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Atmospheric moisture contribution to the growing season in the Amazon arc of deforestation

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E-mail: j.c.oconnor@uu.nl**Keywords:** Amazon forest, cropping, ecosystem services, modelling, moisture recyclingOriginal content from
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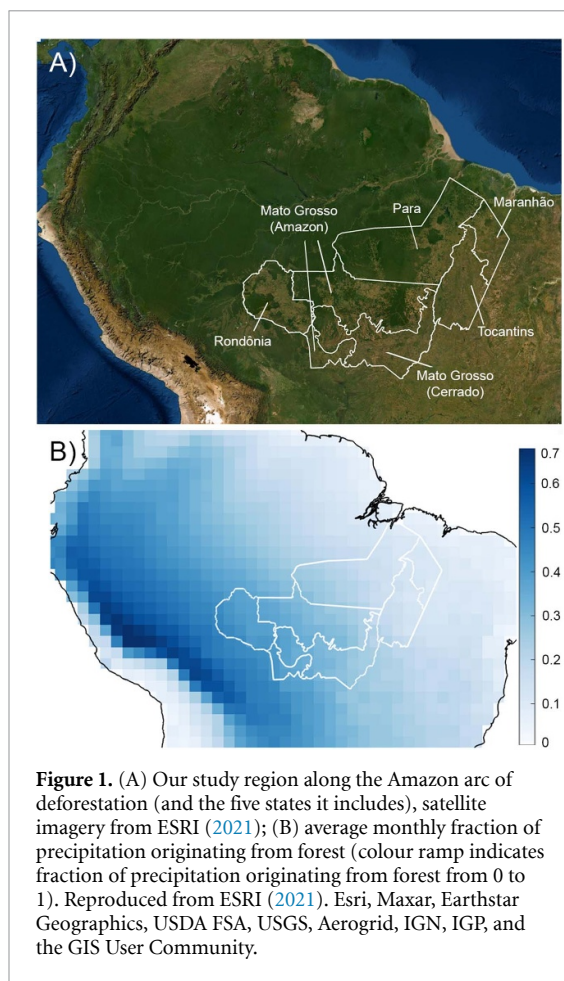
The Amazon moisture recycling system has been widely examined because it is fundamental to maintain some of the global climate processes, however, we have yet to know to what extent the agricultural growing season is dependent on the evapotranspiration contribution from the Amazon forest. Here we use a moisture tracking model to calculate the forest's contribution to downwind precipitation. Specifically, we calculate the influence of moisture recycling on the seasonality of precipitation in the arc of deforestation with respect to the agricultural growing season. We calculated the wet season start, end and length using three scenarios (a) total precipitation with existing vegetation cover; (b) where we replace forest's contribution to precipitation by replacing it with the equivalent from short vegetation; (c) where the forest's contribution to precipitation is completely removed. We found that forest moisture recycling contributes up to 40% of monthly precipitation in the arc of deforestation. However, there is a strong spatial gradient in the forest's contribution to precipitation, which decreases from west to east. This gradient also coincides with suitability for double-cropping agriculture. Our scenarios excluding precipitation originating from forest indicated that forest is a key contributing factor in determining the wet season start. We found that even when the precipitation originating from forest was replaced by short vegetation there was a significant delay in the wet season start in our study regions. Interestingly the wet season end was more resilient to changes in precipitation source. However it is clear that moisture recycling plays a key role in determining the wet season end as when forest's contribution to precipitation was entirely removed the wet season end arrived significantly earlier. These differences in wet season length were not detectable in the eastern states of Tocantins and Maranhão, as much less of the precipitation in these states originates from the forest. Our findings demonstrate the importance of forest in supporting double-cropping agriculture in the arc of deforestation. As agricultural intensification by double-cropping increases land-use efficiency, it may also reduce the demand for further deforestation. Therefore it is important to identify how the current forest extent provides this important ecosystem service.

1. Introduction

The Amazon rainforest is the largest tropical forest on Earth and plays a large role in regulating climate. The high evapotranspiration rates lower temperatures (Li *et al* 2015) and replenish atmospheric moisture, which provides water for agriculture. Degradation and deforestation lead to losses in evapotranspiration (O'Connor *et al* 2019) and in turn lower atmospheric

moisture and precipitation, which can impact the growing season (Aragão 2012).

The large evapotranspiration flux from the Amazon returns around 1000 mm yr⁻¹ of water to the atmosphere (Swann and Koven 2017) where it can then precipitate out either locally or be carried downwind and precipitate remotely at distances of thousands of kilometres (van der Ent and Savenije 2011). This process, known as moisture recycling, is



of high importance as the recycled water can be transpired several times, effectively increasing the volume of water available for plants (Zemp *et al* 2014). The moisture recycling not only maintains the Amazon rainforest itself but provides water outside the biome, and is critical for hydropower, human consumption and agriculture (Keys *et al* 2016). Specifically, rates of moisture recycling range from 30% to 40% in the Amazon itself and contributes up to 70% of precipitation in parts of South America (van der Ent and Savenije 2011, Keys *et al* 2016, Staal *et al* 2018).

