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Deforestation triggering irreversible transition in Amazon hydrological cycle

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E-mail: jjong@tea.ac.cn**Keywords:** Amazon forest, decoupling, deforestation, drying, moistureSupplementary material for this article is available [online](#)**Abstract**

The Amazon is hypothesized to reach an irreversible 'tipping point' when deforestation slows the hydrological cycle sufficiently that tropical forest ecosystems cannot be sustained. However, inception of such a tipping point has not been supported by observations and the relevant links between deforestation and atmospheric moisture recycling are poorly understood. Here we show that reduction in evapotranspiration from 20 years of deforestation dried the atmosphere persistently and caused moisture decoupling, i.e. an opposite sign of moisture change between the lower and middle troposphere. Increased deforestation exacerbated the lower troposphere drying and caused it to penetrate deeper into the middle troposphere in the dry and transition seasons over monsoon forests and savannas. Deforestation induced warming-enhanced buoyant updrafts, elevated hot and dry air and thereby reduced downward mixing of water supplies from the tropical Atlantic that normally moisten the Amazon forests. The severe atmospheric desiccation in the southern and eastern Amazon cannot be compensated by enhanced water supplies from the Atlantic Ocean, demonstrating an irreversible transition in Amazon hydrological cycle exacerbated by rapid deforestation. The more recent drying through the seasons over rainforests and during the wet season over the transition zones from rainforests to monsoon forests and savannas, however, suggests a window of opportunity for preventing ecosystem collapse with forest conservation.

1. Introduction

Tropical forests maintain high rates of evapotranspiration and thereby strong cooling year-round (Li *et al* 2015). In Amazonia, more than one-third of the moisture that forms precipitation is locally supplied through recycling of evapotranspiration (Davidson *et al* 2012). Intensive forest loss driven by high demand for commodity production and agricultural expansion in this region (Curtis *et al* 2018), however, causes large reductions in evapotranspiration and

downwind moisture transport (Ellison *et al* 2017), and thereby moisture recycling. The reduced moisture recycling leads to increased water vapor pressure deficit, and increases frequency and intensity of forest water stress (Barkhordarian *et al* 2019, Staal *et al* 2020) and therefore forest degradation and tree mortality (Saatchi *et al* 2013, Brando *et al* 2014, Zemp *et al* 2017). Forests under water stress are more flammable and facilitate the spread of fires that are often lit intentionally for land clearing (Barlow *et al* 2020). Therefore, the positive feedback loop among

fires, deforestation, and weakening moisture recycling highlights the potential for dramatic declines in Amazonian forests (figure S1 available online at stacks.iop.org/ERL/17/034037/mmedia).

The potential consequence of this positive feedback loop is an irreversible ‘tipping point’ when the shrinking hydrological cycle cannot support the forest ecosystem, and ultimately transforms the forests into savanna-like ecosystems (Nepstad *et al* 2008). In the Amazon, around 17% of the forests has been lost in the last 50 years due to deforestation (Lovejoy and Nobre 2019). Model simulations indicated a 40% deforestation, projected to occur by 2050 (Soares-Filho *et al* 2006), would cause substantial precipitation reduction over the entire Amazon (Sampaio *et al* 2007). This drying drives the advent of ecosystem transition towards savannization (Nobre *et al* 2016). A recent hypothesis suggested that accelerated deforestation rates combined with climate change and fires could initiate the tipping point at 20%–25% deforestation (Lovejoy and Nobre 2018). However, these hypothetical tipping point thresholds are debated because of resilience of Amazon vegetation and complicated land-climate interactions. For example, rising atmospheric CO₂ levels promote forest growth and can counteract adverse climate change impacts (Huntingford *et al* 2013). Furthermore, increased water supplies from a warming tropical Atlantic Ocean (Gloor *et al* 2013) may mitigate desiccation and facilitate vegetation growth that can compensate canopy losses from deforestation and fires.

The existing studies linking deforestation and Amazon hydrological cycle mostly focus on the impact of deforestation on precipitation (Bagley *et al* 2013, Spracklen and Garcia-Carreras 2015, Staal *et al* 2020). The large-scale effects of deforestation on vertical atmospheric moisture profiles and subsequent effects on surface water budgets have largely been ignored. In this study, we show with observational evidences how deforestation induced atmospheric moisture changes interact with external water supplies from Atlantic Ocean and how these interactions may drive an irreversible transition in Amazon hydrological system.

