technology, Open University, Heerlen, The Netherlands

Correspondence to: John C. O Connor (j.c.oconnor@uu.nl)

Abstract:

The Amazon rainforest evapotranspiration (ET) flux provides climate regulating and moisture provisioning ecosystem services through a moisture recycling system. The dense complex canopy and deep root system creates an optimum structure to provide large ET fluxes to the atmosphere forming the source for precipitation. Extensive land use and land cover change (LULCC) from forest to agriculture in the arc of deforestation breaks this moisture recycling system. Crops such as soybean are planted in large homogeneous monocultures and the maximum rooting depth of these crops is far shallower than forest. This difference in rooting depth is key as forests can access deep soil moisture and show no signs of water stress during the dry season while in contrast crops are highly seasonal with a growing season dependant on rainfall. As access to soil moisture is a limiting factor in vegetation growth, we hypothesised that if crops could access soil moisture they would undergo less water stress and therefore would have higher evapotranspiration rates than crops which could not access soil moisture.

We combined remote sensing data with modelled groundwater table depth (WTD) to assess whether vegetation in areas with a shallow WTD had higher ET than vegetation in deep WTD areas. We randomly selected areas of forest, savanna and crop with deep and shallow WTD and examined whether they differ on MODIS Evapotranspiration (ET), Land Surface Temperature (LST) and Enhanced Vegetation Index (EVI), from 2001 to 2012, annually and during transition periods between the wet and dry season. As expected, we found no differences in ET, LST, and EVI for forest vegetation between deep and shallow WTD, which because of their deep roots could access water and maintain evapotranspiration for moisture recycling during the entire year. We found significantly higher ET and lower LST in shallow WTD crop areas than in deep WTD during the dry season transition, suggesting that crops in deep WTD undergo higher water stress than crops in shallow WTD areas.

The differences found between crop in deep and shallow WTD, however, are of low significance with regards the moisture recycling system as the difference resulting from conversion of forest to crop has an overwhelming influence (ET in forest is ≈ 2 mm day^{-1} higher than that in crops) and has the strongest impact on energy balance and ET. However, access to water during the transition between wet and dry seasons may positively influence growing season length in crop areas.

Introduction

The Amazon rainforest has been reduced to 80% of its original size due to deforestation over the past few decades (Davidson et al., 2012). Land use and land cover change (LULCC) from forest to agricultural land disrupts the Amazonian water cycle due to changes in evapotranspiration, infiltration, and runoff (Fearnside, 1997; Lawrence and Vandecar, 2014). Changes in evapotranspiration result in major changes to the water energy balance, as forest vegetation has high evapotranspiration rates and is replaced with agricultural vegetation with lower evapotranspiration which results in a lower latent heat flux and higher sensible heat flux (Swann et al., 2015). In addition changes in evapotranspiration reduce the available atmospheric moisture which can reduce rainfall.

Differences in vegetation structure are suggested to be the main drivers affecting the evapotranspiration rates. Forest vegetation has a high total leaf surface area while agricultural vegetation usually have a lower leaf area (Asner et al., 2003; Costa et al., 2007). This difference lowers the potential surface area for both interception evaporation and transpiration. In addition, the rooting depth of forest and agricultural vegetation differs greatly (Costa and Foley, 2000). Forest vegetation have deep roots which facilitate access to deep soil moisture maintaining their supply of water necessary for photosynthesis even during the dry season. Forests can maintain a high rate of evapotranspiration during the dry season, unaffected by low rainfall (Maeda et al., 2017; Staal et al., 2018a). Following LULCC the new vegetation cover may lack deep roots and therefore no longer accesses deeper soil moisture. However, little is known whether LULCC that occurred in areas with a shallow WTD facilitates access to water and leads to higher vegetation productivity and evapotranspiration compared to areas with a deep WTD. Over the past few decades, the developing agricultural industry driven by international demand encouraged extensive LULCC (Brando et al., 2014; Foley et al., 2007; Sampaio et al., 2007) concentrated along the southern and eastern edge of the Amazon in an area known as the arc of deforestation (Costa and Pires, 2010; Malhi et al., 2008). LULCC negatively impacts the ecosystem service provision of the Amazon including highly valuable services such as carbon storage and sequestration and moisture recycling and regulation. Understanding the effect that LULCC has on evapotranspiration is important as the loss of evapotranspiration impacts both climate and precipitation on local and regional scales.

Local climate can be impacted by LULCC due to changes in the energy balance as loss of evapotranspiration reduces latent heat and increases sensible heat. Studies in the Amazon have shown that temperatures increase on average 1.4 ˚C with a max of 7 ˚C following conversion to crop (Badger and Dirmeyer, 2015). The seasonal impact of LULCC is particularly strong during the dry season as crop evapotranspiration is at its lowest, latent heat flux can be reduced by 78% and the sensible heat flux can increase by 85% relative to forest (Ponte De Souza et al., 2011). The loss of evapotranspiration impacts rainfall both locally and on the continental scale. Evapotranspiration returns water to the atmosphere where it can precipitate again either in situ or be carried further downwind (Eltahir and Bras, 1994). Large forests like the Amazon, because of their density and extent create large evapotranspiration fluxes, leading to underpressure over land and the pressure differences draw moisture towards land (Makarieva and Gorshkov, 2007; Sheil, 2014). As high as 70% of rainfall in the Amazon and southern Brazil is a result of Amazonian evapotranspiration (van der Ent and Savenije, 2011). This evapotranspiration precipitation cycle is highly important in both maintaining the forest itself but also providing precipitation to non forested areas. LULCC reduces the evapotranspiration and breaks this moisture recycling system resulting in lower rainfall locally and downwind. The seasonal loss of evapotranspiration in crop areas during the dry season is of great significance,

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evidence already suggests that LULCC has resulted in a lengthening of the dry season (Costa and Pires, 2010; Debortoli et al., 2017). Model simulations predict that if deforestation continues by 2050 the loss of evapotranspiration will result in a negative effect further reducing forest cover and evapotranspiration (Foley et al., 2007; Spracklen et al., 2012). The conversion of forest in Brazil is driven by an increasing demand for agricultural production which has almost doubled since 2000 (Zalles et al., 2019); however, losses in evapotranspiration could lead to subsequent losses in agricultural productivity as rainfall is reduced and the growing season is shortened (Oliveira et al., 2013).

