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Evidence that deforestation affects the onset of the rainy season in Rondonia, Brazil

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[1] Anecdotes from local residents and modeling studies suggest that deforestation may delay the onset of the rainy season (O) in western Brazil, but detection studies using climatological time series are not available. Here we investigate trends in O in the state of Rondonia, Brazil, a region that has been continuously deforested since the 1970s. Daily rainfall data from 16 station time series, spanning periods of at least 25 years, with five covering more than 30 years, are used. We define O as the first day after 1 September with rainfall greater than 20 mm d^{-1}. A t test indicates that for stations that lie inside the major deforested area, O has significantly shifted to, on average, 11 days (and up to 18 days) later in the year over the last three decades. However, for stations that lie in areas that have not been heavily deforested, O has not shifted significantly. Nonparametric and parametric trend analyses all gave similar results for the change of O with time, and all of the statistically significant results indicated a delay in O. Twenty-five percent (four) of the stations analyzed showed a marked shift in timing of O: these stations are located inside deforested areas, primarily near the BR 364 highway that crosses Rondonia. Delayed onset may be a result of land use change, and this signal may strengthen in future: current delaying trends may be as great as 0.6 days per year, and after 30 years of deforestation the onset of the rainy season is expected to be 18 days later.

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1. Introduction

[2] Deforestation can influence regional hydrological processes through decreasing evapotranspiration and increasing run off and, atmospherically, by perturbing the regional precipitation [*Nobre et al.*, 1991; *Costa and Foley*, 2000; *Coe et al.*, 2009]. The decrease in evapotranspiration is primarily a consequence of three interacting factors [*Senna et al.*, 2009]: (1) the increased albedo of the land surface reduces the net radiation at the surface and alters the relative partitioning of this reduced radiation between sensible, latent, and ground heat flux and storage terms; (2) the reduction in "surface roughness" associated with the transition to crops or pasture decreases atmospheric turbulence, weakening vertical motions; and (3) physiological differences between forested and nonforested land: the reduced root depth of grasses/scrub vegetation reduces the amount of soil moisture available to plants, as well as the large differences in leaf area index (LAI) and stomatal conductance, and seasonal differences in crop land cover. Moreover, the reduction in net surface radiation, and the way in which this reduced radiation is partitioned, cools the upper atmosphere over the deforested area, inducing a thermally driven circulation [*Eltahir*, 1996]. One of the most significant consequences of these fundamental changes in the water and surface energy balance may be a reduction in rainfall, although this effect may only be noticeable for larger scales of deforestation [*Sampaio et al.*, 2007].

[3] The change in land cover also strongly influences runoff. Paired catchment studies on the effect of vegetation change on discharge [*Bosch and Hewlett*, 1982; *Bruijnzeel*, 1990; *Andréassian*, 2004; *Brown et al.*, 2005] suggest a general trend of increased water yield as a function of deforestation: a direct consequence of changes in rainfall infiltration capacity and evapotranspiration due to changes in soil/root functioning. Although many of these findings are derived from temperate zone experiments [*Bosch and Hewlett*, 1982; *Bruijnzeel*, 1990], recent work from tropical sites [*Bruno et al.*, 2006; *de Moraes et al.*, 2006; *Trancoso*, 2006] has also supported this relationship.

[4] The strong coupling between land cover (forest) and hydrological processes in the Amazon basin has been well documented [e.g., *Silva Dias et al.*, 2002; *Costa*, 2005], and as in other ecosystems, it can be understood in terms of the relationship between net surface radiation and precipitation. Where forest cover is replaced by cropland or pasture, as is often the case, resultant changes in the partitioning of net radiation lead to changes in the warming of the air layer above the vegetation and related evaporative processes [*Bruijnzeel*, 2004]. Differences in rooting depth between trees and field

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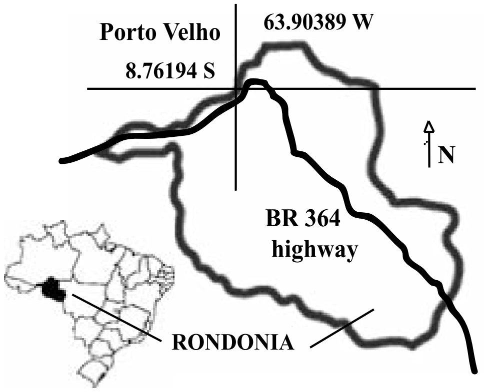


