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Key Points:
- Amazon deforestation reduces rainfall far from the deforested area
- Deforestation systematically erodes the resilience of the southwestern Amazon forest
- Hot spots where forest loss would most threaten the integrity of the entire Amazon forest are likely to be deforested in the near future

Supporting Information:
- Supporting Information S1

Correspondence to:
D. C. Zemp,
dzemp@gdwg.de

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Deforestation effects on Amazon forest resilience

D. C. Zemp[1,2,3], C.-F. Schleussner[2,4], H. M. J. Barbosa[5], and A. Rammig[2,6]

[1]Department of Geography, Humboldt Universität zu Berlin, Berlin, Germany, [2]Earth System Analysis, Potsdam Institute for Climate Impact Research, Potsdam, Germany, [3]Now at Biodiversity, Macroecology and Conservation Biogeography, University of Goettingen, Göttingen, Germany, [4]Climate Analytics, Berlin, Germany, [5]Instituto de Física, Universidade de São Paulo, São Paulo SP, Brazil, [6]TUM School of Life Sciences Weihenstephan, Technical University of Munich, Freising, Germany

Abstract Through vegetation-atmosphere feedbacks, rainfall reductions as a result of Amazon deforestation could reduce the resilience on the remaining forest to perturbations and potentially lead to large-scale Amazon forest loss. We track observation-based water fluxes from sources (evapotranspiration) to sinks (rainfall) to assess the effect of deforestation on continental rainfall. By studying 21st century deforestation scenarios, we show that deforestation can reduce dry season rainfall by up to 20% far from the deforested area, namely, over the western Amazon basin and the La Plata basin. As a consequence, forest resilience is systematically eroded in the southwestern region covering a quarter of the current Amazon forest. Our findings suggest that the climatological effects of deforestation can lead to permanent forest loss in this region. We identify hot spot regions where forest loss should be avoided to maintain the ecological integrity of the Amazon forest.

Plain Language Summary The Amazon forest is a giant water pump. It releases huge amount of water to the atmosphere by transpiration. This water is then recycled back as precipitation over the forest, sometimes in remote locations following large-scale transport in the atmosphere. We use an empirical approach based on satellite images to quantify changes in the water flux following 21st century deforestation scenarios. We find rainfall reductions by up to 20% downwind of the deforested area (western Amazon and subtropical South America). This in turn increases the ecological vulnerability of the remaining forest to perturbations (logging, fire, and extreme drought), in particular, in southwestern Amazonia. Our results suggest that increasing deforestation might lead to permanent forest loss in this region. We show that the regions where deforestation would most increase the ecological vulnerability of the whole forest coincide with regions likely to be deforested or degraded in the near future. Therefore, forest protection strategies should be defined to maintain the water pump, in order to avoid changes in rainfall over South America and to sustain the ecological integrity of the Amazon forest.

1. Introduction

Deforestation already reached almost 20% of the original forest area of the Brazilian Amazon alone [*Aguiar et al.*, 2016]. Deforestation rates recently increased after a decade of stability and future prospects are looking progressively dire [*Fearnside*, 2015; *Aguiar et al.*, 2016]. Increasing deforestation is expected to alter regional and global climate [*Werth and Avissar*, 2002; *Sampaio et al.*, 2007; *Da Silva et al.*, 2008; *Medvigy et al.*, 2011; *Bagley et al.*, 2014]. Unlike pasture or croplands, tropical forest trees maintain high evapotranspiration rate during the dry season [*Von Randow et al.*, 2004; *Da Rocha et al.*, 2009], which is an important source of atmospheric moisture that is recycled back to precipitation regionally and over the subtropical La Plata basin [*Eltahir and Bras*, 1994; *Trenberth*, 1999; *Zemp et al.*, 2014]. Deforestation also affects atmospheric circulation patterns by altering land-surface physical properties, as well as the carbon cycle and the energy budget [*Sampaio et al.*, 2007; *Lejeune et al.*, 2015; *Khanna et al.*, 2017]. As a result of vegetation-atmosphere interactions, clear cutting of Amazonian trees is expected to amplify the dry season [*Nobre et al.*, 1991; *Sampaio et al.*, 2007; *Medvigy et al.*, 2011; *Spracklen et al.*, 2012], as well as interannual drought [*Da Silva et al.*, 2008; *Bagley et al.*, 2014]. Several coupled biosphere-climate models simulate a nonlinear decrease of regional rainfall with increasing deforestation rate, suggesting the existence of deforestation thresholds (30–50%) beyond which rainfall changes become more drastic [*Nobre et al.*, 1991; *Sampaio et al.*, 2007; *Senna et al.*, 2009; *Pires and Costa*, 2013; *Boers et al.*, 2017]. Due to such drastic rainfall reduction, the forest might shift permanently toward a drier type of ecosystem