Agricultural vegetation in the arc of deforestation experiences high seasonality during the dry season unseen in forest vegetation. Forest vegetation provides an optimum structure for evapotranspiration due to its tall complex, dense canopy and deep root systems which can access deep soil moisture stores and maintain high transpiration rates even during periods of low rainfall (Nepstad et al., 1994; Sheil, 2014). Agricultural crops, on the other hand, are known to contribute much less to evapotranspiration as a result of their shorter canopy and simpler structure (Fearnside, 1997). In addition, agricultural crops lack the deep root systems of forest which are credited for maintaining evapotranspiration throughout the dry season (Nepstad et al., 1994). In theory, if vegetation continues to access the water table within the root zone then this vegetation will continue to transpire during periods of reduced rainfall. Thus access to soil moisture is an important limiting factor for photosynthesis and transpiration. Shallow water table depths across South America are widely distributed and correspond to an area of approximately 36% of the Amazon (Fan and Miguez-Macho, 2010). We hypothesize that areas of shallow water table depth (WTD) allow vegetation to access soil moisture, with both shallow and deep rooted vegetation potentially facilitating vegetation productivity and higher evapotranspiration when compared to areas of deep WTD. Experimental manipulation of WTD using sub irrigation systems of soybean demonstrated that shallow WTD benefitted productivity and increased yield (Kahlown et al., 2005; Mejia et al., 2000). During the wet season, soybean can reach rates of evapotranspiration similar to that of forest(Costa and Foley, 2000). Some studies have suggested that the difference in annual ET between forest and agricultural crops is primarily due to access to water during the dry season (Costa et al., 2007).

In this study, we investigate if naturally occurring shallow water table depth could increase evapotranspiration compared to deep water table depth. We use a number of freely available remote sensing products in combination with modelled WTD to assess whether differences in evapotranspiration occur in areas of deep and shallow WTD, especially crop vegetation. We expect that the influence of WTD will be greater in the transition periods between wet and dry seasons as rainfall as a water source is limited. In areas of shallow WTD, the saturated zone is closer to the root zone of the vegetation. In these locations we, therefore, expect vegetation to be buffered against the reduction in rainfall during the dry season transition and experience drought conditions later, thus delaying the effect of the dry season. Similarly, during the wet season transition (WST), we expect that areas of shallow WTD will have higher productivity as vegetation may access the shallow WTD to supplement their demand when rainfall is low, therefore growing sooner than areas with deep WTD, effectively shortening the dry season. Finally, we discuss whether differences found in ET between deep and shallow WTD are important for moisture recycling, vegetation productivity and what are the implications for future LULCC.

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2 Methods

2.1 Study Area

The study area is located in the southern Amazon region, mostly in the northern region of Mato Grosso and incorporating the border area with Pará (Figure 1). Mato Grosso is classified into three major biomes with rainforest in the North, cerrado in the central region and wetlands in the southwest (Kastens et al., 2017; Lathuillière et al., 2012). The climate has two seasons, the wet season in the austral winter and the dry season in austral summer, the dry season lasts around 5 months with an annual average rainfall of 2000 mm and annual average temperatures ranging between 22 - 26 ˚C (Arvor et al., 2014). This region is well-known as a dynamic agricultural frontier – the arc of deforestation – with high rates of LULCC, where forest was converted for extensive agriculture, mostly cattle ranching and soy production (Kastens et al., 2017). Mato Grosso is the leading producer of agricultural crops such as soybean in Brazil (Gusso et al., 2014). We chose a study area which is centrally located in the arc of deforestation and has both large areas of primary forest and agricultural frontier regions, covering an area of approximately 750 km x 750 km. Within the selected study area, the dominant land cover is forest (73 %), followed by savanna (19 %), with cropland accounting for 3 %.

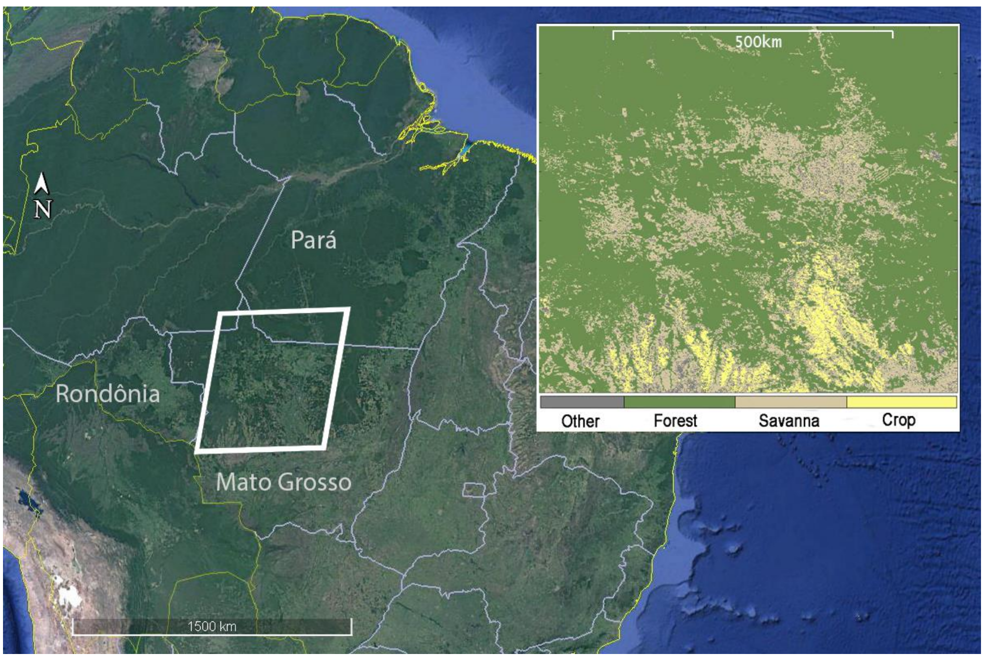

Figure 1: Study area on the arc of deforestation the Amazon, in Northern Mato Grosso. Inlayed image shows MODIS land cover classification map (2001) for the three land cover classes analysed. Forest – Green, Savanna – Beige, Crop – Yellow and Other - Grey. Due to the sinusoidal projection of MODIS satellite data, the study area looks distorted.