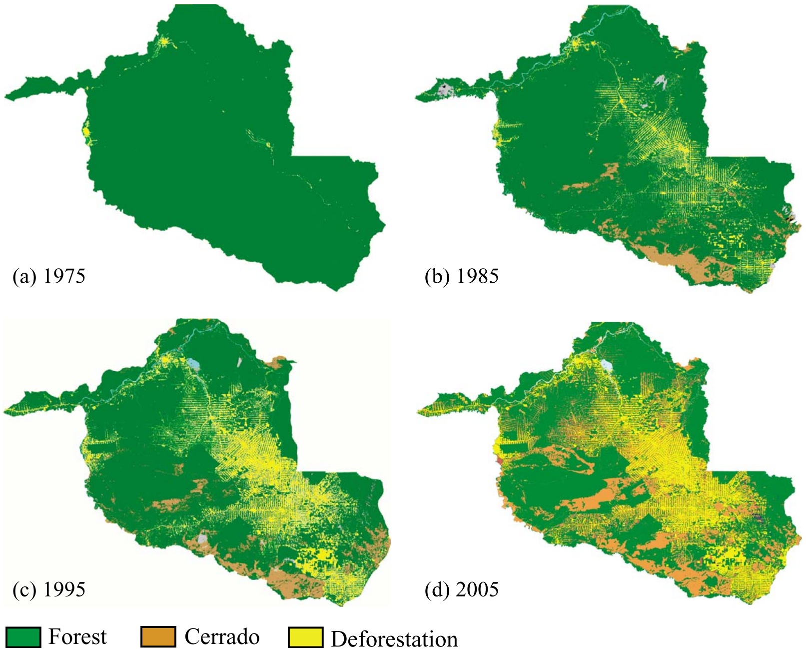
Figure 1. Location of Rondonia state within Brazil.

layer species exacerbate this disparity in radiative properties between the two types of land cover surface. This may then also affect atmospheric circulation processes.

[5] Atmospheric humidity and moisture convergence are greater in treed/forested landscapes as evapotranspiration and surface inhomogeneity or roughness is greater; cloud formation and precipitation are thus enhanced [*André et al.*, 1989] as the atmospheric boundary layer is more unstable than over nonforested sites [*Wang et al.*, 2009]. Observations indicate that replacement of forest with other land cover leads to feedbacks in temporal and spatial distribution of clouds at differing scales: in deforested areas of southwest Amazonia cloud evolution shifted by several hours [*Cutrim et al.*, 1995], while over larger areas the effects could be powerful enough to disrupt rainfall patterns on a continental scale [*Bruijnzeel*, 2004]. Convective boundary evolution affects cloud development and differs between the wet and dry seasons in Rondonia after deforestation: the depth of the boundary layer is a function of several factors including radiation balance, energy budget and surface roughness [*Fisch et al.*, 2000; *Chambers*, 1998].

[6] The rain in Rondonia is monsoonal and thus only occurs during the time of year when the continent is heated above ocean surface temperature levels and becomes a major convection center and there is an ample supply of moisture for condensation. Convection depends on surface net radiation rates: during the early phases of the wet season Coastal Occurring (convective) Systems (COS) move south and west from the northern coast of the continent to Rondonia, most frequently during August–September [*Silva Dias et al.*, 2002]. Deforested areas have a higher albedo than forested areas (18% and 13%, respectively [*Culf et al.*, 1996]), lower moisture storage capacity (shallower rooting plants) and drier soils, which results in lower heating rates of near-surface air. Cleared land can have a latent heat flux 30% lower than that of forested land [*Gash and Nobre*, 1997], and reduced latent heat flux means that stronger moisture transport and deeper convection are needed to trigger rainfall. Moisture supply from the ocean is low during the dry season and most of tropical South America, including Rondonia, is a major divergence center during this period. Local evapotranspiration, however, around 3 mm d^{-1} for forests and 1 mm d^{-1} for cleared pastureland [*Culf et al.*, 1996], provides sufficient moisture for localized, mesoscale convective events.

[7] Although the problem of determining the effects of small levels of deforestation on rainfall is primarily mesoscale by nature, GCMs are able to simulate it on the synoptic scale if the deforestation is also at this scale: the results of recent coupled biosphere-atmosphere models predict that deforestation could cause delay in rainy season onset (O) in the



(a) 1975

(b) 1985

(c) 1995

(d) 2005

Figure 2. Evolution of deforestation in Rondonia: (a) 1975, (b) 1985, (c) 1995, and (d) 2005. The BR 364 highway runs from the northwest to the southeast across the state. Cerrado is tropical savanna.