Despite its high value in terms of carbon gain, biodiversity and moisture recycling, the Amazon forest and the surrounding savanna-like cerrado biome have undergone decades of deforestation for timber production and land clearing for agricultural production of cattle, soy and maize (Fearnside 2005, Strand *et al* 2018, Zalles *et al* 2019). Since 1982, over 385 000 km² of the Amazon forest has been deforested (Song *et al* 2018). The majority of deforestation is concentrated along the southern and eastern border of the Amazon, the arc of deforestation (figure 1).

Deforestation leads to changes in the hydrologic system of the Amazon as the tall complex canopy of the Amazon forest vegetation has high rates of rainfall interception and transpiration. Trees also have deep root systems that can access deep soil moisture, which facilitates transpiration throughout the dry season

(Nepstad *et al* 1994, Sheil 2014). Evapotranspiration values from the forest are on average 3 to 4 mm d⁻¹ (Costa *et al* 2010, da Motta Paca *et al* 2019, O'Connor *et al* 2019). Following conversion from forest to agriculture, annual evapotranspiration is reduced by 30% or even more (Nobre *et al* 1991, de Souza *et al* 2011, Sampaio *et al* 2007, O'Connor *et al* 2019). This reduction is largely caused by an extremely low dry season evapotranspiration, linked to rooting depth. In rangelands, the shallow rooting depth of grasses disables access to deeper groundwater (Nepstad *et al* 1994), and in crop agriculture, in addition to shallow root vegetation, fields are often left fallow (Pires *et al* 2016, Costa *et al* 2017). This reduction in evapotranspiration interrupts the natural moisture recycling cascade, lowers atmospheric moisture, and therefore reduces precipitation. The impact of these losses of evapotranspiration for anthropogenic systems is still uncertain.

The agriculture in the arc of deforestation is almost entirely rainfed, with less than 10% of land under irrigation (Lathuilière *et al* 2012, Spera *et al* 2016). If agricultural expansion continues at the expense of the forest or the cerrado, it could lead to a scenario where increases in area of agriculture can lead to losses in production elsewhere due to the reduced precipitation (Oliveira *et al* 2013). Double cropping has been proposed and implemented in some areas of the arc of deforestation as a way to intensify production that could relieve land clearing pressure on the natural biomes and safeguard precipitation (Stabile *et al* 2020). Traditionally the crop agriculture in the arc of deforestation has been based on a single crop system. More recently, due to improvements in plant breeding technology, soybean varieties can be planted earlier because new varieties are less dependent on the photoperiod, therefore increasing the effective growing season length and enabling a second crop of maize or cotton (Abrahão and Costa 2018). Because of the more effective use of the growing season length, double cropping systems have increased in prevalence in the arc of deforestation. In the state of Mato Grosso alone, the area of double cropping soy systems increased by 45 000 km² between 2001 and 2014 (Kastens *et al* 2017) corresponding to 44% of the state's total soy area (IGBE 2020), and this accounts for 16% of Brazilian soy production (Garrett *et al* 2018). While there are a number of economic and infrastructure factors that affect whether farmers implement double cropping, climatological restrictions may be far stronger.

Crop production in the arc of deforestation is tightly coupled to the wet season length in the austral summer from October to April. In this region, the wet season needs to be of sufficient length to afford the conditions for the two sequential crops. Conservatively, a 200 d growing season is sufficient for double cropping (Abrahão and Costa 2018). This

means 110 d to grow and harvest soybean and a further 90 d for growth of a second crop (primarily maize), which can be harvested after the wet season end. For most of the wet season, daily precipitation ($10 \pm 5 \text{ mm d}^{-1}$) consistently exceeds the maximum actual evapotranspiration for growing soybean (8 mm d^{-1}) under optimum conditions (Setiyono *et al* 2008). In contrast, the transition period between dry and wet seasons can be much less predictable, with both dry and wet season start dates differing considerably and varying in the amount of precipitation.

There is increasing evidence that suggests that deforestation decreases the length of the wet season (Costa and Pires 2010, Leite-Filho *et al* 2019). Both a delay in the wet season start and earlier wet season end have been observed (Butt *et al* 2011, Debortoli *et al* 2015) and this reduces the possibility of a second crop. However, the connection between forest evapotranspiration, its effect on rainfall amount and wet season length necessary for agriculture is still relatively unknown. Previous modelling studies have demonstrated connections between evapotranspiration sources with downwind precipitation (Zemp *et al* 2014, van der Ent and Tuinenburg 2017), however, these often focus on longer seasonal or annual periods, and have not specifically assessed the feasibility of double cropping (Antônio-Sumila *et al* 2017).

Our goal is to understand whether forest evapotranspiration is important for double cropping. We used a state-of-the-art lagrangian moisture tracking model and three scenarios to investigate to what extent forest evapotranspiration facilitates double cropping across the arc of deforestation (Tuinenburg and Staal 2020). We address the following questions: (a) what fraction of precipitation in the arc of deforestation originates from forest and how does this vary seasonally? (b) How does precipitation from forest influence the wet season length? (c) Does forest cover influence the location and extent of areas where double cropping is feasible? Our results improve our understanding of the role of moisture recycling in water provision for agriculture.