2.2 Datasets

2.2.1 Remote sensing data

Remote sensing offers excellent tools for monitoring changes in vegetation over large regions as it provides full geographic coverage, high temporal frequency at spatial scales relevant to most Earth system processes (Chambers et al., 2007). Here we use three separate products from the Moderate Resolution Imaging Spectrometer (MODIS), namely MODIS Evapotranspiration (MOD16A2), MODIS Land Surface Temperature (MOD11A2), and MODIS Enhanced Vegetation Index (MOD13A2), to assess the influence of WTD on evapotranspiration. MODIS remote sensing products were used as they offer a moderate spatial resolution and a high temporal resolution which is ideal for examination of seasonal processes. We chose to perform the analysis for the currently available MODIS land cover archive using data from 2001 to 2012. In addition, this period represents a time with high variability of precipitation extremes in which the Amazon experienced droughts, floods and could depict the variability the system experiences (Nobre et al., 2016). Data was downloaded from the NASA data sharing portal (earthdata.nasa.gov). Data was rescaled to 1 km resolution, no additional post-processing was conducted.

MODIS Evapotranspiration (hereafter ET) data (Mu et al., 2011) provides 8 day accumulated evapotranspiration at 500 m resolution (rescaled to 1 km). The ET dataset is one of the best available datasets due to its relatively high spatial and temporal resolution as such it has been widely used to investigate the effect of land use change on evapotranspiration in the Amazon (Loarie et al., 2011; Neill et al., 2013; Vergopolan and Fisher, 2016). The baseline algorithm to the MODIS ET product is based on the Penman-Monteith equation, and combines parameters such as land cover, leaf area index (LAI), Albedo and Fraction of Photosynthetically Active Radiation (FPAR) directly observed with or modelled from MODIS data, with reanalysis data on Radiation, Air Temperature and Humidity from the Global Modelling and Assimilation Office (Mu et al., 2011). The MODIS ET products were previously tested over the Amazon by comparing its outputs with eddy covariance tower data, showing that the product is more accurate over longer temporal scales and larger areas (Ruhoff et al., 2013). Therefore, the ET product may not be able to represent expected local differences in ET created by difference in WTD at the scale we want to answer our research questions, and we chose to analyse additional remote sensing products in which the differences might be detectable, and potentially show a signal to the effects of WTD on the water cycle.

MODIS Land Surface Temperature (hereafter LST) provides an 8 day mean day time land surface temperature in degrees Kelvin at 1 km resolution. LST data are produced by detection of thermal infrared radiation between 3 – 15 µm spread across 15 bands of the thermal sensor on board the MODIS satellite system and temperatures are modelled based on land cover classification with a clear sky accuracy of 1 degree K (Wan, 2014). MODIS LST data was converted to degrees Celsius. Despite low albedo in the Amazon and high net radiation, the strong evapotranspiration results in a net cooling effect (Bonan, 2008). We expected that areas with lower LST will be observed in areas of higher ET (Eltahir and Bras, 1994).

MODIS Enhanced Vegetation Index (hereafter EVI) provides a 16 day repeat observation on vegetation greenness at 500 m resolution (rescaled to 1 km). EVI is a vegetation index that measures greenness as a proxy for productivity (Huete et al., 2002). It was developed to improve upon the normalized difference vegetation index (NDVI), as it is less sensitive to saturation in highly dense canopies as those in the Amazon, and EVI also corrects for canopy background effects and atmospheric aerosol effects (Huete et al., 2002). This MODIS product offers an observation of vegetation productivity as it measures "greenness" and is correlated to photosynthesis/evapotranspiration (Sims et al., 2006). Thus we expect that vegetation with adequate access to water near their root zone will have a comparatively higher EVI than vegetation which is water stressed. This higher EVI, in turn, would correspond to areas of higher ET.

In addition, we also used the MODIS land cover product for selection of our analysis sites (see below). MODIS land cover (hereafter land cover) provides a classification of global land cover at 1 km resolution, and it is annually updated and used as input for other MODIS datasets utilised in this study (Friedl et al., 2010). For this study, we only used pixels that were classified as the same land cover type during the entire study period 2001 - 2012. The study area chosen provides a sufficient number of representative pixels for random selection of each land cover type. The use of stable land cover classes was necessary to determine and describe the patterns of ET, LST, and EVI over time and assess the effects of WTD on such trends without the confounding effect of land cover change. Further, this choice avoids potential circularity in using land cover classification to detect an effect on a parameter that uses land cover classification to produce its modelled value.

Finally, Tropical Rainfall Measuring Mission (hereafter TRMM) 3B42 provides daily precipitation at a resolution of 0.25^{0} (downloaded from earthdata.nasa.gov). The TRMM data was used to calculate the seasonality of rainfall, i.e. start of the dry season and the wet season (see below for further details).

2.2.2 Water table depth

Water table depth (WTD) values were extracted from the Fan et al. (2010) equilibrium WTD model of South America at 30 arc seconds (~ 1 km). The model was created using a combination of literature reported depths and national databases of groundwater table depth most of which are from drinking water wells mostly from areas of high population. This data is interpolated using a groundwater model forced by present day climate, terrain, and sea level. Very few of these observation points are located in or near our study area. We used the output of the model to obtain WTD data, which was projected to the same sinusoidal projection of the MODIS data. The equilibrium WTD model is intended for use in dynamic simulations, and although our study is not the intended use of the WTD model, it is the best currently available. The authors compared their WTD calculations with values reported in the literature and found good agreement and shallower WTD however, the model over estimated deep WTD. We selected two broad WTD classes in order to further reduce some of the uncertainty around this key parameter: Shallow <2 m and Deep >8 m (and we will refer to these as such from hereafter). Figure 2. shows a theoretical graphical representation of the difference between forest (deep rooting depth) and crop (shallow rooting depth) land cover classes. These depths were selected as they represented rooting depth values for crop and forest vegetation from literature (Fan et al., 2016; Moreira et al., 2000; Nepstad et al., 1994; Setiyono et al., 2008).