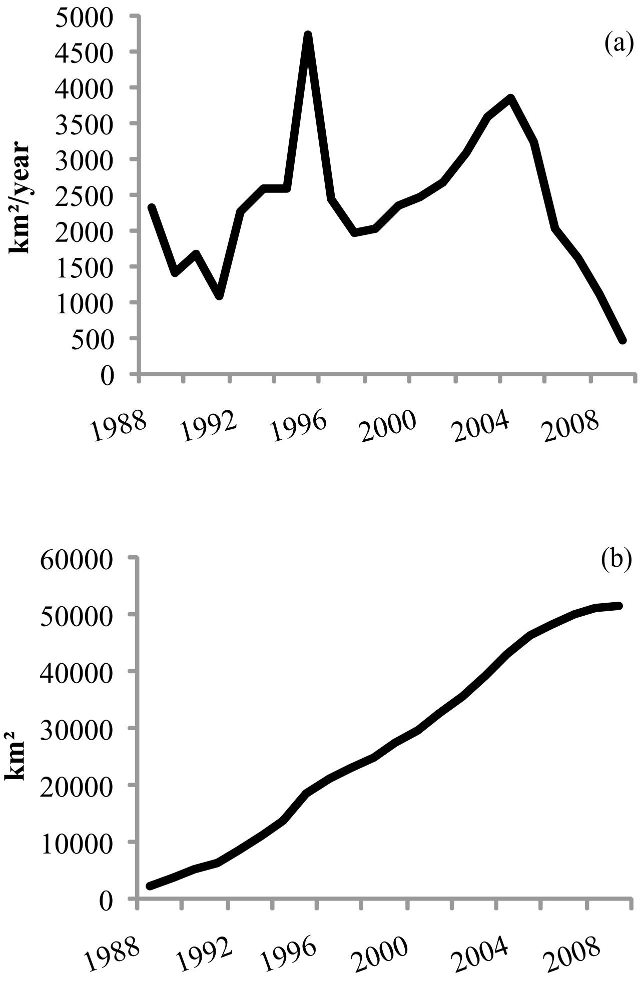


Figure 3. Deforestation in Rondonia: (a) annual rates and (b) cumulative deforestation. Source is the Monitoring Program of the Brazilian Amazonian Forest by Satellite (PRODES), http://www.obt.inpe.br/prodes/prodes_1988_2009.htm.

central Brazilian "arc of deforestation" [*Costa and Pires*, 2010]. These modeled results suggest an increase in the length of the dry season, with a reduction of precipitation, under deforestation scenarios. This is caused by rainfall decrease in the dry-to-wet season transition period, rather than a significant reduction in either wet or dry season rainfall: decreased evapotranspiration means that there is less moisture in the atmosphere at the start of the rainy season [*Costa and Pires*, 2010]. Although anecdotal evidence from local residents in Rondonia (inside the "arc of deforestation") indicates that the rainy season has been starting later in recent years, there is a lack of analysis based on observational data for this phenomenon. However, with negligible deforestation in the 1970s and extensive rates thereafter, Rondonia is the perfect natural laboratory to investigate the effects of deforestation on climate.

[8] Standard approaches to detect the effects of changes in land cover on precipitation are (1) *t* test analysis of two periods of large changes in land cover and (2) trend analysis of rainfall in a period of continuous variation of land cover. Our aim in this paper is to use these methods to detect and quantify changes in O in the State of Rondonia, Brazil, using long-term daily station precipitation data and forest cover data.

2. Materials and Methods

2.1. Region Studied

[9] The state of Rondonia covers an area of around 240,000 km^2 and lies in western Brazil, in southwestern Amazonia (Figure 1). Over the last few decades, immigration into the region, internal migration, agricultural expansion, and urbanization, as well as the related development and paving of the BR 364 road, which runs between the Rondonia state capital, Porto Velho and Cuiabá, state capital of Mato Grosso, have led to deforestation which was negligible until the 1970s [*Leite et al.*, 2011]. Agriculture is dominated by crops, such as soya, and pastureland. Deforestation has followed the classic "fishbone" pattern (Figure 2) and in 1980 accounted for >8,000 km^2, rising to 28,000 km^2 by 1985 [*Malingreau and Tucker*, 1988]. Deforestation rates increased in the early 1990s [*Pedlowski et al.*, 1997], facilitated by the arrival of mechanized agriculture [*Brown et al.*, 2004]. Currently, 51,766 km^2, about 22% of the state, has been deforested (Figure 3) (Monitoring Program of the Brazilian Amazonian Forest by Satellite (Programa de Monitoramento da Floresta Amazônica Brasileira por Satélite, PRODES), http://www.obt.inpe.br/prodes/prodes_1988_2009.htm., 2010).