2. Methodology

2.1. Study area

We focus our study along the arc of deforestation at the southern edge of the Amazon forest which straddles two natural biomes, tropical forest in the North and the cerrado in the South and East (figure 1(A)). This area covers five states, however as Mato Grosso has two distinct biomes Amazon (north and southwest) and Cerrado (south) we have divided Mato Grosso into two separate study regions. Based on their natural biomes we consider for the Amazon: Rondônia, Mato Grosso (Amazon) and Pará, and for the cerrado: Mato Grosso (Cerrado), Tocantins and Maranhão. Since 2015 all five states have introduced

double cropping with soy and maize as a second crop (IGBE, 2020). The Amazon forest and the cerrado are distinct in their natural vegetation, with closed forest in the Amazon forest, transitioning to more open forest and a mixture of trees and grasslands in the cerrado. Vegetation differences in these biomes are partly defined by annual rainfall, with the Amazon forest receiving $>2000 \text{ mm yr}^{-1}$ while the cerrado receives approximately $\sim 1500 \text{ mm yr}^{-1}$. This precipitation has different origins, forest vegetation, short vegetation and ocean (figure 1(B); Tuinenburg and Staal 2020). In the southern Amazon the climate has two seasons. The wet season lasts approximately from October to April with precipitation of $200\text{--}300 \text{ mm mo}^{-1}$. The precipitation in the remaining dry season is about 50 mm mo^{-1} (Bagley *et al* 2014). The annual temperature is stable ranging on average between $20 \text{ }^\circ\text{C}$ and $24 \text{ }^\circ\text{C}$.

2.2. Data sources

We downloaded the biome and state boundaries from the Brazilian Institute for Space Research (INPE; www.inpe.br/dados_abertos/). As the state of Pará covers a large area of undisturbed forest, we decided to draw the north-eastern boundary of our polygon to reflect better the arc of deforestation, which we will refer to as Pará throughout. For our analysis, these polygons were rasterized at 1° grid cells to match the grid used in our model output (see section 2.3).

Our forest cover data was derived from Song *et al* (2018). This dataset provides an estimate of land cover for 1982–2016, categorizing 0.05° resolution grid cells as bare soil, short and tall vegetation. We consider forest to be equivalent to tall vegetation cover. We upscaled forest cover data to a 1° resolution to match the scale of the moisture tracking model (see section 2.3).

MODIS (Moderate Resolution Imaging Spectroradiometer) evapotranspiration (MOD16) and land cover (MOD12) data were used to calculate the relative difference between forest and short vegetation (average of grassland and cropland) evapotranspiration from 2002 to 2017. MOD16 provides modelled evapotranspiration values at 1 km resolution as an 8 d accumulation. We used image tile H12V10 as this tile is centrally located in the arc of deforestation. We first converted these data to daily average evapotranspiration values and then as monthly accumulated evapotranspiration. Finally, we randomly selected 5000 pixels from each of the three land cover classes (forest, grassland and crop) to calculate average monthly evapotranspiration per land cover.

2.3. Moisture tracking model

We used the lagrangian moisture tracking model UTrack from Tuinenburg and Staal (2020). The model calculates the movement of water through the atmosphere from source (evapotranspiration)

through transport (wind) to sink (precipitation). The model is forced using the latest reanalysis data from the ECMWF, ERA5 (Copernicus Climate Change Service, C3S). Specifically surface values of evapotranspiration and precipitation, and vertical values (at 25 levels) of specific humidity and wind (u, v) are interpolated from hourly to 0.1 h timesteps.

The atmospheric moisture tracking works as follows. During each model timestep of 0.1 h, a number of moisture parcels are released into the atmosphere. The amount of evaporation into the atmosphere is determined by ERA5 and modelled to be 100 parcels per mm h⁻¹ of evaporation, with a minimum of one parcel per timestep. The amount of moisture evaporated as parcels are randomly dispersed throughout the area of each ERA5 grid cell.

Subsequently, these parcels are traced forward through the atmosphere by using a lagrangian trajectory scheme, during which there is explicit vertical mixing once every 24 h on average. This explicit vertical mixing redistributes the parcels to follow the local vertical specific humidity profile. This procedure is necessary because the large-scale winds may not represent the atmospheric vertical mixing processes; however, this is the greatest source of uncertainty in the UTrack model (Tuinenburg and Staal 2020).

During the path of a parcel through the atmosphere, the local moisture budget is determined by assessing the ERA5 precipitation (P) and precipitable water (PW) at the location and moment of the parcel. If P is larger than zero, a fraction (P/PW) of the parcel's moisture is assumed to be raining out at that present location of the parcel. This means that the amount of moisture that is still present in the parcel decreases with time and the amount of moisture that is allocated to precipitation increases with time.

Each parcel is tracked until either less than 1% of the original moisture is still present, or 30 d have passed since the release of the parcel.

The UTrack model is entirely forced with data from ERA5 which is the current state-of-the-art atmospheric reanalysis dataset. The full explanation of the UTrack model and sensitivity analyses is available in Tuinenburg and Staal (2020). The sensitivity analysis highlights that the three-dimensional lagrangian approach used in the UTrack model is an improvement compared to other grid-based moisture tracking models. Global model output is calculated as either a forward or backward projection. Forward projection maps each cell as a source and follows moisture to the sink location while backward projection identifies the source region for a given sink cell. For this study, we calculated backward projected moisture transport for all sink cells in our study area at monthly intervals and 1° resolution, from 2002 to 2017.