2.3 Sampling design

2.3.1 Spatial sampling

We chose to avoid pixels which experienced LULCC during the study period as we wanted to use the full time series for each pixel. We used MODIS land cover to identify pixels of each land cover class which remained unchanged between years and used these for analysis. We combined three land cover classes with the two water table depths and analysed the following classes: Forest Deep, Forest Shallow, Savanna Deep, Savanna Shallow, Crop Deep, and Crop Shallow.

For each class, we randomly selected 1000 pixels and performed this random selection 20 times to account for the effect of the randomization process in the results. This random selection method increased computational efficiency by limiting the number of total pixels examined and producing even group sizes for statistical analysis.

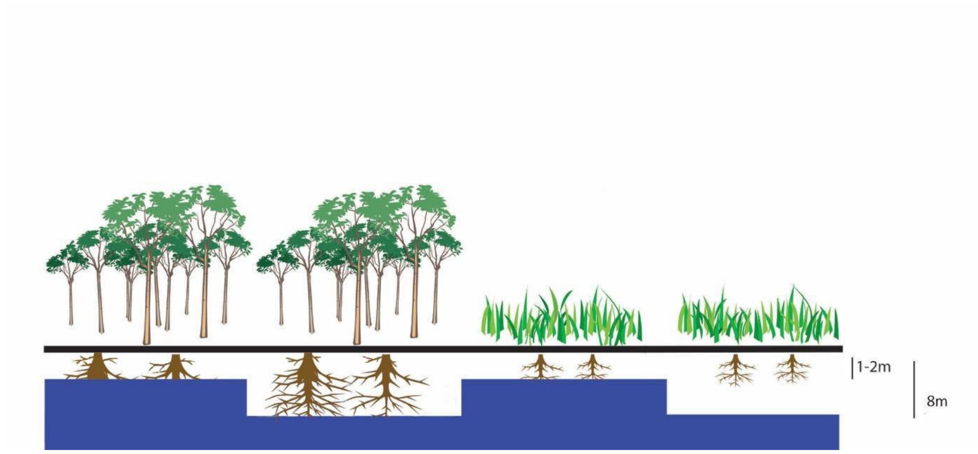

Figure 2: Diagram showing that forest root depth can infiltrate until the saturated zone in both shallow (< 2 m) and deep (> 8 m) WTD, while other vegetation has a lower maximum rooting depth. These roots may infiltrate soil until the saturated zone in shallow WTD (< 2 m); however, does not penetrate further in deep WTD (> 8 m).

2.3.2 Data analysis

The Amazon arc of deforestation is located in a region that has two major seasons defined by the difference in rainfall, the wet season from October to March (approximately 1500 mm) and the dry season from April to September (approximately 400 mm). The difference in rainfall can have significant impacts as the area can be prone to both seasonal flooding and droughts. In recent years the Amazon arc of deforestation has undergone an increased frequency of extreme weather events with drought in 2005, 2010 and flooding in 2009, 2012 (Nobre et al., 2016). These extreme climatic conditions can have a large influence on ET, investigation into the drivers of these extreme variations and how each land cover class is influenced is however beyond the scope of this study.

Analysis of the data was conducted using two primary time periods. At first, we compared mean daily values of ET, EVI and LST between deep and shallow WTD as this gives an indication of the influence of WTD on our land cover classes without considering the seasonal variation. Secondly, we compared ET, EVI and LST of our land cover classes during the dry and wet season transition periods.

For each year we calculated the dry and wet season transitions using daily precipitation data from the TRMM mission with the anomalous accumulation method of Liebmann et al., (2007). This method uses the following equation:

$$A(n) = \sum_{n=1}^{day} [R(n) - \bar{R}]$$

Where *R(n)* is daily precipitation and $\overline{R}$ is the average daily precipitation. Calculation of the anomalous accumulation begins at the driest month of the year, when the difference between daily precipitation and annual average is summed to a running total of the anomalous accumulation (*A*). The wet season onset is defined as the beginning of the longest period where the anomalous accumulation remains positive while the dry season onset is defined as the day after this anomalous accumulation reaches its maximum (Figure 3). These onset points of the dry and wet seasons were applied to find the closest time stamp from each MODIS product in the time series. We then considered the dry season transition to last on average 8 repeats in the MODIS record (5 for EVI due to the lower frequency of the product) and the wet season transition 7 repeats (4 for EVI). We used an average value over these transition periods to assess the difference between shallow and deep WTD on evapotranspiration.

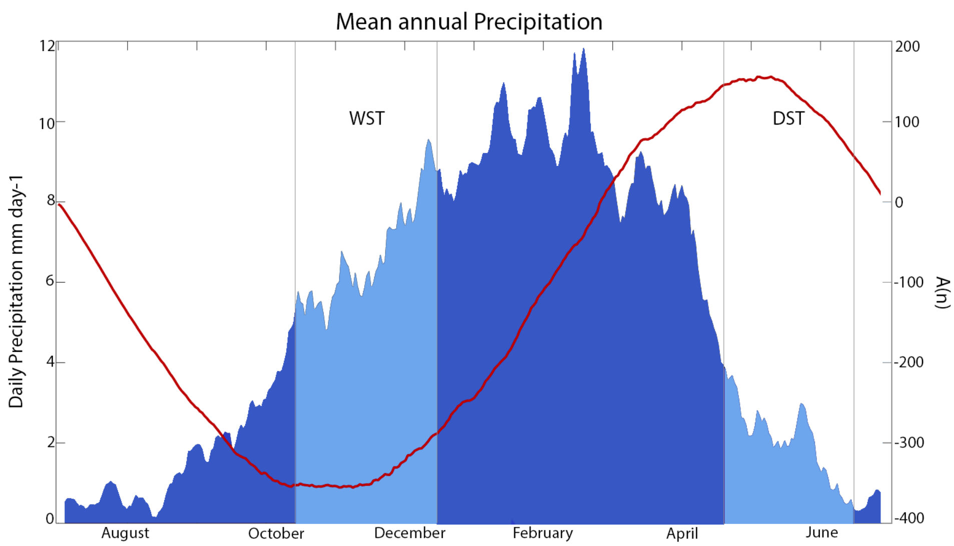

Figure 3 Mean annual precipitation of the study area calculated from TRMM with 7 day average for graphical smoothing. wet season transition (WST) and dry season transition (DST) periods are represented in lighter blue. The vertical lines represent the average start and end dates, however exact dates were calculated per year between July 2001 and July 2012. Red line represents anomalous accumulation method A(n) from Liebmann et al. (2007).