[10] In Rondonia, the wet-to-dry season transition takes place from April to May, and the peak dry season months are June–August. The dry-to-wet season transition is during September to October and the peak wet season months are December–March. The peak mean dry season rainfall is 22 mm month^{-1}; peak wet season rainfall is 268 mm month^{-1} and annual total rainfall is 2910 mm [*New et al.*, 1999].

2.2. Rainfall Data

[11] The rainfall data we use in our analyses are daily data obtained from the ANA (National Water Agency) Hydrological Information System (HidroWeb, http://hidroweb.ana.gov.br/, accessed 2010), for 16 stations across the state (Figure 4). The data are time series of daily mm from rain gauge records. Deforestation in the region began to increase

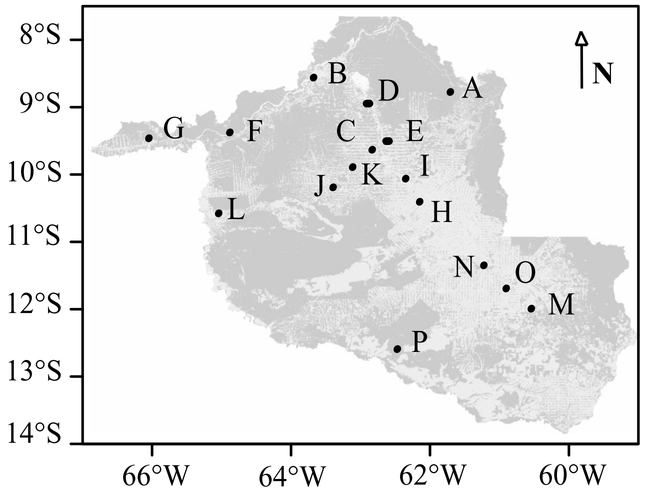


Figure 4. Distribution of rainfall stations in Rondonia.

Table 1. Meteorological Station and Data Series Information

Station	ANA Code	Station Name	Latitude (deg)	Longitude (deg)	Times Series	n[a]
A	00862000	Tabular	−8.93333	−62.05389	1978–2008	25
B	00863000	Porto Velho	−8.76666	−63.91666	1961–1998	28
C	00963000	Ariquemes	−9.93167	−63.05694	1975–2008	33
D	00963001	Santo Antônio BR 364	−9.26056	−63.16194	1978–2008	29
E	00963004	Fazenda Rio Branco	−9.88722	−62.98778	1980–2008	26
F	00965001	Abunã	−9.70306	−65.36472	1976–2008	27
G	00966000	Nova California	−9.75556	−66.61167	1978–2008	31
H	01062001	Jaru	−10.44583	−62.46556	1977–2008	30
I	01062002	Seringal 70	−10.23639	−62.62722	1979–2008	30
J	01063000	Escola Caramurú	−10.50500	−63.64611	1979–2008	26
K	01063001	Mineração Ponte Massangana	−10.35000	−63.41667	1980–2008	25
L	01065002	Guajará-Mirim	−10.79250	−65.34778	1972–2008	32
M	01160000	Marco Rondon	−12.01528	−60.85500	1978–2008	29
N	01161000	Vista Alegre	−11.44083	−61.48389	1978–2007	28
O	01161001	Pimenta Bueno	−11.68361	−61.19222	1980–2008	27
P	01262000	Pedras Negras	−12.85139	−62.89917	1981–2008	25

[a] Years per time series.

significantly in the 1970s: we accordingly use data series commencing in this decade as far as possible. All data series span more than 25 years, five of them more than 30 years (Table 1). We define O as the first day after 1 September (inclusive) where daily precipitation >20 mm. We then calibrate these dates so that 1 September becomes “1,” 2 September “2,” and so on: each station is accordingly allocated a number for O between 1 and 115 for each year. If there was a single missing day between 1 September and the day of onset of rain for any year, that entire year was eliminated from the analysis.

2.3. Statistical Analyses

[12] We apply four statistical analyses to the data: initially, we select the time series that range from the 1970s to the 2000s, and select data from 1970 to 1980 (a period of little land use; see Figure 2), and from 2000 to 2008, a period of intense land use. We then apply a *t* test to test the null hypothesis that the mean onset of the rainy season is not significantly different from one period to the other. Four stations (C, F, H and L; Figure 4) had sufficient degrees of freedom in both periods to be tested.