2.4. Calculation of the precipitation fraction

The moisture recycling model provides the source locations of the precipitation over our study region (figure 1(B)). Subsequently, we calculate the fraction of precipitation originating from the ocean and from the land, where we further subdivide land into fractions from forest using tall vegetation from Song *et al* (2018), as described above. This method may underestimate the contribution of forest cover in cells with multiple land cover types as the evapotranspiration flux from forest is up to two times larger than other land cover types in this region (O'Connor *et al* 2019).

2.5. Calculation of the wet season

Calculation of the wet season start, end and length was based on the anomalous accumulation equation from Liebmann *et al* (2007):

$$AA(\text{day}) = \sum_{n=1}^{\text{day}} [P(n) - \hat{P}]. \quad (1)$$

The anomalous accumulation (AA (mm)) begins on the first of August of each year AA(1) as this is the beginning of the driest month of the year. For each day we calculate the difference between the daily precipitation $P(n)$ (mm d⁻¹) and the average annual daily precipitation over the month \hat{P} (mm d⁻¹). Each subsequent timestep is an accumulation where the lowest point in the anomalous accumulation marks the wet season start, while the highest value marks the wet season end. Recent literature has adapted this formula to calculate a specific double cropping growing season replacing \hat{P} with a crop-specific precipitation threshold (Arvor *et al* 2014, Abrahão and Costa 2018). Specifically, Abrahão and Costa (2018) defined a precipitation threshold (\hat{P}) of 2.5 mm d⁻¹ that corresponds to the amount needed for soybean seedlings to survive and grow. Arvor *et al* (2014) defined their precipitation threshold as 5.1 mm d⁻¹, which represents the water demand of soybean at the start of the vegetative cycle. The precipitation threshold of 5.1 mm d⁻¹ is also in line with late-season evapotranspiration of maize (Lyra *et al* 2016). In this study we decided to calculate the wet season start and end using both precipitation thresholds. We took the lowest value using the 2.5 mm d⁻¹ precipitation threshold as our wet season start and the highest value using the 5.1 mm d⁻¹ precipitation threshold as our wet season end. The wet season length is calculated as the difference in days between the wet season start and wet season end.

2.6. Deforestation scenario

Our goal was to understand whether forest evapotranspiration is important for double cropping. The moisture transport model provides us with a comprehensive calculation of the contribution of different sources, i.e. from ocean evaporation, forest

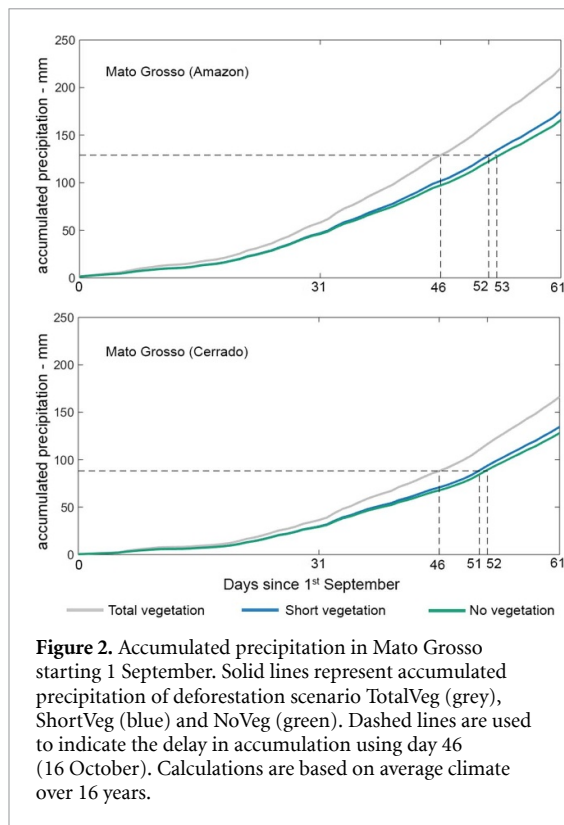


Figure 2. Accumulated precipitation in Mato Grosso starting 1 September. Solid lines represent accumulated precipitation of deforestation scenario TotalVeg (grey), ShortVeg (blue) and NoVeg (green). Dashed lines are used to indicate the delay in accumulation using day 46 (16 October). Calculations are based on average climate over 16 years.

evapotranspiration and evapotranspiration from other land sources. We calculated and compared the wet season start, end and length for three scenarios. The first is total vegetation (TotalVeg) which uses the total precipitation as determined by ERA5 and therefore includes all sources within the precipitationshed to calculate the wet season (section 2.5). For the second scenario, we replace the fraction of precipitation originating from all forests within the precipitationshed of a cell with a relative fraction from short vegetation (ShortVeg). We calculated the level of replacement using the average monthly difference in evapotranspiration fraction between forest and short vegetation from MODIS (see above). In the third scenario, we remove the fraction of precipitation originating from all forest vegetation in the precipitation and do not replace it with another vegetation type (NoVeg). These scenarios do not try to capture expected or modelled future deforestation but instead aim to highlight the importance of the moisture recycling system, in particular the role of forest in the whole Amazon in maintaining the wet season for the study area. Figure 2 demonstrates how reducing or excluding moisture recycling would delay the accumulation of precipitation during the wet season start for the state of Mato Grosso. Previous studies have shown that double cropping is more common when the wet season start occurs before 16 October (Arvor *et al* 2014). In figure 2 we highlight the accumulated precipitation on 16 October (day 46 after 1 September). There is a delay of 6–8 d to