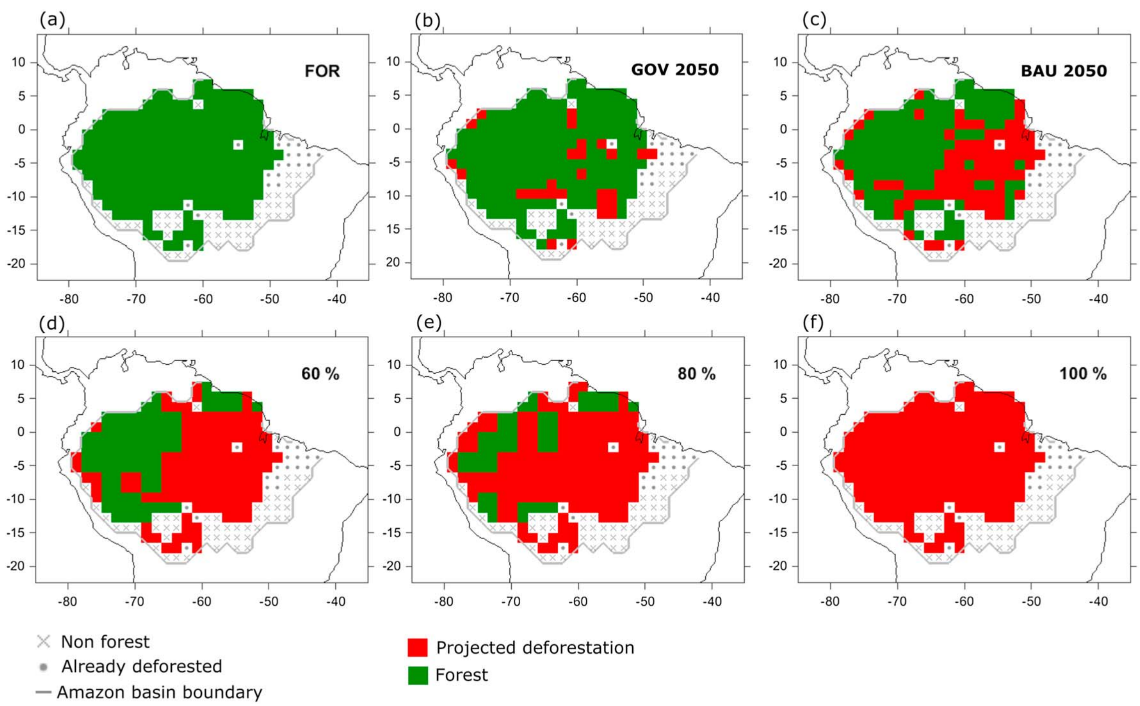

Figure 1. Deforestation scenarios. (a) Observed forest cover in 2003 when already 10% of the original forest extend is lost (gray dots). This land-cover map is used as baseline for control runs. (b) Governance (GOV) deforestation for 2050 reaching 20% of the original forest cover. (c) Business-as-usual (BAU) deforestation for 2050 reaching 45% of the original forest cover. (d–f) Deforestation reaching approximately 60, 80, and 100% of the original forest cover.