These seasonal periods were selected as we wanted to examine the difference between deep and shallow WTD during a period when access to moisture is limiting. We hypothesized that differences between deep and shallow WTD will be most discernible during the dry season transition as rainfall is limited and vegetation rely on deep soil moisture to survive this season, while during the wet season it might not be necessary as the higher rainfall provides more near surface water. Thus, vegetation in shallow WTD areas may have higher access to water as their root zone is closer to the water table this will likely produce higher ET, EVI and lower LST during the dry season transition than vegetation in deep WTD areas. This is because the WTD is much deeper and further from the vegetation rooting zone, which leads to a lack of access to water and the vegetation will likely be stressed. Similarly, during the wet season transition, we expect vegetation in shallow WTD to exhibit higher ET, EVI and lower LST than that in deep WTD because vegetation cannot yet be sustained by precipitation alone. In shallow WTD areas, vegetation will have greater access to the WTD areas and show accelerated growth when compared to deep WTD areas.

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We tested whether ET, LST, and EVI followed a normal distribution using the Kolmogorov–Smirnov test. This test served two purposes, to assess whether parametric statistics could be used and also indicate whether the WTD influences the frequency distribution of ET, LST, and EVI. Since a large number of response variables were not normally distributed, we chose to use non-parametric methods. Therefore, Wilcoxon rank sum test was used to test whether there was a significant difference in median ET, LST, and EVI due to the deep and shallow water table.

We further examined the frequency distribution of deep and shallow WTD of each of the datasets using the methodology of Wilcox (2012) where the lower and upper quantiles of the distribution are compared. Wilcox's method utilises bootstrapping in order to compare the distribution of the 10^{th} and 90^{th} quantile using the Wilcoxon–Mann–Whitney test. Due to our large sample size, 100 bootstrapped datasets were used.

Statistical analysis between each deep and shallow land cover pair was performed separately each year for all 20 randomisations e.g. differences in forest ET was tested for significance 12 years * 20 randomisations. A year was considered statistically significant when more than 66.7% of randomisations were significant and an overall significance was determined if the majority (>50 %) of the years were significant. Statistical analysis was performed using Matlab R2018a (The MathWorks Inc., Natick, USA) statistical toolbox and Wilcox (2012) quantile distribution tool.

3. Results

The following results section is split into three subsections, one for each of the MODIS products used in the analysis. Each of the subsections and accompanying figures follows the same structure. Each figure uses three panels for the three time periods on the analysis A) annual daily mean, B) daily mean during DST, C) daily mean during WST. Each panel has three pairs of box plots which represent the deep and shallow WTD data for forest, savanna and crop.

3.1 Effect of ground water depth on Evapotranspiration

None of the three land cover classes had significant differences in the average daily evapotranspiration (ET_{daily}) between deep and shallow WTD areas (Figure 4A). However, while we did not find consistent significant differences in both forest and crop ET_{daily} we do see a trend towards higher ET_{daily} in shallow WTD areas for both crop and forest (average ± standard deviation: Forest Deep = 3.953 ± 0.08 mm day^{-1}, Forest Shallow 3.967 ± 0.0.09 mm day^{-1}; Crop Deep = 1.697 ± 0.07 mm day^{-1}, Crop Shallow= 1.713 ± 0.08 mm day^{-1}). Interestingly, we found significant differences for Savanna at the extremes of the distributions, depicted by the arrows in Figure 4A. Both the 10^{th} and 90^{th} quantiles of ET_{daily} were significantly higher in deep WTD areas than in shallow (difference of 10^{th} = 0.017mm day^{-1}, difference of 90^{th} = 0.02 mm day^{-1}, see supplemental information table S.2.4 for all the quantile analyses).

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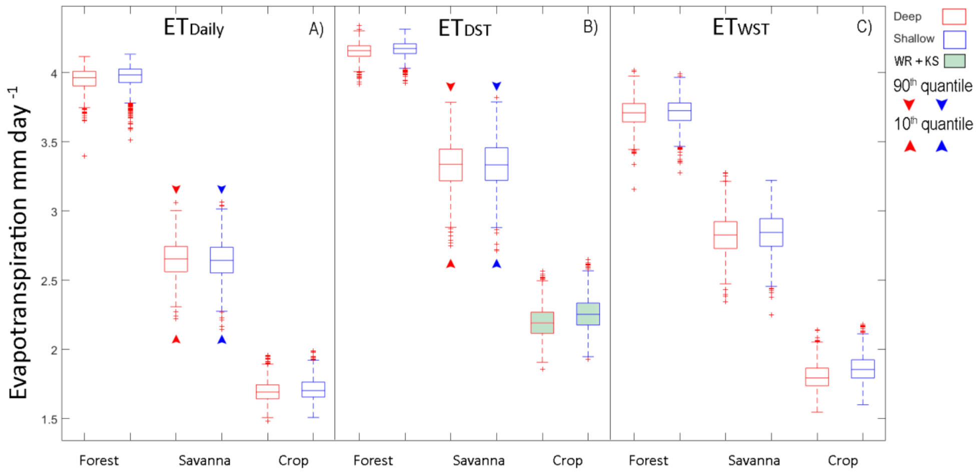

Figure 4. (A) Average daily evapotranspiration (ET) annually ET_{daily}, (B) during the dry season transition period ET_{DST}, (C) during the wet season transition ET_{WST}. Red boxes represent deep WTD Blue boxes represent shallow WTD. Significant results are shown by the green filled boxes if significance was found with both Wilcoxon Rank (WR) and Kolmogorov–Smirnov (KS). Significant differences in 10th and 90th quantile are depicted by the arrows.