2. Materials and methods

The Amazon extends over three tropical climate zones (supplementary figure S2(A)): tropical rainforest (Af), tropical monsoon (Am), and tropical savanna winter dry (Aw) climate zones with a gradient of precipitation magnitude and seasonality from the northwest to the southeast according to Köppen–Geiger climate classification for 1951–2000 period (Beck *et al* 2018). We obtained the major vegetation types observed at 2449 sites in the three climate zones from NeoTropTree database (Oliveira-Filho 2017) to illustrate the spatial distribution of the vegetation

types. The spatial and seasonal precipitation patterns shape the distribution of dominant natural vegetation types in Amazon region. Tropical rainforest climate is wet and humid year-round with slightly drier months between June and September, and dominated by rainforest vegetation that maintain relatively stable canopy structure and function throughout the year (Morton *et al* 2014). The dominant vegetation in the monsoon climate zone is monsoon forests or seasonal forests with annual wet–dry cycles and seasonal variation of canopy structure and primary production (Miranda *et al* 2005, Wright *et al* 2017). The tropical savanna climate zone shows a contrasting seasonal precipitation, characterizing a mosaic of seasonal forests/woodlands and savannas around the southern border of Amazon basin (figure S2(A)). Human activities, interacting with climate change and fires, modify the natural vegetation (Malhi *et al* 2008), which are particularly severe in the southeastern forest-to-savanna transition region (Xu *et al* 2021). We analyzed the regional pattern of the deforestation and moisture change based on the Af, Am and Aw climate zone classification to reconcile the seasonality and spatial gradient of precipitation and vegetation.

We calculated the 30 years (1961–1990) mean monthly total precipitation from the 0.5° Global Precipitation Climatology Centre (GPCC) monthly gridded gauge-analysis products of precipitation (Schneider *et al* 2014) for the rainforest, along with monsoon and savanna climate zones to the south with a similar precipitation seasonality (figure S2(B)). We defined three periods with distinctive precipitation patterns for our analysis according to the shared precipitation pattern in monsoon and savanna climate zones in the south of the rainforest: (a) wet season with the highest precipitation from January to March, (b) dry season with the lowest precipitation from August to October and (c) transition season with gradual decrease in precipitation from May to July. Monthly precipitation in the wet, transition and dry season were 194 ± 17 mm, 111 ± 26 mm and 64 ± 29 mm, respectively for monsoon climate zone and 222 ± 23 mm, 95 ± 18 mm and 87 ± 20 mm, respectively for savanna climate zone over 1961–1990. We apply this seasonal classification to rainforest where the seasonal precipitation contrast is much smaller. According to this classification, the dry season (191 ± 37 mm month⁻¹) and transition season (189 ± 26 mm month⁻¹) have slightly lower precipitation than the wet season (230 ± 27 mm month⁻¹) in the rainforests.

The air temperature, specific humidity, omega vertical velocity at pressure levels from 1000 to 300 hpa, meridional and zonal wind at 850 hpa, evaporation and vertical integral of eastward water vapor flux were analyzed with European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 monthly reanalysis at 0.25° (ERA5 2019,

Hersbach *et al* 2020). All variables were resampled to 0.5° using 2×2 0.25° grids to accommodate the resolution of Köppen–Geiger climate classification. The relative change in specific humidity, and absolute change in air temperature between two periods, 1980–1999 and 2000–2019, were calculated for rainforest, monsoon, and savanna climate zones. Omega vertical velocity (w , Pa s^{-1}) at pressure level P (in Pascal, Pa) was converted to vertical velocity of w (m s^{-1}) with $w = -(wRT/gP)$, in which T (in Kelvin, K) is air temperature at level P , g is constant gravitational acceleration of 9.80665 m s^{-2} , R is the gas constant of $287.058 \text{ m}^2 \text{ s}^{-2} \text{ K}^{-1}$. According to opposite change of the specific humidity in the lower and middle troposphere dividing at around 850 hpa level (Xu *et al* 2020), we calculated the changes in relative specific humidity and updraft wind velocity in the boundary layer within the lower troposphere (1000–900 hpa) and middle troposphere (800–500 hpa) to show their spatial pattern. The number of years with decreasing specific humidity during 2000–2019 relative to the mean over 1980–1999 were counted to show the variability and persistency of humidity change. The time series of precipitation anomalies for each season were analyzed with ERA5 over 1980–2020 and GPCC over 1980–2016 for their overlapping period (1980–2016) in this study. Spatial patterns of monthly precipitation trends in the dry, transition and wet seasons were analyzed. Precipitation anomalies were calculated as the seasonal total precipitation in each year relative to their mean value over 1980–1999.

The global forest change dataset (Hansen *et al* 2013) at 30 m resolution provides forest cover information in 2000 and forest loss and gain for each year during the period 2000–2017 (Global Forest Change, GFC v1.5). Forest loss and gain are defined as the transition between forest and non-forest, by taking forest cover in 2000 as a base condition. We first resampled the forest cover and forest change to 0.05° and calculated the percent of forest cover in 2000 and accumulative forest loss since 2000 in each 0.05° grid. Significantly disturbed forests are identified if forest cover (F_L) in 2000 was greater than 70% and the accumulated loss (F_L) during 2001–2017 was greater than 65%. Intact forest is identified if F_C in 2000 was greater than 70% and F_C during 2000–2017 was less than 5%. This identification ensures that the number of gridcells is rational to evaluate the effects of disturbed forests on land surface temperature and evapotranspiration (Xu *et al* 2020).