(savanna or Amazonia-cerrado transitional forest) [*Nepstad et al.*, 2008; *Malhi et al.*, 2009; *Hirota et al.*, 2011; *Coe et al.*, 2013; *Pires and Costa*, 2013] in response to perturbations such as fire, logging, or extreme drought events [*Brando et al.*, 2014]. However, the existence of such tipping points in the Amazon vegetation-rainfall system is under debate as it depends on the model structure and assumptions [*Lawrence and Vandecar*, 2015; *Lejeune et al.*, 2015]. Recently, it has been suggested that biogeophysical effects of deforestation are unlikely to trigger such tipping points [*Lejeune et al.*, 2015].

Here we rely on an empirical approach [*Zemp et al.*, 2017] to evaluate the effect of increasing deforestation on water fluxes across the South American continent. We quantify the resulting reduction in forest resilience, defined here as the ability of the forest to recover from perturbations [*Verbesselt et al.*, 2016] and quantified based on the observed distribution of tree cover across rainfall regimes [*Hirota et al.*, 2011]. Compared to previous modeling approaches that have been used to study the existence of tipping points of Amazon deforestation [*Sampaio et al.*, 2007; *Pires and Costa*, 2013; *Boers et al.*, 2017], here we focus on changes in continental moisture recycling and quantify the ecological impact on the forest.

2. Method

2.1. Deforestation Experiments

The effect of Amazon deforestation on regional rainfall and forest resilience is evaluated by comparison with control runs for which the land-cover map is based on the observed forest cover in 2003 when already 10% of the original forest cover is lost. We use five deforestation simulations from *Soares-Filho et al.* [2006] (see Figure 1): deforestation for 2050 assuming a governance (GOV) and business-as-usual (BAU) scenarios reaching approximately 20% and 45% of the original extent of the forest, respectively, and longer-term deforestation based on BAU reaching approximately 60%, 80%, and 100% of the original extent of the forest. These scenarios ignore the existence of protected areas comprising already 40% of the Brazilian Amazon [*Walker et al.*, 2009]. However, the aim of the present study is to improve the understanding of the dynamic of the Amazon forest-rainfall system rather than providing projections based on more realistic Amazon deforestation scenarios [e.g. *Aguiar et al.*, 2016]. Furthermore, our findings can be directly compared with previous modeling studies [*Sampaio et al.*, 2007; *Spracklen et al.*, 2012; *Pires and Costa*, 2013] that used the scenarios from *Soares-Filho et al.* [2006]. Here the original data from *Soares-Filho et al.* [2006] is upscaled to 1.5° resolution by selecting the most frequent value, which might lead to underestimation of the original deforested area. In our experiments, deforested areas are replaced by a treeless state.

2.2. Moisture Recycling Networks

We use moisture recycling networks [*Zemp et al.*, 2014], in which nodes represent grid cells covering the South American continent and links represent the amount and direction of atmospheric moisture transported between each pair of grid cells. These networks are build using numerical tracking of atmospheric moisture data [*van der Ent et al.*, 2010, 2014] (see supporting information Text S1). They can be used to estimate changes in water fluxes from sources (evapotranspiration) to sinks (precipitation) in a spatially explicit way [*Zemp et al.*, 2017].

2.3. Forest Resilience Calculation

The distribution of remotely sensed tropical tree-cover (TC) suggests the existence of alternative stable states in the vegetation [*Hirota et al.*, 2011; *Staver et al.*, 2011]. We distinguish a high TC state (TC ≥ 55%) corresponding to evergreen forest, an intermediate TC state (55% > TC ≥ 5%) corresponding to deciduous forest, shrubs, and herbaceous and a treeless state (TC < 5%) [*Zemp et al.*, 2017]. The probability of being in the high TC state varies nonlinearly as a function of the rainfall regime and can be used as an indicator of forest resilience to critical transition [*Hirota et al.*, 2011]. Like in *Zemp et al.* [2017], here rainfall regime is characterized by mean annual precipitation and maximum cumulative water deficit, which are key hydroclimatic drivers controlling tropical vegetation cover [*Malhi et al.*, 2009]. The probability of being in the high TC is estimated using a logistic regression fitted to the data (see supporting information Text S2). For simplicity, hereafter this probability is called forest resilience.