[13] In addition, we apply three trend tests to the data: Pearson’s product moment correlation coefficient, Spearman’s R rank analysis and Kendall’s τ test [*Kanji*, 1999]. We use the parametric as well as the nonparametric tests for comparison: these nonparametric regressions make no assumption of linearity or distribution of the values, often a consideration with meteorological data series [*Yue et al.*, 2002]. The Spearman R test is equivalent to the regular Pearson product moment correlation coefficient with regard to the proportion of variability accounted for and is computed from ranked data. Kendall’s τ test is statistically equivalent to the Spearman R and is more robust than Spearman, especially in the case of small data sets.

Table 2. Results of the Independent Two-Sample *t* Test With Unequal Sample Sizes and Unequal Variance of the Means (μ) of the Periods 1 (1971–1980) and 2 (2001–2008)

Station	μ_1	μ_2	n_1	n_2	s_1^2	s_2^2	$\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}$	t_{calc}	P_{1-tail}
C	13.2	33.4	6	8	93.77	645.7	9.82	2.06	0.034
F	30.8	16.8	5	6	847.7	50.97	13.34	−1.05	0.675
H	14	36.8	4	8	84.67	259.64	7.32	3.11	0.006
L	17.6	24.4	9	7	401.78	73.29	7.42	0.93	0.187

3. Results and Discussion

[14] The *t* test results for the four stations tested (Table 2) indicate that for stations that lie inside the major deforested area (C and H), the null hypothesis is rejected at $\alpha = 0.05$, indicating that O has shifted to later in the year over the last three decades. However, for stations that lie in areas that have not been heavily deforested (F and L), the null hypothesis is not rejected at $\alpha = 0.05$, indicating that O has not shifted to later in the year over the last three decades. This suggests a dependent change in the onset of the rainy season in regions with important changes in land use.

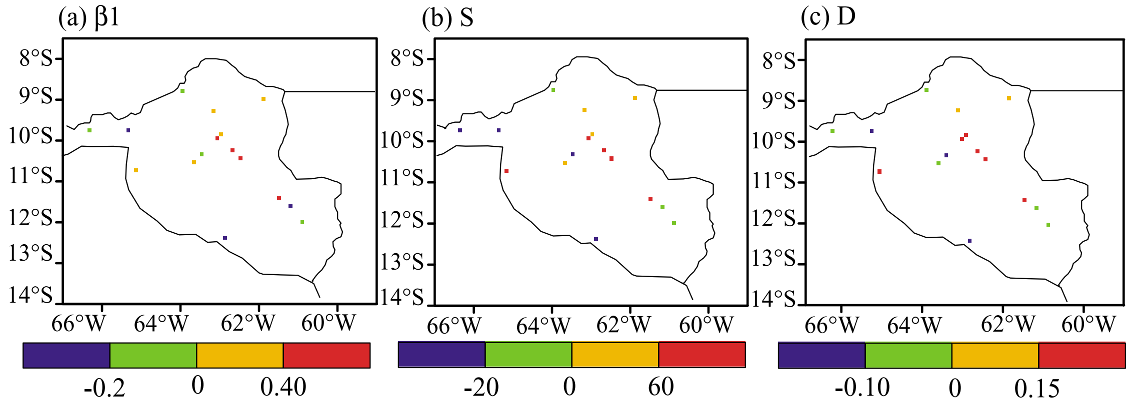
[15] The results of the two nonparametric trend tests are in very close agreement with each other, and the linear regression also gives similar P values (see Table 3). The positive statistics indicate an increase in the number of days after

Table 3. Test Statistics and P Values for the Analyses Indicating the Direction of Trend in Timing of O and Magnitude of Shift, Kendall’s S, and Spearman’s D

	Regression Analysis[a]		Mann-Kendall		Spearman	
Station	$\beta 1$	P	S	P	D	P
A	0.108	0.329	24	0.296	0.12	0.274
B	−0.046	0.594	−10	0.571	−0.05	0.593
C	0.616	0.023[b]	134	0.020[b]	0.37	0.019[b]
D	0.143	0.265	22	0.347	0.09	0.316
E	0.316	0.148	45	0.109	0.24	0.118[b]
F	−0.576	0.869	−31	0.734	−0.14	0.755
G	−0.175	0.782	−21	0.633	−0.08	0.679
H	0.507	0.045[b]	96	0.045[b]	0.31	0.046[b]
I	0.510	0.036[b]	86	0.065[b]	0.31	0.049[b]
J	0.017	0.473	7	0.447	−0.01	0.523
K	−0.099	0.681	−27	0.728	−0.15	0.765
L	0.267	0.205	104	0.047[b]	0.31	0.041[b]
M	−0.055	0.573	−8	0.552	−0.02	0.537
N	0.544	0.104[b]	96	0.030[b]	0.35	0.036[b]
O	−0.297	0.773	−10	0.574	−0.04	0.572
P	−0.289	0.775	−32	0.766	−0.12	0.725