Due to the lack of long-term of observational evapotranspiration and land surface temperature data, we evaluate changes in the evapotranspiration and land surface temperature caused by forest loss by comparing their values between the significantly disturbed and intact forests. We assume that the background climate is similar in each 0.5° gridcell. Thus, difference in land surface temperature

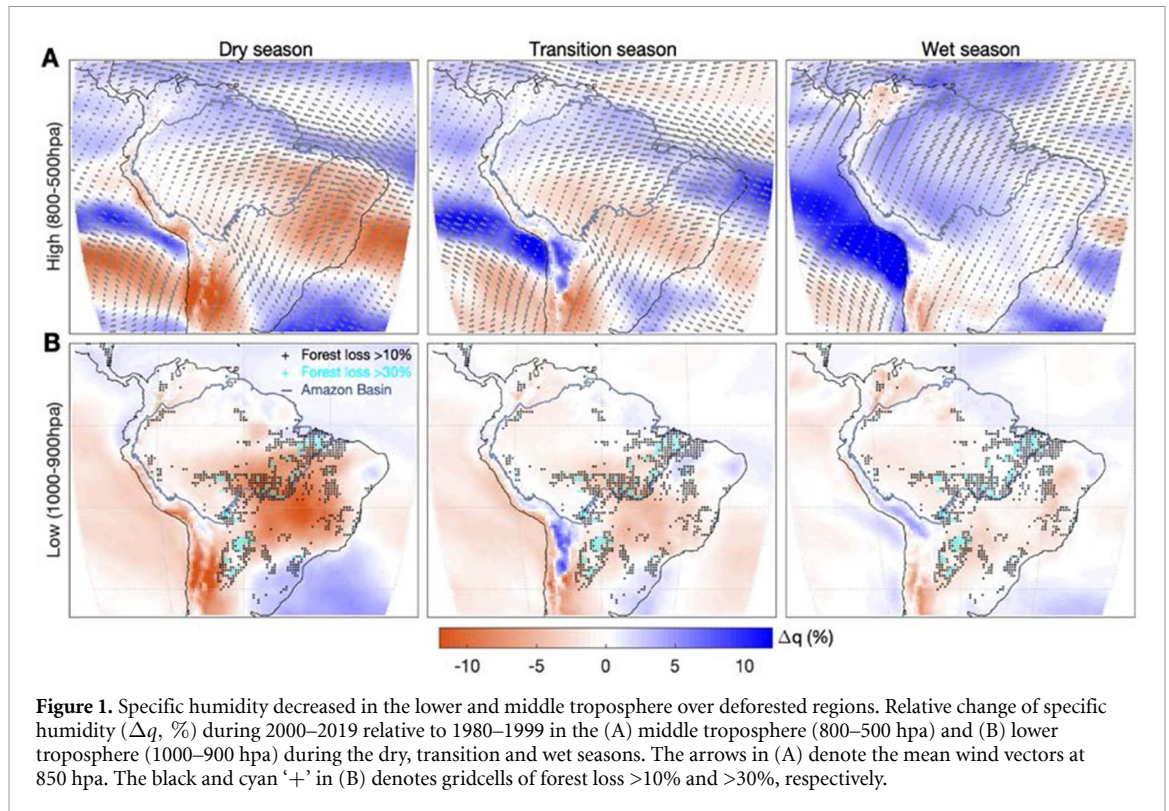
and evapotranspiration between the significantly disturbed and intact forests in the same 0.5° gridcell is caused by the significant disturbance to forest. We searched 10×10 0.05° grids within each 0.5° gridcell. If significantly disturbed and intact forests were both present in the same 0.5° gridcell, this 0.5° gridcell is valid for comparison of the land surface temperature and evapotranspiration between disturbed and intact forests. After the above screening processes, there are 288 0.5° gridcells with comparable disturbed and intact forest, most of which are located at the ‘arc of deforestation’ across the southern and eastern boundary of Amazon basin. The land surface temperature and evapotranspiration between the disturbed and intact forests are compared with the resampled Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) 8 day Land Surface Temperature and Emissivity (LST&E) L3 Global products (MYD11C2 version 6) (Wan *et al* 2015) and MODIS evapotranspiration and latent heat flux product (MOD16A2 version 6) (Running *et al* 2017), respectively.

We further resampled forest cover and forest loss to 0.5° and calculated the accumulative forest loss since 2000 in each 0.5° gridcell. The fraction of forest loss (F_L) in 0.5° gridcells are classified into five levels, i.e. 0%–5%, 5%–10%, 10%–20%, 20%–30%, and >30% to indicate the intensity of deforestation and then identify the specific humidity and air temperature change in each deforestation category for rainforest, monsoon, and savanna climate zones in different seasons. The number of 0.5° gridcells with different fraction of forest loss were provided in table S1. The differences in specific humidity and air temperature between 1980–1999 and 2000–2019 at all the pressure levels for each category of forest loss were evaluated with t -test. When F_L in a 0.5° gridcell is smaller than 5%, forests in this gridcell are identified being intact. Temperature changes between 2000–2019 and 1980–1999 in intact forests are assumed to occur only from background warming. At each atmospheric vertical level, the total warming for each forest loss category minus the background warming is assumed to be contributed by deforestation. The vertical levels below which deforestation shows positive contributions to total warming are identified.