2.4. Simple Evapotranspiration Model

We use a simple evapotranspiration model [*Zemp et al.*, 2017] that considers the most important factors controlling evapotranspiration in the Amazon region [*Von Randow et al.*, 2004; *Hasler and Avissar*, 2007; *Da Rocha et al.*, 2009; *Costa et al.*, 2010]: atmospheric demand for evaporation (potential evapotranspiration) and the capacity of the vegetation to access subsurface water during drought. The latter is represented as a linear function of the cumulative water deficit derived from monthly rainfall [*Aragão et al.*, 2007] (see model description in Text S3).

2.5. Coupling Experiment

We combine moisture recycling networks, the simple evapotranspiration model, and the calculation of forest resilience in an integrative modeling framework (supporting information Figure S1). In a first step, evapotranspiration is estimated for the initial vegetation cover. In a second step, monthly water fluxes (including evapotranspiration, atmospheric moisture transport, and precipitation) are updated assuming that in each grid cell, the tagged fraction of precipitation is linearly proportional to the tagged fraction of evapotranspiration and the tagged fraction of transported moisture [*Zemp et al.*, 2017]. This means that the water pools (soil and lower layer of the atmosphere) are assumed to be well mixed, which is generally a valid assumption on a seasonal time scale for the central part of the Amazon basin. However, this assumption might not fully hold during the dry season in the southern Amazon forest, where transpired water might originate from storage from the preceding wet season [*Miguez-Macho and Fan*, 2012]. In addition, local rainfall is assumed to decrease linearly with atmospheric moisture, in agreement with a recent study reporting a linear correlation between these variables for the Amazon region [*Boers et al.*, 2017]. Once equilibrium in water fluxes on both the monthly and annual time scales is reached, grid-cell forest resilience is updated.

2.6. Hot Spots of Vegetation-Rainfall Feedbacks

To identify hot spots of vegetation-rainfall feedbacks, each high TC grid cell within the Amazon basin is deforested individually by setting its value to a treeless state. The resulting reduction of the resilience of the remaining Amazon forest is averaged and normalized by the maximum value (over all individual deforestation experiments).

2.7. Data

There are still large discrepancies on estimated land-atmosphere water fluxes in the tropics depending on the underlying data sets [*Fisher et al.*, 2009]. Therefore, in our analysis we use merged historical (1989–1995) hydroclimate data: evapotranspiration from LandFlux-EVAL [*Mueller et al.*, 2013] and precipitation from an average of four observation-based products. To build moisture recycling networks, we include humidity and wind data from ERA-Interim reanalysis [*Dee et al.*, 2011]. In our statistical models for evapotranspiration and