We find that land cover types show different seasonal behaviour (see supplemental information figures S.3.1, S.3.2 and S.3.3). As hypothesized, crop ET during the dry season transition (hereafter ET_{DST}) was significantly higher in shallow than deep WTD areas (average ± standard deviation ET: Deep = 2.196 ± 0.11 mm day^{-1}, Shallow = 2.26 ± 0.12 mm day^{-1}, see the green filled boxes in Fig 4B). Again we observed significant differences at the extremes of the distribution for savanna, on average the 10th quantile of ET_{DST} was higher in shallow (average difference = 0.003 mm day^{-1}) and on average the 90th quantile of ET_{DST} was higher in shallow (average difference = 0.005 mm day^{-1}).

During the wet season transition (WST), while on average ET_{WST} was higher in shallow WTD areas than in deep WTD areas (average difference: Forest = 0.01 mm day^{-1}; Savanna = 0.01 mm day^{-1}; Crop = 0.06 mm day^{-1}) this difference was not significant (Figure 4C).

3.2 Effect of ground water depth in Land Surface Temperature

We found that the distribution of the average land surface temperature (LST_{daily}) was significantly different only for savanna and the 90th quantile of crop. Deep WTD areas of savanna showed a distribution skewed towards lower temperatures (average ± standard deviation LST: Deep = 31.705 ˚C ± 0.38, Shallow = 31.848 ˚C ± 0.37), see yellow filled boxes in Figure 5A. The 90th quantile of crop LST_{daily} deep WTD areas was on average 0.1 ˚C higher than in shallow WTD areas. Although this is only part of the distribution, it indicates that the warmest crop areas are found in deep WTD.

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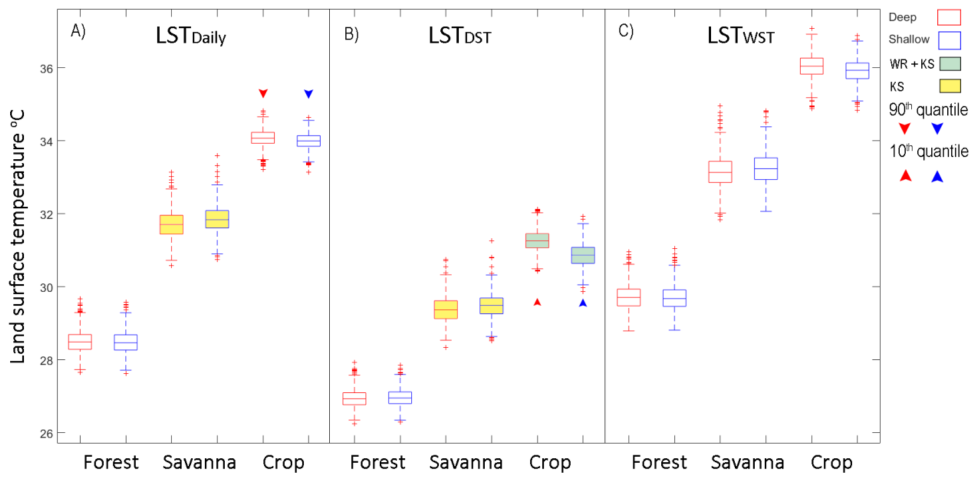

Figure 5. (A) Average daily land surface temperature (LST) annually LST_{daily}, (B) during the dry season transition period LST_{DST}, (C) during the wet season transition LST_{WST}. Red boxes represent deep WTD Blue boxes represent shallow WTD. Yellow filled boxes represent a statistical difference in skewness, calculated by Kolmogorov–Smirnov, and green filled boxes represent statistical differences by both Wilcoxon-rank and Kolmogorov–Smirnov. Significant differences in 10th and 90th quantile are depicted by the arrows.

LST also shows clear seasonal patterns (Supplemental information figure S.5.1, S.5.2 and S.5.3). During the dry season transition, we found that crop in deep WTD areas had a significantly higher LST than in shallow WTD areas (average ± standard deviation LST: Deep = 31.256 ± 0.29 °C, Shallow = 30.864 ± 0.31 °C, green filled boxes in Figure 5B). In addition, the 10th quantile of the crop distributions was significantly higher by 0.42 °C in deep WTD areas than in shallow. During these periods we found again a significant difference in the distribution of savanna, where deep savanna distribution was skewed towards lower LST values. No significant differences were found during the wet season transition (Figure 5C).

3.3 Effect of ground water depth on Enhanced Vegetation Index

We found significant differences in daily average EVI (EVI_{daily}) between deep and shallow only in crop (average ± standard deviation EVI: Deep = 0.352 ± 0.01; Shallow = 0.357 ± 0.01), with shallow WTD areas EVI being higher than that of deep WTD areas (Figure 6A green filled boxes).

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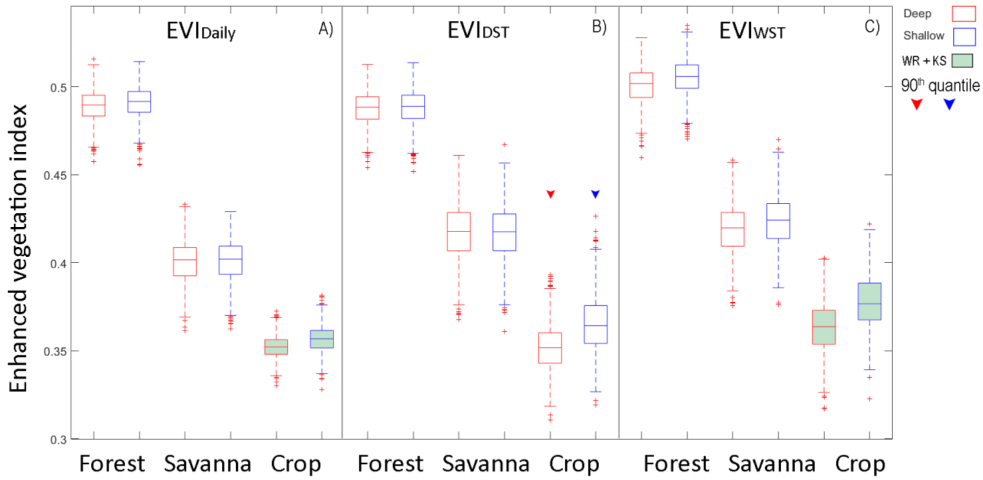

Figure 6. (A) Average enhanced vegetation index (EVI) annually EVI_{daily}, (B) during the dry season transition period EVI_{DST}, (C) during the wet season transition EVI_{WST}. Red boxes represent deep WTD Blue boxes represent shallow WTD. Green filled boxes represent statistical differences by both Wilcoxon-rank and Kolmogorov–Smirnov tests. Significant differences in 90th quantile are depicted by the arrows.