3. Results and discussion

3.1. Deforestation induced moisture decoupling between the lower and upper atmosphere

The Amazon basin extends over tropical rainforest, monsoon, and savanna climate zones with dominated vegetation cover of rainforests in the rainforest climate zone, a transition from rainforests to monsoon forests in the monsoon climate zone, and mixed monsoon forests and savanna woodlands in savanna climate zone (figure S2(A)). Over the past

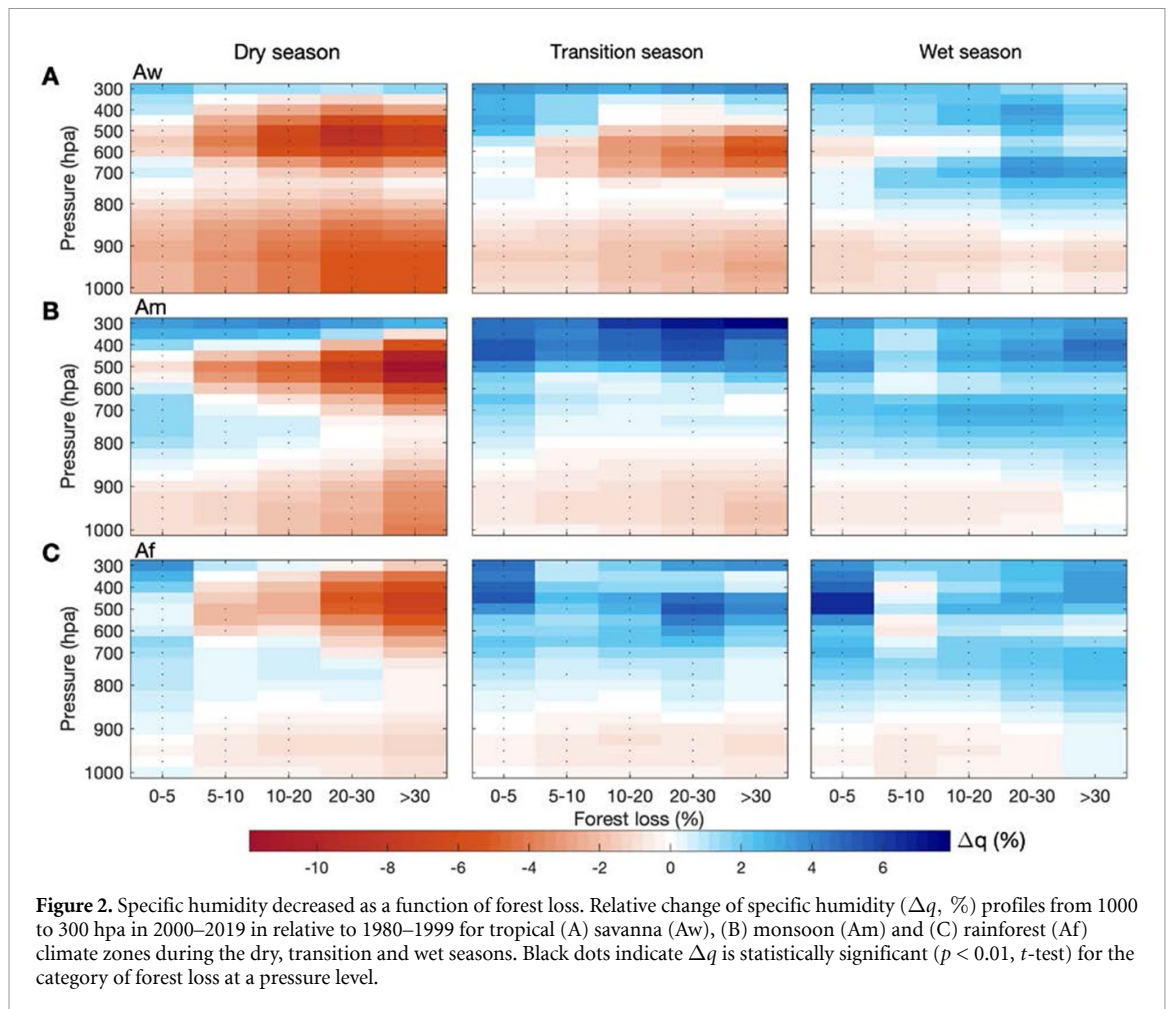


two decades, an opposite sign of moisture changes between the lower and middle-to-upper troposphere over the Amazon indicates moisture decoupling at around 850 hpa where a large proportion of moisture is conveyed from Atlantic Ocean by easterly winds (figure 1). The boundary layer within the lower troposphere (1000–900 hpa) has dried by up to 12% in the dry season across the southeastern boundary of the Amazon basin (figure 1(B)) where the forests have experienced severe negative interactions among climate change, deforestation and fires (Malhi *et al* 2008, 2009). In the middle troposphere (800–500 hpa) the northern Amazon has been moistened (figure 1(A)), because of enhanced water vapor transport from the tropical Atlantic where the warming ocean temperatures lead to more evaporation as atmospheric moisture source (figure S3). In the wet season, the boundary layer has been slightly drying although enhanced water supply from the Atlantic Ocean moistened the middle troposphere over the entire basin. The lower troposphere drying occurred throughout most of the region and well beyond the edge of deforestation (figure 1(B)). Unlike the wet season water vapor variability, increase in dry season water vapor pressure deficit over southeastern Amazon, which implies near-surface moisture reduction, cannot be explained by natural variability of the climate system (Barkhordarian *et al* 2019).