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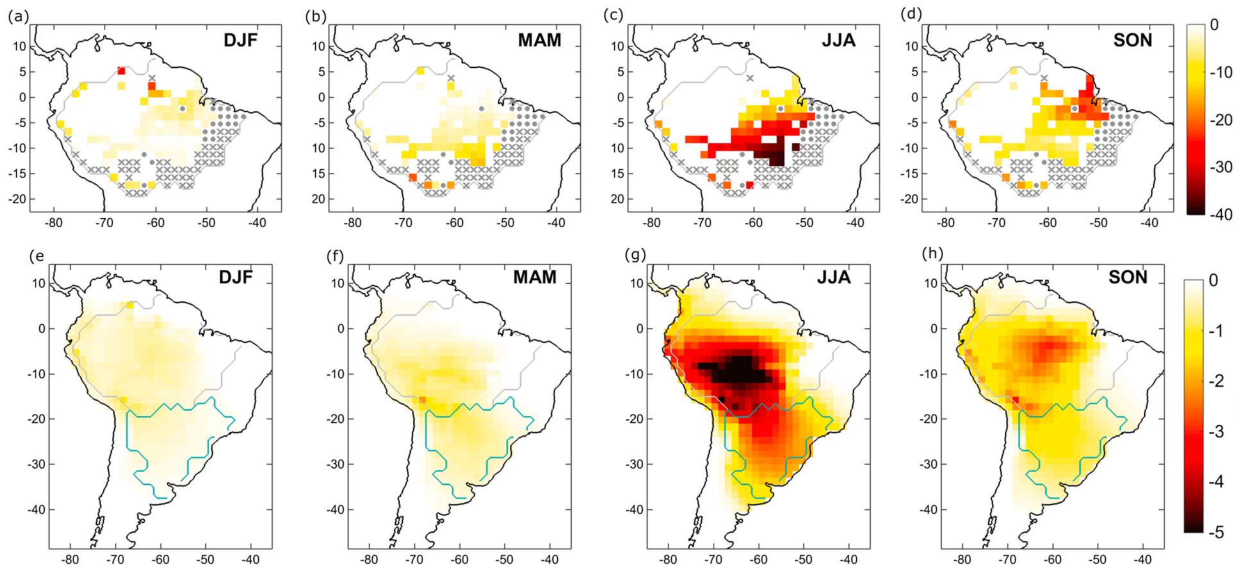

Figure 2. Relative changes of (a–d) seasonal evapotranspiration and (e–h) seasonal precipitation following BAU deforestation scenario for 2050. Seasonal results correspond to the average for December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). Boundaries of the Amazon basin (gray line) and the La Plata basin (green line) are also shown. Note that the color bars have been truncated for better visibility.

forest resilience, we also use potential evapotranspiration data that have been corrected with observations [*Sheffield et al.*, 2006, 2012] and remotely sensed tree cover from MOD44B v5 [*DiMiceli et al.*, 2011]. A detailed description of the data is provided in Text S4.

3. Results and Discussion

3.1. Effects of Deforestation on Hydroclimate: Intensity of Changes

Our estimations of evapotranspiration changes after deforestation are shown in Figures 2 and S2. While flux tower measurements showed a relative decrease of 20% from December to March and 41% from June to September of latent heat in pasture compared to forest in southwestern Amazon (10°S, 61–62°W) [*Von Randow et al.*, 2004], our simulations for this location indicate a decrease of 2% and 27%, respectively. One possible explanation for this discrepancy is the omission of other factors controlling evapotranspiration changes in our approach, such as leaf area affecting intercepted water by the canopy that represents around 40% of total evapotranspiration flux over the Amazon forest [*Wang-Erlandsson et al.*, 2014]. Another reason might be that we use large-scale data to calibrate our evapotranspiration model for a range of different hydroclimatic regimes in tropical South America. By doing so, we may also run the risk of underestimating the differences introduced in evapotranspiration following deforestation, compared to study using fine-scale observations over already deforested areas [*Silvério et al.*, 2015].

Our estimates of rainfall reduction following deforestation are highly sensitive to the calibration of the evapotranspiration model applied [*Zemp et al.*, 2017]. For a BAU scenario, our best estimate for 2050 points toward 2% Amazonian rainfall reduction during the dry season (June–August), compared to other estimates that are as high as 21% [*Spracklen et al.*, 2012; *Pires and Costa*, 2013]. To estimate the effect of potentially much higher evapotranspiration reductions, we also assess an upper bound of estimated evapotranspiration difference. For this upper bound, we attribute the 95th percentile for evapotranspiration estimates over high TC grid cells and the 5th percentile for intermediate TC and treeless grid cells, based on uncertainties in evapotranspiration model parameters. Considering this upper bound, dry season rainfall reduction in 2050 under a BAU deforestation scenario averages 8% over the Amazon basin and reaches a local maximum of 20%.