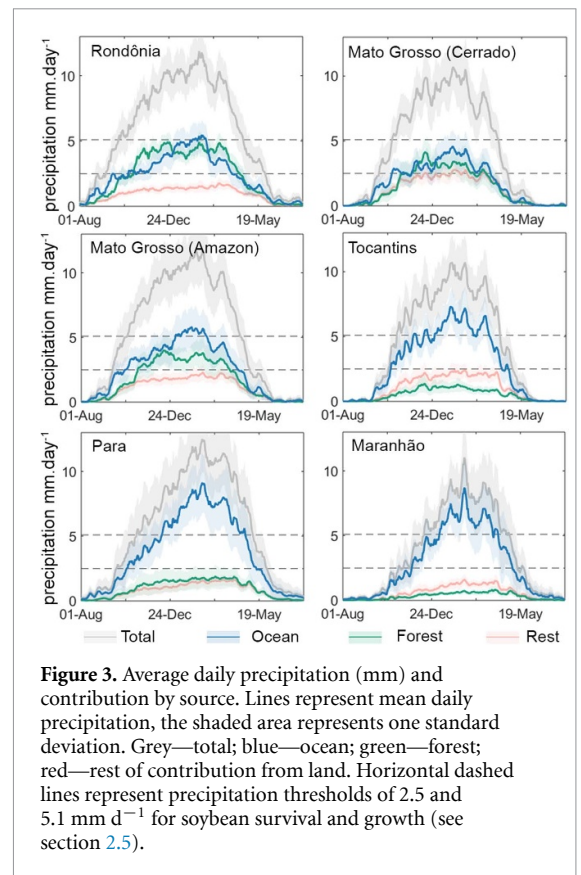


Figure 3. Average daily precipitation (mm) and contribution by source. Lines represent mean daily precipitation, the shaded area represents one standard deviation. Grey—total; blue—ocean; green—forest; red—rest of contribution from land. Horizontal dashed lines represent precipitation thresholds of 2.5 and 5.1 mm d^{-1} for soybean survival and growth (see section 2.5).

reach the same accumulation of precipitation when moisture recycling is reduced.

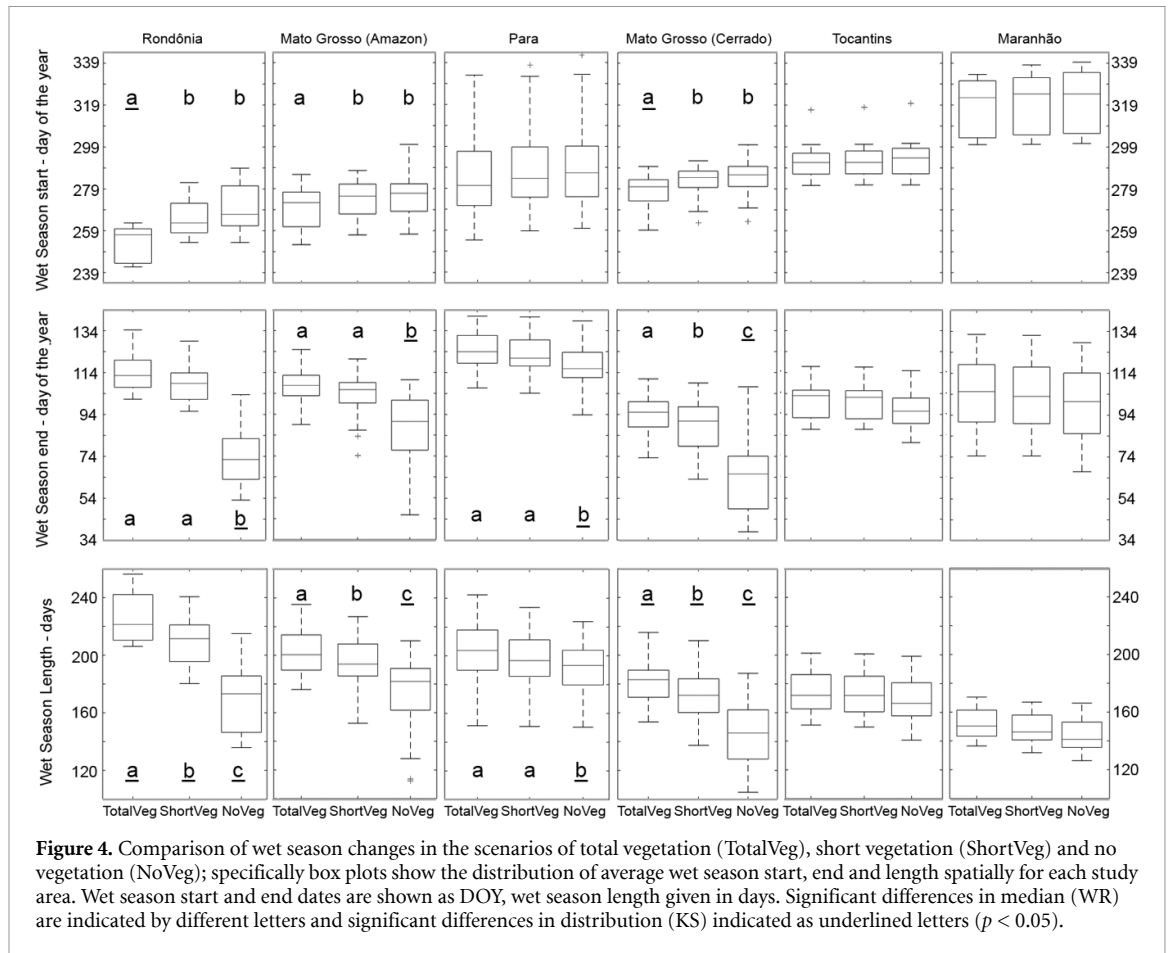
We used one-sided Wilcoxon rank tests to identify statistically shifts in median, and Kolmogorov–Smirnov tests to identify differences in the distribution of the grid cells of wet season start, end and length between TotalVeg, ShortVeg and NoVeg in each of our six study regions.