The drying of the lower troposphere strongly depends on the rate of forest loss (F_L) in monsoon and savanna climate zones (figures 2 and S4). Higher forest loss coincided with greater atmospheric moisture reduction, particularly in the dry and

transition seasons. This relationship occurs because forest loss causes strong reduction in evapotranspiration (figure S5(A)), and tree transpiration is the major moisture source to the atmosphere in the Amazon dry and transition seasons (Staal *et al* 2018). The lower troposphere drying has been persistent during the dry season over 2000–2019 (more than 16 out of 20 years had moisture reduction compared to the average over 1980–1999; figures S4(A) and (B)). The drying penetrated into the middle troposphere during the dry and transition seasons in savanna climate zone and dry season in monsoon climate zone ($p < 0.01$; figure 2). We note that the wet season exhibited frequent drying up to the top of lower troposphere (~ 850 hpa), while in contrast, the enhanced moisture transport from the tropical Atlantic moistened the middle and upper troposphere by up to 6% (figure 2). The intensified moisture supply from the Atlantic Ocean, however, did not compensate the lower atmosphere drying caused by deforestation. As a result, the decoupling occurs between the lower and middle to upper troposphere.

The consequence of the atmospheric desiccation is declined precipitation (figure S6). The total precipitation declined substantially since 1980 in the Amazon region in the dry (-2.52 to -2.99 mm yr $^{-1}$, $p < 0.005$) and transition (-0.59 to -0.83 mm yr $^{-1}$) seasons. Whereas, precipitation increased in the wet season, especially in rainforest and monsoon climate zones, consistent with the enhanced moisture supplies from tropical Atlantic Ocean. ERA5 precipitation anomalies well agreed with GPCP gridded precipitation anomalies in representing the interannual



variation of precipitation in different seasons and climate zones ($r > 0.7$, $p < 0.001$). The wet season drying suppresses vegetation growth (Yuan *et al* 2019) and impedes ecosystem recovery from drought and fire disturbances in the previous dry season. The legacy effects of repeated dry season or persistent dry–wet season water stress can last for up to 3 years (Huang *et al* 2018, Yang *et al* 2018) and trap the forests into a self-amplified dieback cycle (Zemp *et al* 2017).

The atmospheric boundary layer above rainforests, which receive much higher and more evenly distributed rainfall year-round than that above monsoon and savanna climate zones in the south (figure S2(B)), has clearly dried over the past 20 years (figure 2(C)). In its relatively dry months (August–October), this drying has been emerging in the lower troposphere although more moisture has been conveyed from the tropical ocean than that for monsoon and savanna climate zones (figure S4(C)). The drying only tends to be insignificant in the rainforests when forest loss is high because rainforests have not experienced intensive loss (e.g. $F_L > 30\%$), so that the low number of sample windows ($n = 5$, table S1) affects the significance. The plant species in rainforests are much less drought tolerant (Amissah *et al* 2018) and take longer to recover than species

frequently exposed and adapted to seasonal water stress in more xeric biomes (Schwalm *et al* 2017). Atmospheric drying that exceeds the observed water stress tolerance of rainforest trees in extremely dry years can cause persistent alteration to the canopy structure (Saatchi *et al* 2013).

3.2. Enhanced buoyant updrafts reducing downward mixing of water supplies from tropical Atlantic

The upward desiccation in the atmosphere is driven by deforestation-induced warming. Compared to intact forests ($F_L < 5\%$), severe forest loss ($F_L > 65\%$) contributed to 0.9 ± 0.5 °C and 1.2 ± 0.7 °C warmer annual mean land surface temperature in monsoon and savanna climate zones, respectively and deforestation induced warming is particularly severe in the dry and transition seasons (figure S5(B)). Here, we show that the atmospheric column also warmed with deforestation: the higher the deforestation rate, the stronger the warming in the dry and transition seasons (figure 3). The near-surface (1000 hpa) atmospheric temperature warmed by 0.6 °C– 1.0 °C and 0.6 °C– 0.8 °C during the dry season for savanna and monsoon climate zones, respectively, over the past 20 years, in which forest loss contributed up