3.2. Effects of Deforestation on Hydroclimate: Spatiotemporal Patterns

As a result of deforestation, factional reduction in evapotranspiration is strongest during the dry season (June–August) in the southern part of the Amazon forest (Figures 2 and S2). In our simulations, decrease in evapotranspiration after deforestation firstly results from a reduction of the capacity of the vegetation to access subsurface water. This reduction is more drastic during drought conditions, when cumulative water deficit increases. This is in agreement with measurements from flux towers showing that savanna and pastures exhibit stronger water stress in regions where dry seasons are more pronounced, while forest maintain high transpiration rates [*Hasler and Avissar*, 2007; *Da Rocha et al.*, 2009; *Restrepo-Coupe et al.*, 2013]. This can be explained by the root system of the trees that can access soil moisture at great depth [*Nepstad et al.*, 1994] and redistribute it in the soil profile [*Oliveira et al.*, 2005]. Second, evapotranspiration decrease in our simulations is slightly accentuated by increasing water deficit, which represents the depletion of subsurface water storage. In our modeling approach, these processes are estimated statistically. This is an advantage compared to deterministic land-surface models, for which simulated evapotranspiration in the Amazon region are usually very sensitive to rooting depth and ground water level that remain poorly constrained by observations [*Miguez-Macho and Fan*, 2012].

BAU deforestation leads to rainfall reduction mainly downwind of the deforested areas and during the dry season in 2050 (Figures 2e–2h). Here rainfall decrease is only due to a reduction of the amount of atmospheric water transport following reduction in evapotranspiration. Effects of deforestation on winds and atmospheric circulation patterns induced by changes on energy fluxes, surface friction, and on the carbon cycle [*Bonan*, 2008] are not accounted for. These effects might alter the intensity and spatiotemporal patterns of rainfall changes after land use change [*Khanna et al.*, 2017]. Despite this simplification, our simulated spatiotemporal variability of rainfall reduction following deforestation is in good agreement with previous simulations from mechanistic coupled climate-biosphere models [*Da Silva et al.*, 2008; *Bagley et al.*, 2014; *Lejeune et al.*, 2015].

Surprisingly, however, our results differ from *Spracklen et al.* [2012] who used empirical relationships between canopy cover and rainfall along 10 days air mass back trajectories. While we find major rainfall reduction over western Amazon forest and the La Plata basin, *Spracklen et al.* [2012] found a maximal rainfall reduction over the deforested areas and comparably less reduction further downstream. Several potential reasons for this discrepancy come to mind.

1. Due to well-mixing assumptions in the Eulerian atmospheric moisture tracking model used here, our results are more reliable at the continental scale than at local scale, in particular, in tropical regions with prominent wind shear [*van der Ent et al.*, 2013]. It might thereby be that we systematically underestimate local moisture recycling.
2. Rainfall reduction projections from *Spracklen et al.* [2012] in western Amazonia and the La Plata basin are likely to be underestimated due to the saturation of the signal when air passes over dense vegetation for a long period of time [*Spracklen et al.*, 2012].
3. The use of moisture recycling networks allows us to account for moisture transport over large distances including reevaporation cycles along the way [*Zemp et al.*, 2014], while the air mass back trajectories used in *Spracklen et al.* [2012] are based on the residence time of water vapor in the atmosphere [*Numaguti*, 1999] and do not account for such cascading moisture recycling.

3.3. Effects of Deforestation on Forest Resilience

Our results reveal that the impact of Amazon deforestation on the resilience of the forest is maximal in the southwestern part of the Amazon, a region that covers a quarter of the current forest (Figure 3). For a complete Amazon deforestation scenario, which is unrealistic but can be used to evaluate the maximal potential ecological impact of deforestation, fractional reduction in forest resilience averages 5% (best estimate) and 25% (upper bound) in the southwestern Amazon. In our simulations, regions where forest resilience decreases often overlap with deforested areas. Practically, this implies a difficult recover to the forest state even with proper restoration efforts [*Hirota et al.*, 2011].

While the intensity of changes vary for different deforestation scenarios, spatial patterns remain the same (Figure 3). Indeed, the southwestern part of the Amazon basin is a sink of continental moisture recycling [*van der Ent et al.*, 2010; *Zemp et al.*, 2014], and the resilience of its forest is originally low due to more pronounced dry season and lower annual rainfall [*Zemp et al.*, 2017]. Our results agree well with *Pires and Costa* [2013], who found that southwestern Amazon forest is likely to enter the bioclimatic equilibrium of savannas following Amazon deforestation.