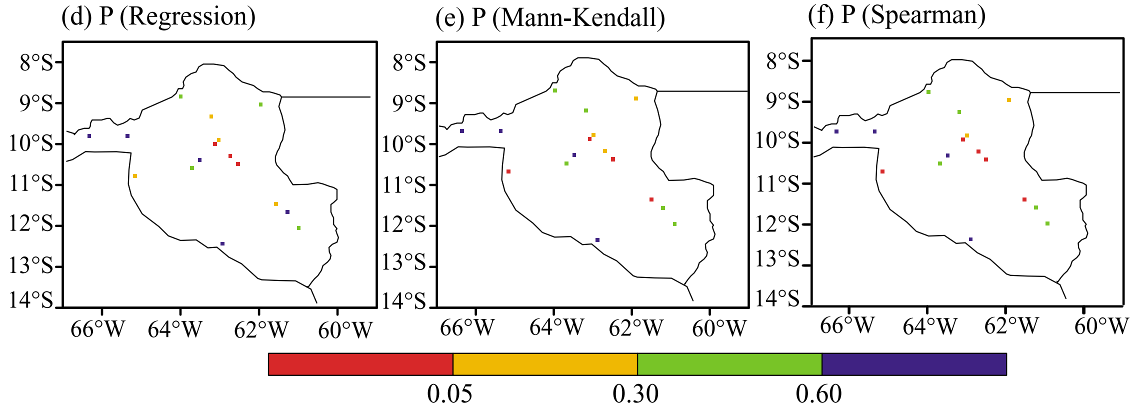
[a] Slope of regression β_1 (shift in timing, days per year).

[b] Denotes $P \leq 0.1$.


(a) β1

(b) S

(c) D


(d) P (Regression)

(e) P (Mann-Kendall)

(f) P (Spearman)

Figure 5. Trend test statistics (Figures 5a–5c) and significance, P, of the trend in delayed O (Figures 5d–5f) for each station by trend test timing of the rainy season onset. (a and d) Regression analysis; (b and e) Kendall's S; and (c and f) Spearman's D (see Table 3).

1 September for O and the negative numbers indicate a decrease; the larger the positive number, the greater the significance in delay of O. We focus on the results of the nonparametric tests, for the reasons outlined in section 2.

[16] If there were no dependency between the onset of the rainy season and deforestation, we would expect that the trend results would provide normally distributed results for the 16 stations tested, with a mean trend not different from zero. Although we find a range of positive and negative trends across all stations, the trend statistics are skewed to the right, that is, to a delay in onset of the rainy season.

[17] More than two thirds of the stations (11; 69%) show an increase in the number of days after 1 September for O, implying a delay in the onset of the rainy season. Six stations indicate a strong delay in O: stations C, E, H, I, L, and N (Figure 4): five of them are located in the heavily deforested area in the center of the state, while station L is located in a deforested region in the western part of the state. Four of these stations, C, H, L and N, show a very strong signal, with trends significant at $P < 0.05$ for both Kendall and Spearman tests, while the other two stations, E and I, show trends significant at $P < 0.12$. For the other stations there is no significant trend. For the stations with $P < 0.05$, we use the linear regression slope values to estimate the rate of delay. For station C, which had the most marked delay in rainy season onset, we calculate that the shift in O is 0.6 days per year: this equates to an overall delay of 18 days in rainy season onset over the 30 year period, consistent with the change in the mean obtained by the *t* test. Station L had the smallest shift in O: 0.26 days per year, or 8 days over the three decades. For all of the stations indicating a delay in O, the average delay is 0.37 days per year, or 11 days over the 30 year period. None of the stations shows a significant negative trend.

[18] We map the stations according to the strength of the trend over time of O delay: four of the six stations where there is a strong signal of delayed O lie along the BR 364, and in the area of highest deforestation. These stations are represented by the red and yellow squares in Figure 5. The stations with the strongest negative trend in O over time (indicating no delay in rainy season onset) are represented by the purple squares and lie furthest away from the BR 364 highway (Figure 5).

[19] For both nonparametric tests, station L, though situated a long way from the road and the center of deforestation, shows a strong trend in delayed O. This is not the case for the regression analysis, however, suggesting that the trend in delayed O is not linear for this station. However, there has also been increasing deforestation in this local area (Figure 2) over the last few decades.