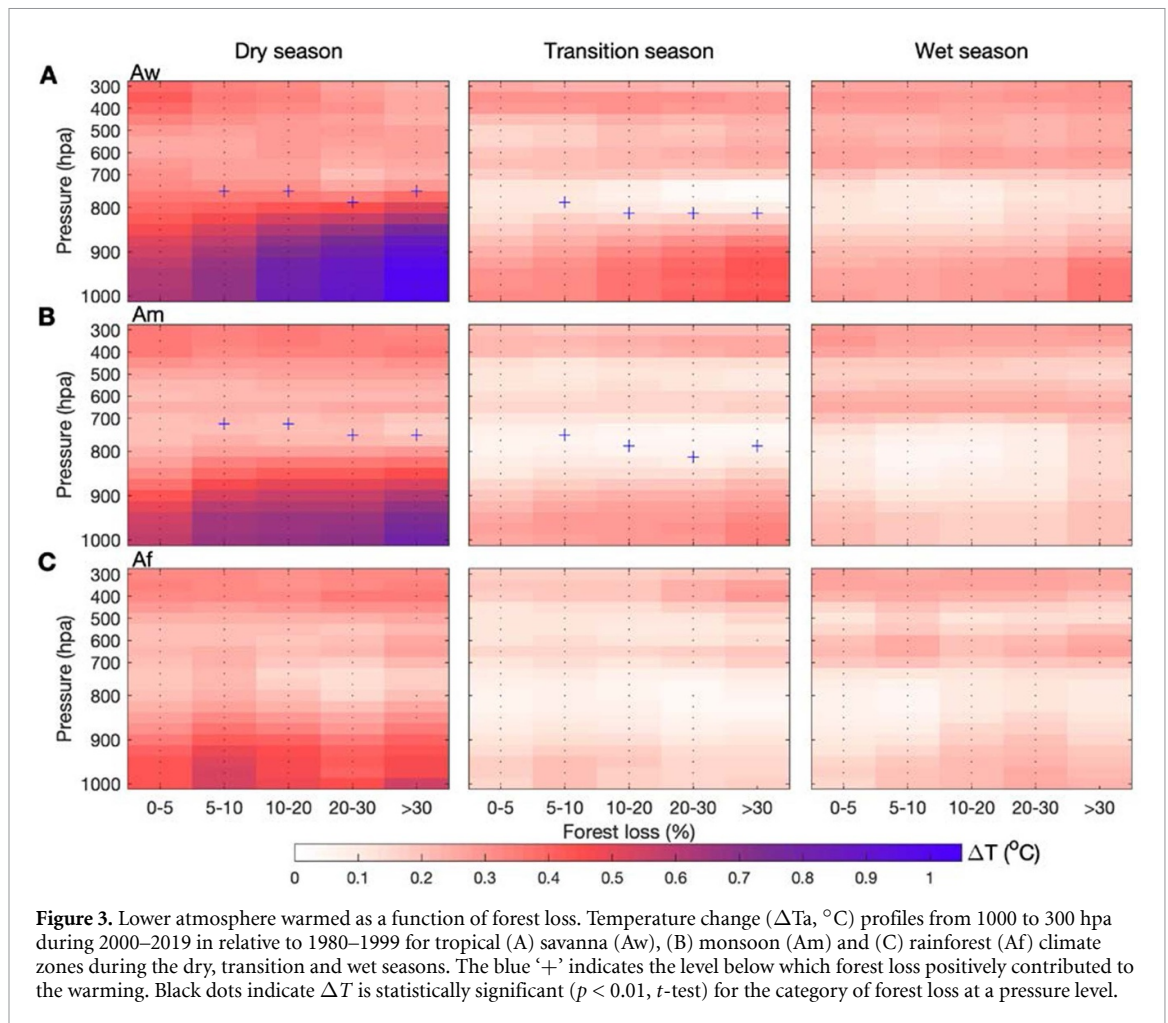


Figure 3. Lower atmosphere warmed as a function of forest loss. Temperature change (ΔT_a , °C) profiles from 1000 to 300 hpa during 2000–2019 in relative to 1980–1999 for tropical (A) savanna (Aw), (B) monsoon (Am) and (C) rainforest (Af) climate zones during the dry, transition and wet seasons. The blue ‘+’ indicates the level below which forest loss positively contributed to the warming. Black dots indicate ΔT is statistically significant ($p < 0.01$, t -test) for the category of forest loss at a pressure level.

to 0.4 °C and 0.2 °C of the warming for savanna and monsoon climate zones, respectively. The warming contributed by forest loss increased with deforestation rate in the savannas and monsoon climate zones, accounting for up to 40% of the near-surface warming in the dry season when $F_L > 30\%$ (figure S7). The positive warming consequences of deforestation extended to the level of atmospheric moisture decoupling.

The land surface temperature change in deforested areas is a tradeoff between warming impacts from reductions in turbulent heat loss and cooling impacts from increases in surface albedo. In the dry and transition seasons, reduction in latent heat dominates the warming impact from the land surface to the overlying atmospheric column. However, the warming contribution of forest loss is less uniform in the rainforests and during the wet season because the humid atmosphere buffers the temperature change, and cooling effects of increased albedo overwhelms warming effects of declined latent heat due to loss of dense canopy (Xu *et al* 2020). The warming above the lower troposphere is much less dependent on forest loss (figure S7), because the vertical structure of tropical warming follows moist adiabats, and hence the upper troposphere warms more than the lower

troposphere under normal climate warming, resulting in a negative lapse rate feedback (Santer *et al* 2005). The deforestation induces greater warming in the lower troposphere, therefore increases the adiabatic lapse rate, which leads to a less negative or even positive lapse rate feedback.