Our approach to quantify forest resilience does not include the effect of "CO_2 fertilization" on the vegetation. It has been shown that increasing atmospheric CO_2 concentration enhances water-use efficiency of tropical trees [*van der Sleen et al.*, 2015]. CO_2 fertilization may also stimulate tropical tree growth, although this effect remains highly uncertain [e.g., *Rammig et al.*, 2010; *van der Sleen et al.*, 2015]. On the other hand, it can induce stomatal closure and hence reduce transpiration and associated rainfall in parts of the Amazon

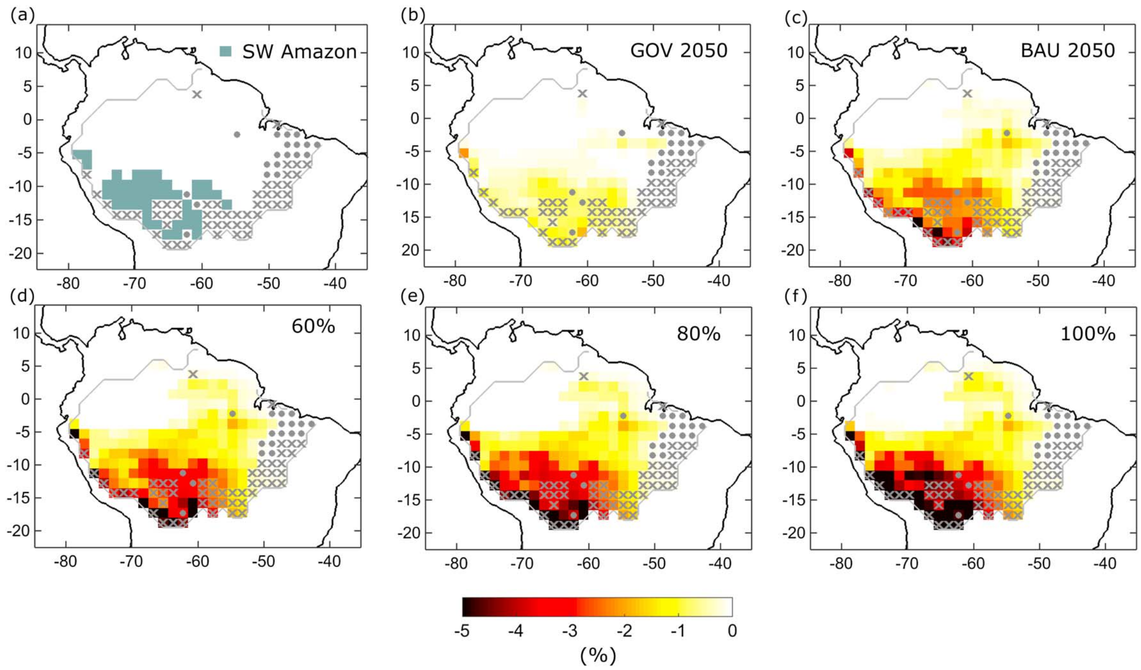

Figure 3. (a) Southwestern (SW) Amazon forest region at risk by remote deforestation, obtained by selecting grid cells where the reduction in forest resilience following complete Amazon deforestation exceeds the 75th percentile. (b–f) Reduction in forest resilience with increasing deforestation. Note that the color bars have been truncated for better visibility.

[*Costa and Foley*, 2000]. Further research is needed to assess the combined effect of increasing atmospheric CO_2 concentration and deforestation on vegetation-rainfall feedbacks and Amazon forest resilience.