Finally, we mapped the frequency of >200 d growing season between 2002 and 2017 for TotalVeg, ShortVeg and NoVeg to examine the temporal variability in wet season length.

3. Results

3.1. Forest cover effect on precipitation

The contribution of forest to precipitation varied across our study area, with the highest average monthly fraction of precipitation from forest occurring in the western state of Rondônia (40%) and the lowest in the eastern states of Tocantins and Maranhão (10%) (figure 1(B)). The different precipitation sources show varied patterns in seasonal variation among the regions (figure 3). In the most westerly region of Rondônia, we see that both forest and ocean contribute a similar amount of precipitation; we find that forest contribution reaches its highest level in November and is sustained for much of the wet season while ocean contribution peaks in January/February and does not last the entire season.



A similar seasonality can be observed in Mato Grosso; however, in Mato Grosso there is a high contribution by non-forest areas. In the three easterly regions, we see a different pattern with precipitation originating mostly from the ocean. Further, in the two cerrado areas, Tocantins and Maranhão, more of the precipitation originates from non-forest than forest sources.

3.2. Forest cover effect on wet season start

We find an eastward gradient in wet season start, with the earliest in Rondônia and the latest in Maranhão (figure 4(A)), with a difference of 65 d between the two.

When comparing the TotalVeg scenario to the scenarios of ShortVeg and NoVeg, we observe a significant delay in the wet season start in half our study region. We find the greatest delay in Rondônia, 6 d ShortVeg and 10 d NoVeg, the smallest delay in Mato Grosso (Amazon forest) with 3 d for ShortVeg and 4 d for NoVeg, while in Mato Grosso (Cerrado) we find a delay of 4 d for ShortVeg and 6 d for NoVeg.

We also observe differences in the distribution of the wet season start dates (KS test) in Rondônia and Mato Grosso (Cerrado) (figure 4(A)). For the TotalVeg scenario, in 75% of Rondônia the wet season starts by the 16 September, day of the year (DOY) 259. We find significant delays in ShortVeg, when only 25% of the area experiences wet season start dates

around DOY 258, and in NoVeg around DOY 261. We infer that the estimated differences will approximately delay the wet season start for a given area in Rondônia by 12 and 16 d for ShortVeg and NoVeg, respectively. In the state of Mato Grosso's cerrado biome, we also identified significant differences in distribution of the wet season start dates between TotalVeg and ShortVeg/NoVeg. In this biome, in the TotalVeg scenario 75% of the area starts its wet season by 10 October (DOY 283) while under ShortVeg only 50% of the area reaches the wet season start on DOY 284 and under NoVeg on DOY 285. The average delay in wet season start for Mato Grosso (Cerrado) was estimated as ~4 and 7 d for ShortVeg and NoVeg, respectively. In the other three regions, we found no statistical differences in wet season start date between our scenarios.

3.3. Forest cover effect on wet season end

We found significant differences in wet season end between TotalVeg and NoVeg in four out of the six study regions (figure 4(B)); however, we only found significant differences in wet season end between TotalVeg and ShortVeg scenarios for Mato Grosso (Cerrado). In fact, in Mato Grosso (Cerrado) we found significant differences in median wet season end between all three scenarios. For this region, the difference between TotalVeg and ShortVeg was only 4 d and the difference between TotalVeg and NoVeg

was seven times larger, 29 d. The largest difference was again in Rondônia, where we found the latest wet season end for the NoVeg scenario on 13 April (DOY 103), 2 d after the earliest wet season end for TotalVeg. This corresponds to a shortening on average of ~ 40 d between TotalVeg and NoVeg. In Mato Grosso's cerrado biome, the wet season end arrives ~ 30 d earlier for 75% of the region under NoVeg, within 1 d of the earliest dates for TotalVeg. In Mato Grosso's Amazon biome, we find that 75% of the area with the NoVeg scenario reaches the wet season end on 10 April (DOY 100). We found no significant differences between TotalVeg, ShortVeg or NoVeg scenarios in the states of Tocantins or Maranhão.

3.4. Forest cover effect on wet season length

We find that the variability in the wet season length across our study regions makes it not completely suitable for double cropping agriculture, which requires a wet season length >200 d. The average wet season length across the study region is depicted in figure 5(A). The length of the wet season shows a clear spatial pattern; we found the longest wet season in the Amazon biome itself (northwest) and a decrease in length towards the southeast. The effect of reducing and removing precipitation originating from forest is a strong reduction in wet season length in the southwest (figures 5(B) and (C)).