[20] The shift in O is shown for four of the stations with the most significant trends along the BR 364 and demonstrates a clear trend over time toward later onset of the rainy season (Figure 6). The four stations with the strongest signal of delayed O had some of the longest time series, suggesting that O becomes increasingly delayed over time. The slope values show a shift in O greater than 0.5 days a year for all of these stations: this pattern is repeated for all stations showing a significant shift in rainy season onset.

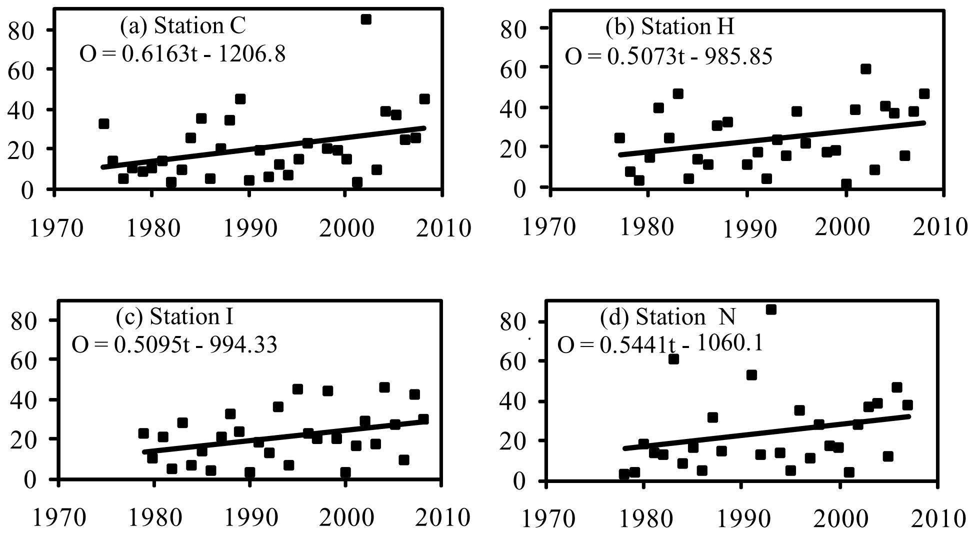


Figure 6. Change in rainy season onset over time (years) for selected stations along the BR 364 highway.

[21] Overall, there is a strong trend for O delay in stations situated along the BR 364 highway and in the most heavily deforested areas in the region, with a mean shift of 0.5 days per year. The results imply that continuing deforestation will result in increasing delays in rainy season onset, locally and regionally, and that areas close to roads are therefore especially vulnerable to changes in rainfall patterns. If the length of the dry season continues to increase it could result in wide-scale ecosystem transformation. For example, *Senna et al.* [2009] used a coupled climate-biosphere model to investigate how bidirectional feedbacks might control the recovery of secondary forest after different deforestation scenarios. Their simulations indicated that regrowth of forest would be impeded in northern Mato Grosso (adjacent to Rondonia) owing to an increase in dry season length from 4 to 5 months over the 50 year period of the simulation, closely comparable with the results of this analysis, with an annual increase of around 0.5 days.

[22] Analysis of the four stations with the longest delays (C, H, I, N) indicate the changes are restricted to the delay in the onset of the rainy season. We did not detect a lateral displacement in the precipitation patterns or changes in seasonal precipitation totals (Figure 7). Because moisture sources are local and there is no significant overall change in total wet season rainfall, there will be a point (probably around late October) where the surface heating and advection of moisture will become more dominant than the land surface coupling, and this would therefore act as a limiting factor for the delay of rainy season onset: the delay could not increase indefinitely.

[23] More generally, the results should also be viewed in the context of ecological tipping points, a critical threshold at which a relatively small perturbation can qualitatively alter the state or development of a system, on a larger scale than that of boundary layer circulation [*Lenton et al.*, 2008]. Some researchers have recently suggested that at least part of the