Seasonality in EVI is shown in Supplemental information figure S.7.1, S.7.2 and S.7.3. Mean EVI during the dry season transition (EVI_{DST}) for crop showed a trend towards higher EVI in shallow WTD areas; however, this difference was only significant in 5 of the 11 years and therefore is not considered consistent enough to be statistically significant (average ± standard deviation EVI: Deep = 0.352 ± 0.01, Shallow = 0.3656 ± 0.01. Figure 6B, Table S.6.8). The 90th quantile EVI of crop was significantly higher in shallow WTD areas than deep. During the wet season transition (EVI_{WST}), crop was the only different class where EVI was significantly higher in shallow WTD areas that in deep WTD areas (average ± standard deviation EVI: Deep = 0.364 ± 0.01, Shallow = 0.378 ± 0.02, green filled boxes in Figure 6C).

4 Discussion

In this study, we tested the hypothesis that areas of shallow water table depth (WTD) would have higher evapotranspiration when compared to areas of deep WTD, primarily in shallow rooted crop vegetation. The annual daily mean ET, however, was not different between crop in deep and shallow WTD areas. Since crop experiences high seasonality, this annual variability may override differences between deep and shallow WTD areas in the daily average values of the MODIS products. For example, average crop ET reaches a high of 3.5 mm day^{-1} in the wet season while the dry season ET reaches a low of 0.4 mm day^{-1}. Interestingly we found significant differences in annual mean LST and EVI for crop. For LST, we found that the upper 90th quantile was 0.11 °C higher in deep than in shallow WTD areas. While this difference is only found in the 90th quantile of the distribution it does indicate that local conditions can be much warmer in deep WTD areas than shallow. In addition, we found that crop in shallow WTD areas had a significantly higher EVI than in deep WTD. Crop EVI in shallow WTD areas is

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1.2 % higher than in deep WTD. This provides support to our hypothesis that crop would have higher EVI in shallow WTD compared to deep WTD areas. The rooting depth of crop vegetation only penetrates to a maximum of 2 m, in shallow WTD areas this means the root zone is close to the WTD and would have access to water while in deep WTD the roots a far from the saturated zone. This access to water in shallow WTD areas could also lead to higher ET and therefore evaporative cooling explaining the cooler temperatures in the 90th quantile.

The second part of our hypothesis was that the effect of WTD would be most evident during the transition periods between wet and dry seasons when rainfall is reduced and vegetation activity is limited by access to soil moisture. We found support for this hypothesis during the dry season transition. In the DST, crop ET was significantly higher in shallow WTD areas and crop LST was significantly lower in shallow WTD areas, while in crop EVI we saw a trend towards higher EVI in shallow WTD areas (significant differences were only found in 5 of the 11 years). While the difference in crop ET is not large (0.063 mm day^{-1}, 2.9 % higher in shallow); during the dry season transition, the results are important as they indicate that crops in the shallow WTD areas have a delayed response to lower rainfall and have a relatively longer growing season. Crop LST further supports our hypothesis as LST in deep WTD areas was 0.39 ˚C higher than in shallow WTD areas, while no significant effects were found in EVI. Therefore cooler temperatures in shallow WTD areas are expected to be the result of higher evaporative cooling from ET. If this extra warming above the canopy is caused by a change in ET, then better estimates of ET should be possible, however, this is not trivial (Glenn et al., 2007). These relatively low differences in ET as measured with MODIS data might also be due to the ET product itself. The MODIS ET model is not optimised for comparison over relatively small spatial extents and short temporal scales (Ruhoff et al., 2013). In addition, the model does not take into account water storage and ET is based largely on atmospheric forcing and global land cover parameterisation. Therefore, the modelled data was expected to underperform, making the differences we found for the dry season even more important.

Ponte De Souza et al. (2011) highlighted that one of the strongest impacts of LULCC from forest to crop was due the simultaneous 85% increase in sensible heat flux and 78% reduction in latent heat recorded during the dry season. Studies examining the change in LST due to LULCC found that LST increased by 6 ˚C from forest to crop (Silvério et al., 2015) and 1.5 ˚C from savanna to crop (Loarie et al., 2011). Further global models estimated an increase of 5 ˚C during the summer season for the Amazon, due to a shift from forest to grass (Brovkin et al., 2009; Dekker et al., 2010). This could mean that in deep WTD temperature could even be higher following LULCC, however, WTD were not used as input for these modelling studies. Our results show a maximum temperature of 30 ˚C in forest compared to a maximum temperature of 38 ˚C in crops.

We also expected that the influence of WTD would also be important during the wet season transition, as in this period rainfall is increasing. In areas of shallow WTD vegetation may still access water to supplement if rainfall is not sufficient as their root zone is close to the water table. Therefore, vegetation growth may be accelerated in comparison to areas of deep WTD which rely more directly on precipitation. Crop EVI was significantly higher in shallow WTD than deep by about 3.8 %, and this was the only data for which we found a significant difference. EVI measures vegetation greenness and could be an indication of more rapid growth in shallow WTD areas. As EVI data is directly observed and not modelled the differences are solely reliant on differences in reflected radiation. It may be that smaller differences between deep and shallow WTD areas are more easily detectable using this data. Along the arc of deforestation observations of a lengthening dry season since the 1970s, are linked to a delay in the WST (Butt et al., 2011; Fu et al., 2013). This delay correlates with LULCC and the large reduction this has on ET (Debortoli et al., 2017). Although the difference in WTD seen in crops does not have a strong influence on ET when compared to the difference in ET between the land cover classes, evidence of earlier or faster growth due to the shallow WTD could be beneficial on a local scale.