The Amazon region is dominated by updraft motion (figure S8), which is reinforced by increased upward buoyancy forces due to surface and atmosphere warming. The updraft speed over the lower troposphere increased substantially after year 2000 in more than 60% of the regions that experienced deforestation over 10%, particularly in the dry seasons when deforestation resulted in greater warming impact on the surface and atmospheric columns (figures 4 and S9). The enhanced updrafts in turn lifted the hot and dry air from the surface, which can elevate and invigorate clouds and therefore induce more convective rain storms, meanwhile causing desiccation in adjacent forests (Cochrane and Laurance 2008) and up to the middle troposphere as shown here. In the central Amazon, enhanced sinking motion from the surface up to the middle troposphere (figure S9) prevents upward mixing of moisture from rainforests, which further weakens moisture inflows from Atlantic Ocean (Zemp *et al*

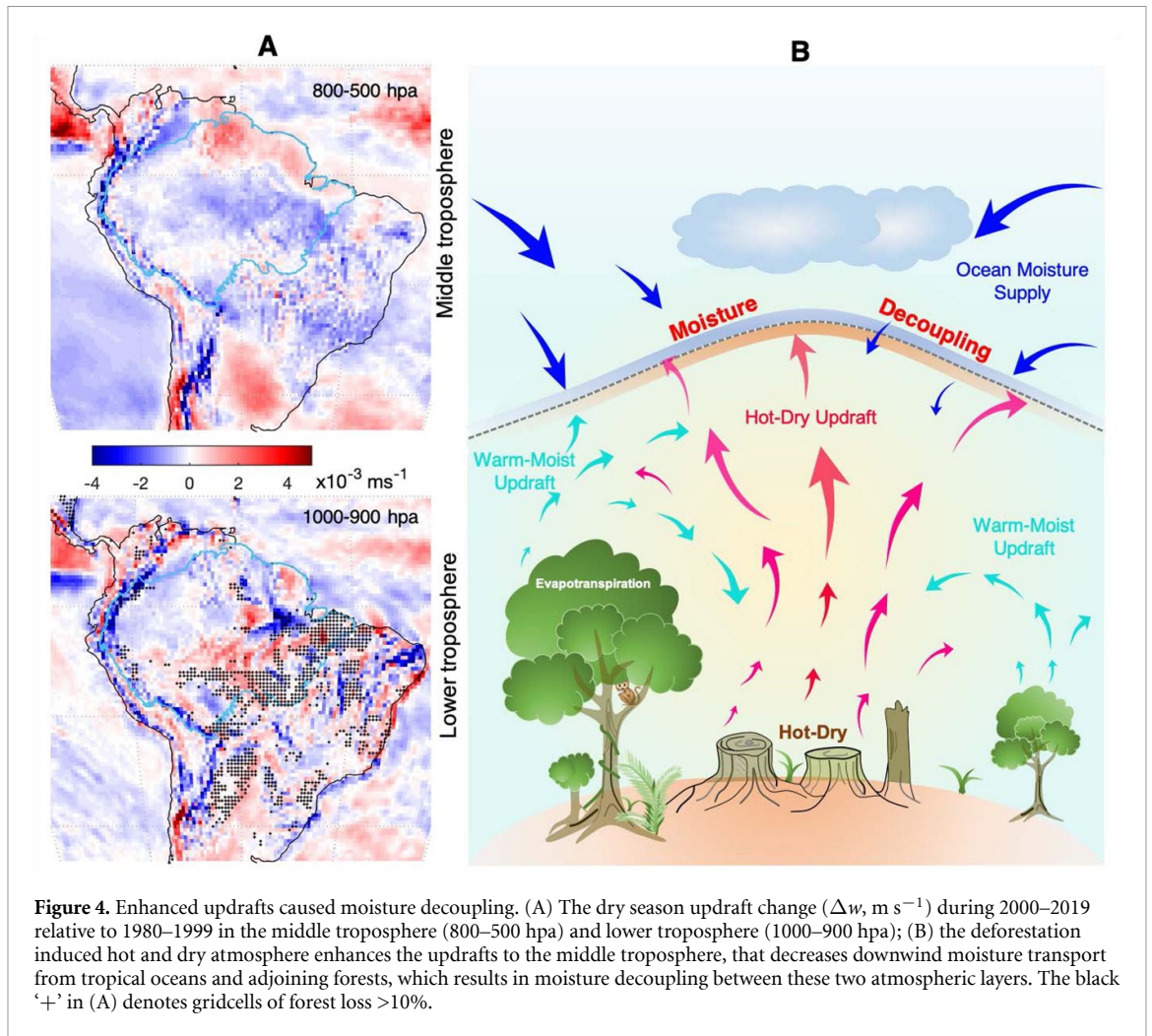


Figure 4. Enhanced updrafts caused moisture decoupling. (A) The dry season updraft change (Δw , m s^{-1}) during 2000–2019 relative to 1980–1999 in the middle troposphere (800–500 hpa) and lower troposphere (1000–900 hpa); (B) the deforestation induced hot and dry atmosphere enhances the updrafts to the middle troposphere, that decreases downwind moisture transport from tropical oceans and adjoining forests, which results in moisture decoupling between these two atmospheric layers. The black ‘+’ in (A) denotes gridcells of forest loss >10%.