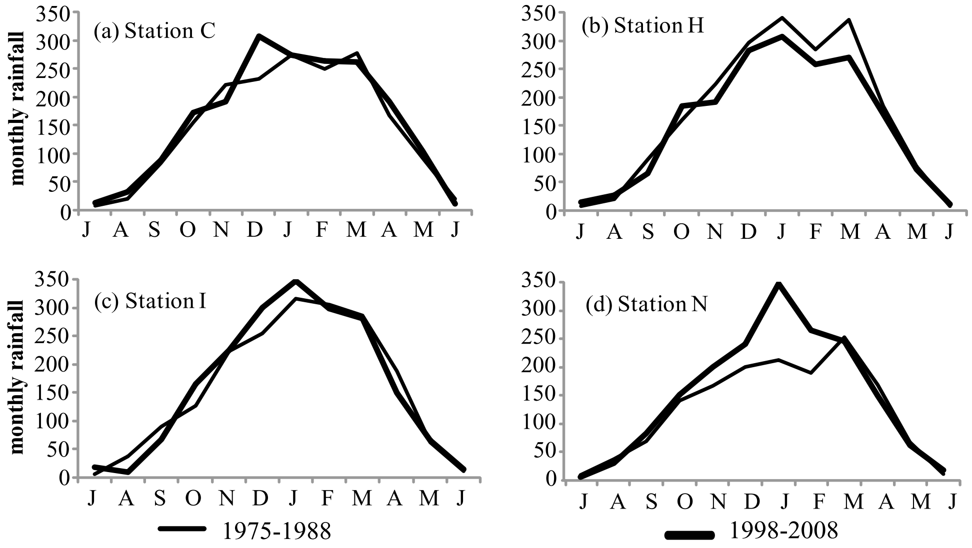


Figure 7. Annual cycle of monthly precipitation (mm) for the four stations that showed significant delays in the onset of rainy season, for the decades at each end of the study period.

Amazon rain forest may cross such a tipping point during this century [*Cox et al.*, 2000; *Oyama and Nobre*, 2003; *Lenton et al.*, 2008; *Malhado et al.*, 2010] owing to the combined impacts of global and regional climate change [*Malhi et al.*, 2009]. Once this tipping point is crossed, any dieback of rain forest would result in a process of positive feedback whereby the shifting land cover causes a further reduction of the rainfall and extension of the dry season. Moreover, a shift in the regional rainfall regime space may not simply be dependent on changes in land use within the impacted region. *Malhado et al.* [2010] demonstrate that regional patterns of climate change in the "arc of deforestation" region of the Amazon will also be significantly influenced by deforestation in the surrounding cerrado ecosystem. Similarly large-scale feedbacks have been demonstrated in the Indian peninsula for the summer monsoon rainfall: land use change has reduced precipitation on a regional scale through land surface flux feedbacks [*Chang et al.*, 2009; *Medina et al.*, 2010; *Niyogi et al.*, 2010], and such delays in the large-scale circulation in Amazonia could also lead to longer and drier dry seasons [*Li and Fu*, 2004]. Consequently, reducing the rates of deforestation of Amazonian forests may not be sufficient per se to prevent southern and eastern parts of the basin experiencing a climate that induces or facilitates ecosystem transition.

4. Conclusion

[24] To the best of our knowledge, this analysis is the first time that a quantitative link between O and deforestation has been demonstrated using daily observed rainfall data and land cover changes at such a large landscape scale; previous attempts have used process-based modeling to attribute the causes of delayed onset [*Costa and Pires*, 2010]. The *t* test indicates that the onset of the rainy season is significantly different between the 2000s and the 1970s in the stations that lie in the heavily deforested area, while it is not significant in the stations that lie outside of the heavily deforested area. The nonparametric and parametric trend analyses all gave similar results for the trend of O over time, and all of the statistically significant results ($\alpha = 0.05$) indicated a delay in O. Twenty-five percent (four) of the stations analyzed showed a marked shift in delaying O ($P < 0.05$) while none showed a marked shift in anticipating the rainy season onset. The detected shift is on average ~0.4 days per year and can be as high as an annual 0.6 day delay, which equates to 18 days over the 30 years of this analysis.

[25] The dry-to-wet season transition period in Rondonia appears to be directly affected by the decreases in forest cover in the region. In a region where precipitation is essentially convective, changes in the surface radiation balance caused by deforestation are the likely drivers of alterations in wet season rainfall patterns. While it is premature to state definitively that deforestation/land use change is a causal factor in the delaying of O, the emergence of a more robust signal in future years would lend support to this theory.

[26] This research represents an important development in our understanding of the interlinked atmospheric and forest hydrological processes in the Amazon region, and provides a first step in disentangling the complicated relationship between deforestation and precipitation in areas of tropical rain forest. While changes in annual precipitation totals are not significant, the implications of a longer dry season are important for a range of water availability and ecological aspects. Large-scale factors, such as sea surface temperature change and other dynamic feedbacks, should also be included in future work to further explore and strengthen this hypothesis. If future deforestation patterns can be better predicted, this link may subsequently allow us to make quantitative calculations about what may happen in terms of area affected and changes in the length of the dry season, one of the critical variables influencing the transition of rain forest into seasonal forest or savannah. Moreover, this knowledge would be useful for informing regional policy/planning on deforestation controls and water resource management and to better validate models of atmosphere-biosphere interactions.

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