These results are even more relevant when comparing the effects of WTD in crop and forest. As forest has been shown to maintain ET throughout the seasons (Kunert et al., 2017) as its deep roots access deeper groundwater (Gash and Nobre, 1997; Nepstad et al., 1994), we hypothesised that no change should be observed in ET, LST, and EVI. Indeed, we found no significant differences across the three MODIS products, both annually or during the dry and wet season transitions. While this does not directly support our hypothesis about the role of WTD for shallow rooted vegetation, this does help validate that our approach reflects our knowledge of the system for vegetation with deep roots.

Savanna is a complex land cover type both in terms of its natural structure (Staal et al., 2018b) and because it is challenging to classify with remote sensing data (Gibbes et al., 2010). MODIS classification accuracy of savanna is about 40 %, about half of that of forest and crop (90 % and 80 % respectively) (Friedl et al., 2010). Savanna includes both trees and grasses, which through the deep roots of trees may access moisture directly and facilitate moisture uptake via hydraulic redistribution (Oliveira et al., 2005) and large areas of shallow root grasses without trees would be negatively affected by water stress. A number of the findings for savanna were not in line with our proposed hypothesis. The distribution between shallow and deep LST was significantly different, with deep WTD areas having a skewed distribution towards lower temperatures. In our hypothesis, we expected to find lower temperature where shallow WTD occurs or no differences in temperature. A similar trend was found in ET where the 10^{th} and 90^{th} quantiles of the distribution were significantly higher in deep WTD areas. The difference in ET was very small < 1 % difference between deep and shallow.

The differences found for crop support our hypothesis that shallow WTD areas may facilitate water uptake compared with areas of deep WTD during the transition between wet and dry seasons. Previous crop production studies have shown that artificially maintaining a shallow WTD through sub irrigation systems can increase the productivity of crops such as soy (Kahlown et al., 2005; Mejia et al., 2000) but this has not been previously shown in the naturally occurring shallow WTD areas of the arc of deforestation in the Amazon. In deep WTD areas, crop vegetation undergoes more severe water stress compared with shallow WTD further reducing evapotranspiration and its potential impact on the moisture recycling system. At the regional scale, the difference between deep and shallow WTD is not that important. The most significant differences in ET are driven by deforestation and strong annual variations in rainfall. Although not analysed specifically in this study, the remote sensing data clearly shows these distinctions between different land cover classes and high seasonal and inter-annual variability. On a local scale, the difference between deep and shallow WTD on crop may be of great importance. During the dry season transition crop areas in shallow WTD maintained higher ET. This difference may be important for overall productivity as the dry season influence is delayed and as a result, is increasing the growing season length. This could facilitate natural double cropping systems without the need for investment in irrigation which is still an uncommon practice in the Amazon arc of deforestation (Lathuillière et al., 2012). Agricultural intensification is a pathway to increasing the sustainability of agriculture in the arc of deforestation if it prevents or reduces deforestation or facilitates reforestation (Oliveira et al., 2013). If agricultural productivity can be increased by focusing on already cleared shallow WTD areas, areas of deep WTD could be reforested or returned to secondary forest. Reforestation of previously degraded or logged forest has been shown to return to near natural levels of ET within a few years (Davidson et al., 2012; Hölscher et al., 1997).

This study is a first approach into gaining a better understanding on the influence of shallow WTD on shallow rooted vegetation and it heavily relies on models and remote sensing data which are most appropriate for analyses at larger spatial and temporal scales. The results presented here are limited by the inherent uncertainty of the data used, both in the WTD model and the remote sensing data. Although we believe that the WTD model used here is the best currently available, due to limited data availability it was created using data located mostly in the coastal regions of the continent with very few observations from near our study site (Fan and Miguez-Macho, 2010). In this study, the authors note that there is an overestimation of deep WTD areas when validated against literature reported values. We believe that by the use of a conservative definition of deep WTD >8 m the model outputs are appropriate for our purposes. As discussed above, the remote sensing data has obvious limitations but does provide some insights into how depth of the water table at a local scale might affect water transfer and evaporative processes. Nonetheless, the second main source of uncertainty is in the MODIS land cover classification. We chose to use this land cover classification as the ET and LST products use this classification in their algorithm. Although the classes used are broad and do not reflect the full complexity and heterogeneity of the arc of deforestation, they are robust enough for our purposes. As the influence of WTD on ET is most relevant on smaller scales, further research in these areas could focus on the smaller spatial scales and validate sites with accurate classification and WTD measurements.

5. Conclusions

The results of this study indicate that crop vegetation in areas of shallow WTD undergoes less water stress than crop vegetation in deep WTD areas, especially during the dry season transition. The influence this difference has on regional evapotranspiration or on the moisture recycling service might be low and most likely not influential, because most of the effects are in the conversion from forest to crop. However, on a local level, this buffering may essentially shorten the total dry season length by delaying the water stress response. This difference could have implications for agricultural productivity in the Amazon arc of deforestation. Utilising areas of shallow WTD to increase agricultural efficiency could mean a reduction in the total agricultural area allowing for areas of deep WTD to be reforested or prevented from being deforested. As evapotranspiration rates of secondary forests have been shown to reach near natural levels, reforestation of these areas could directly benefit the moisture recycling ecosystem services. These ecosystem services provided by the Amazon are highly valuable and ideally should be prioritised. The possible introduction of payment for ecosystem services could target deep WTD areas as they may be of lower agricultural value, very inefficient in terms of their water use, but still, provide the desired ecosystem services.

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An unknown factor will be whether the role of groundwater table depth will become more important in the future due to changes in climate. Many modelling studies predict that the dry season will lengthen and that the arc of deforestation will move to a warmer drier climate (Bonan, 2008). Under this scenario, where possible it would be wisest to conserve the natural forest ecosystems of the Amazon, especially where groundwater is deepest in order to maintain the moisture recycling services as well as the local climate cooling effect.

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