The majority of the suitable area for double cropping is located in the Amazon forest biome with only small areas in the cerrado biome (figures 5(D)–(F)). All scenarios in Rondônia, Mato Grosso (Amazon) and Mato Grosso (Cerrado) were significantly different; TotalVeg and NoVeg were also significantly different in Pará. We found that the largest differences in wet season length were for Rondônia and Mato Grosso (Cerrado); with differences between TotalVeg and ShortVeg of 10 and 11 d, respectively, and between TotalVeg and NoVeg of 48 and 37 d, respectively. The wet season lengths were significantly different between scenarios. The strongest effect was a season shortening in Rondônia, by 16 d under ShortVeg and more dramatically by 57 d with NoVeg. In this region, $\sim 75\%$ of the area would have <185 d wet season length (figures 5(D)–(F)).

Double cropping is not only dependent on the length of the growing season but also on its stability over the years. We found that the northwest study regions have the most consistent wet season length, while the three cerrado regions in the southeast had only a few years with wet seasons longer than 200 d (figure 5(D)). On one hand, for the ShortVeg scenario, we observe that while there is a reduction in the number of years that the wet season length was longer than 200 d, there is no change in the locations where 200 d wet seasons occurred (figure 5(E)). In contrast, under the NoVeg scenario we see a vastly reduced capacity for double cropping with both a reduction in

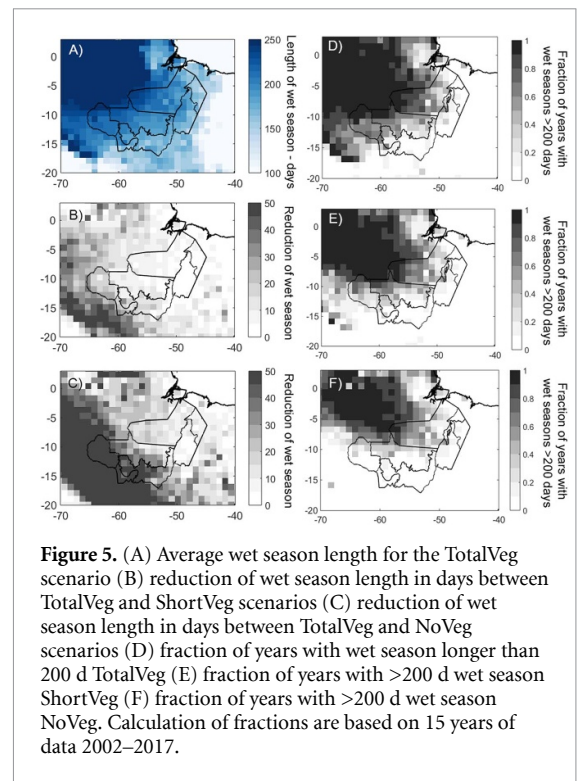


Figure 5. (A) Average wet season length for the TotalVeg scenario (B) reduction of wet season length in days between TotalVeg and ShortVeg scenarios (C) reduction of wet season length in days between TotalVeg and NoVeg scenarios (D) fraction of years with wet season longer than 200 d TotalVeg (E) fraction of years with >200 d wet season ShortVeg (F) fraction of years with >200 d wet season NoVeg. Calculation of fractions are based on 15 years of data 2002–2017.

area and occurrence of wet seasons longer than 200 d (figure 5(F)).

4. Discussion

Intensification of agricultural production may alleviate the demand for deforestation (Stabile *et al* 2020). However, there is uncertainty whether intensification of cropland by double cropping can be implemented across the Amazon arc of deforestation effectively. Our calculations suggest that only some parts of the arc of deforestation are suitable for double cropping, and these areas are extremely dependent on the precipitation originating from the Amazon forest.

We found that across the arc of deforestation there is a strong gradient in the fraction of precipitation originating from forest with a lower fraction in the east $\sim 10\%$ increasing to $\sim 40\%$ in the west. This gradient away from the ocean and into the interior of the continent is in line with that reported in previous studies (Zemp *et al* 2014). In the most western state of Rondônia, air masses would pass over forested areas increasing the fraction of moisture originating from forest sources (Spracklen *et al* 2012).

We found a similar east to west gradient when we calculated the wet season length. The longest wet seasons were found in the Amazon forest biome while the shortest in the cerrado biome. This longer wet season may be attributed to the seasonality of precipitation sources. In the Amazonian forest regions, we see that precipitation originating from forest remains stable throughout the wet season while precipitation from

oceanic sources seems to have a strong seasonal peak (figure 3). This could be because of the migration of the Intertropical Convergence Zone bringing ocean origin precipitation to land (Vera *et al* 2006). The importance of precipitation originating from forests in maintaining the wet season length is highlighted by our ShortVeg and NoVeg scenarios. As expected the two scenarios affected the three Amazonian regions and Mato Grosso (Cerrado) the most, as they receive more of their precipitation from forest. During the transition from the wet to the dry season forest evapotranspiration remains constant while other sources of atmospheric moisture decrease (Christoffersen *et al* 2014, O'Connor *et al* 2019).

Although we found significant differences between the wet season start dates of TotalVeg and ShortVeg/NoVeg in Rondônia, Mato Grosso (Amazon) and Mato Grosso (Cerrado) the delays alone may not have impeded double cropping. The sowing window for soybean double cropping in the arc of deforestation generally takes place from late in September to the end of October (Abrahão and Costa 2018). We found that even with NoVeg these areas reach the wet season start before 16 October (DOY 289) and therefore would have been on time for sowing soybean.