2017). The enhanced sinking motion is likely caused by the warming Atlantic that leads to anomalously northward displacement of Intertropical Convergence Zones (Marengo *et al* 2011, Fu *et al* 2013).

When tree canopies supply adequate water vapor from evapotranspiration in the dry season, the updraft carries warm and humid air that increase downstream rainfall and alleviates forest water stress (Spracklen *et al* 2012). In the late dry season, upward mixing of evapotranspiration triggers deep convection and thus the subsequent onset of the wet season (Wright *et al* 2017). However, the warming Atlantic induced downdrafts impede upward moisture mixing over rainforests, and the enhancement in deforestation-induced updrafts elevate hot and dry air over the southern transition zones from rainforests to monsoon forests. Both of them inhibit vertical development of cloud and prevents occurrence of deep convection (Sherwood *et al* 2010, Langenbrunner *et al* 2019) and may also explain delayed onset of wet season in Amazon over recent decades (Fu *et al* 2013, Leite-Filho *et al* 2019).

With ERA reanalysis dataset in this study, we found moisture decoupling between the lower and middle-to-upper troposphere over the Amazon,

which can be explained by the enhanced updraft motion due to deforestation-induced warming. This decoupling, however, cannot be validated directly due to lack of long-term and large-scale observation of moisture profiles. The agreement in representing the interannual variation of precipitation in different seasons and climate zones between ERA5 and GPCP precipitation anomalies demonstrates that ERA can reproduce the temporal and spatial variation of water supplies in Amazon region. Modeling experiments showed that deforestation in Indochina Peninsula can weaken atmospheric moisture up to 850 hpa and have far-reaching effects on land–ocean interactions (Sen *et al* 2004). Here we show the effects of deforestation in the southern and southeastern Amazon region on the interactions between moisture supplies from the ocean and local recycling. However, quantitative evaluation of how much of the moisture cycle and precipitation were affected by the deforestation is limited because the interannual variation of Amazon hydrological cycle is also linked to large-scale atmosphere–ocean circulations, e.g. Walker circulation (Barichivich *et al* 2018), El Niño–Southern Oscillation and the North Atlantic Oscillation (Yoon and Zeng 2010).

4. Concluding remarks

Our analyses demonstrate that 20 years deforestation has led to a warmer and dryer lower troposphere over the Amazon. As a result, the warmer and dryer lower troposphere enhanced updraft winds that impeded external water supplies from the tropical Atlantic Ocean which would otherwise moisten the lower atmosphere. The lower troposphere desiccation is the strongest during the dry and transition seasons in the monsoon and savanna climate zones, and is emerging in the rainforest climate zone and wet season in monsoon and savanna climate zones despite much greater and more evenly distributed rainfall. The observed atmospheric desiccation suppresses vegetation growth and may offset CO₂ fertilization effects at large spatial scales (Yuan *et al* 2019). Finally, the severe atmospheric desiccation in the southern and eastern Amazon cannot be compensated by enhanced water supplies from the Atlantic Ocean, indicating that the Amazon hydrological system is approaching an irreversible transition exacerbated by rapid deforestation. However, the incipient drying during the wet season and over the Amazon rainforest suggests that large scale forest conservation and ecological restoration are still promising and offer the last opportunities for reversing the drying trend and preventing ecosystem collapse. Forest conservation and restoration have been practiced at large scale in Brazil and other Amazonian countries in past decades through agroforestry systems, assisted natural regeneration and natural regeneration (da Cruz *et al* 2020). From 2004, large areas of tropical forests were set aside for conservation, and expansion of plantation was banned within Amazonian region (Assunção *et al* 2015), which had greatly slowed down deforestation over the period 2004–2015 (Nobre *et al* 2016). Large scale forest conservation and restoration is considered positive to mitigate climate change (Cook-Patton *et al* 2021) and maintain hydrological and ecosystem services (Bradford *et al* 2021, Sankey *et al* 2021), which is also the last chance to sustain the role of Amazon in global carbon cycle and avoid global environmental catastrophe (Lovejoy and Nobre 2019).

Data availability statements

All reanalysis and satellite data used in this study are publicly available: global forest change (GFC v1.5): https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.5.html; MODIS evapotranspiration and latent heat flux product (MOD16A2 version 6): <https://lpdaac.usgs.gov/products/mod16a2v006/>; MODIS Aqua 8 day Land Surface Temperature and Emissivity (LST&E) L3 Global products: <https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MYD11C2/>; Köppen–Geiger climate classification: <http://koeppen-geiger.vu-wien.acat/present.htm>; ECMWF

ERA5 monthly reanalysis at 0.25-degree: www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5; GPCP Global Precipitation Climatology Centre monthly precipitation dataset: <https://psl.noaa.gov/data/gridded/data.gpcp.html>; vegetation type of the Neotropical Region is available at: www.neotropree.info/welcome.

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

X X and G J conceived and designed the study. X X, X Z and Y X performed the data analyses. All authors wrote the manuscript and contributed to results discussion.

Conflict of interest

The authors declare no conflicts of interest.

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