The comparison of wet season end between TotalVeg, ShortVeg and NoVeg show contrasting results. We only found significant difference between TotalVeg and ShortVeg in one area. This suggests that the difference of evapotranspiration between forest and non-forest is not sufficient to affect the wet season end date for double-cropping in most of the arc of deforestation. It is clear however that precipitation generated from moisture recycling is important for double cropping as when precipitation originating from forest was totally removed (NoVeg) we found significant differences where the wet season end came weeks earlier.

As we found more significant differences between TotalVeg and ShortVeg at the wet season start than end this suggests that forest is of particular importance at the start of the season. This result is similar to those from Antônio-Sumila *et al* (2017) which used moisture transport modelling to examine the effect of future deforestation on precipitation in Mato Grosso and those of Mu *et al* (2021) for Rondônia. These authors also found that the lower precipitation was most significant at the start of the wet season. The deeper rooting depth of forest vegetation increases access to deep groundwater at the start of the wet season compared with shorter rooting vegetation (Markewitz *et al* 2010, O'Connor *et al* 2019). Further, ShortVeg is defined using the average evapotranspiration of grassland and crops. At the start of the wet season (September/October) crop vegetation is almost entirely absent and as a result, has a very low evapotranspiration rate. In contrast during and towards the

end of the wet season (April/May) precipitation is still high leading to higher interception evaporation and higher soil moisture than at the start of the wet season (Marin *et al* 2000, Spera *et al* 2016). These differences in seasonality and evapotranspiration explain why there were more areas with significant differences between TotalVeg and ShortVeg at the wet season start than at the wet season end.

We show that a 200 d growing season cannot currently be achieved in all areas of the arc of deforestation—actually in very few of them. Our results also show that without forests double cropping systems would not be a viable option in the arc of deforestation. Although these scenarios do not offer a realistic or probable reality of deforestation we can use them to understand if and when the forest is important for double cropping agriculture. A given area has its own unique upwind area or precipitationshed which contributes to precipitation (Keys *et al* 2016). If a precipitationshed or part of it is deforested it could lead to significant downwind effects comparable to the scenarios presented here. As with any modelling there is inherent uncertainty in the results and conclusions that can be drawn. Tuinenburg and Staal (2020) show that the rate of vertical mixing of moisture in the atmosphere remains the greatest source of uncertainty in moisture tracking models. The improved resolution of the forcing data and the lagrangian style of modelling helps to limit uncertainty due to issues integrating timestep and spatial scale present in Eulerian or grid-based models. Moisture recycling is described as a cascading system (Zemp *et al* 2014) where water undergoes several evapotranspiration-precipitation cycles. In our analysis, we only identify the most recent evapotranspiration sources related to precipitation. This means that precipitation originating from forest or non-forest sources may have already undergone one or more evapotranspiration-precipitation cycles (Staal *et al* 2018). Deforestation which affects the moisture recycling system could therefore result in a positive feedback where the reduction in evapotranspiration at a deforestation site results in a reduction of evapotranspiration further downwind. This possible amplification of deforestation events is yet to be studied and is an important factor in understanding the full impact on the moisture recycling system.

Observational studies have already been able to correlate deforestation with changes in wet season start and end (Butt *et al* 2011, Debortoli *et al* 2015, 2017, Leite-Filho *et al* 2019). Understanding the direct effect of deforestation events on the moisture recycling system is difficult, as the downwind contribution of forest can be distributed over wide geographic areas. By using moisture transport models we can begin to understand these connections between source and sink to develop a more robust understanding of the effects of land use

change in the Amazon. This can be both beneficial to quantify the impact of deforestation but also in planning reforestation projects. Modelling studies have combined moisture transport modelling with future deforestation scenarios to examine the negative impact on the water provisioning ecosystem services (Antônio-Sumila *et al* 2017). While our scenarios do not represent a scenario of imminent deforestation they serve to highlight the importance of moisture recycling as an ecosystem service. If forest conservation policies are not enforced such as the forest code, by 2050 the high deforestation rates are predicted to lead to a further loss of 40 Mha of natural Amazon and Cerrado land (Soterroni *et al* 2018). Studies quantifying the impact of this land cover change need to include moisture recycling as an ecosystem service as it has wide implications for a variety of stakeholders (agriculture, hydropower and human consumption) and could be vital for political discussions. Previous studies which modelled the moisture recycling system identified a tipping point in deforestation which if reached may result in a shift to a much drier biome (Sampaio *et al* 2007, Nepstad *et al* 2008, Staal *et al* 2016). Recent increases in the rate of deforestation once again highlight the urgency to shift from an extensive agriculture system with high deforestation to a more intensive land-sparing system. Currently, soy is the primary crop in each of the states included in our study accounting for between 42% and 58% of cropped land. Since 2015 all of the states included in this study have reported growing maize as a second crop; however, in Pará, Tocantins and Maranhão this remains low <10% of cropped land. Uptake of double cropping systems will be likely driven by developments of new faster-growing or more drought-tolerant crop varieties or possible increases in the use of irrigation. However, for much of the arc of deforestation forest moisture recycling will remain crucial for agricultural production and double cropping.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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