3.4. Tipping Points of Deforestation?

Above 20% of deforestation, reductions of rainfall and forest resilience in the southwestern Amazon forest becomes slightly more drastic. On average, for each step of 10% deforestation, resilience of the southwester Amazon forest is reduced by up to 1.5% before the threshold and up to 2.5% after the threshold (dashed orange line in Figure 4c). However, the nonlinearity found in our simulation is probably not sufficiently pronounced to refer to a "tipping point" [*Lawrence and Vandecar*, 2015; *van Nes et al.*, 2016], as it is the case in simulations from other models [*Spracklen and Garcia-Carreras*, 2015; *Lejeune et al.*, 2015]. Accounting for cascading effects (or feedback) in the vegetation-rainfall system [*Zemp et al.*, 2017], as well as changes in moisture inflow from the ocean following deforestation [*Boers et al.*, 2017], might lead to Amazonian tipping points.

3.5. Hot Spots of Vegetation-Rainfall Feedbacks

Hot spot regions where local deforestation would most reduce the resilience of the entire Amazon forest are shown in Figure 5. This result does not differ using different input data sets (Figure S3). As these hot spots

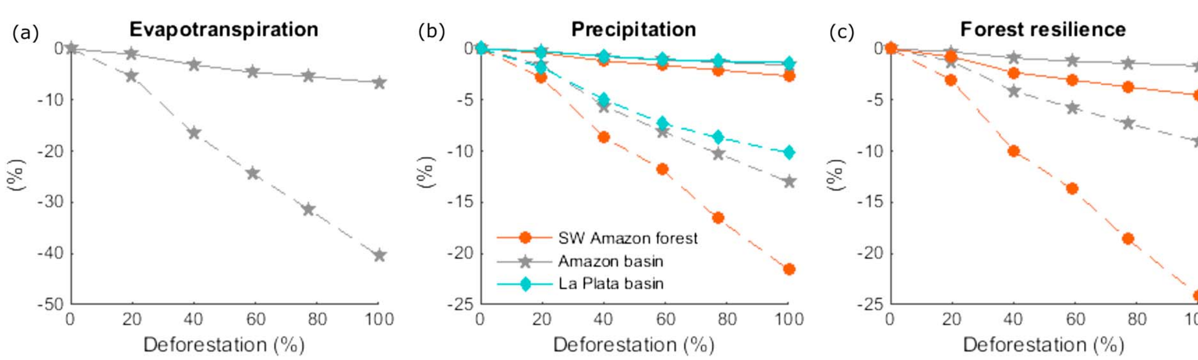

Figure 4. Effect of increasing deforestation on (a) mean annual evapotranspiration, (b) mean annual precipitation, and (c) forest resilience averaged over the southwestern Amazon forest, the Amazon basin, and the La Plata basin. Results are obtained using the estimated changes in evapotranspiration (solid lines) and using the upper bound of estimated changes (dashed lines).

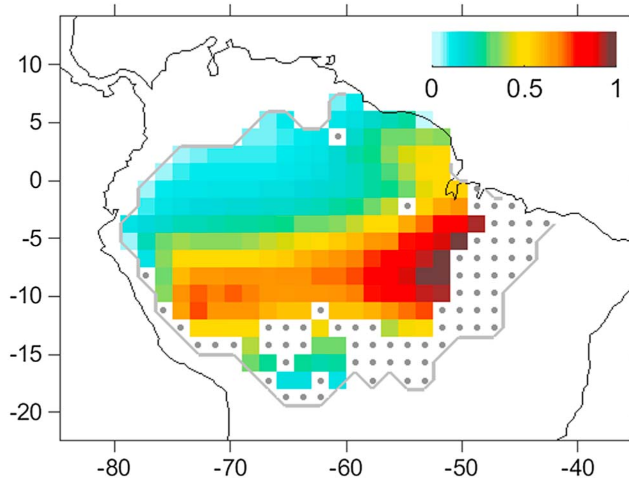

Figure 5. Reduction in resilience of the entire Amazon forest following local deforestation of each grid cell individually. High values indicate hot spot regions where deforestation would most reduce the resilience of the Amazon forest.

coincide with regions likely to be deforested or degraded in the near future [*Davidson et al.*, 2012; *Aguiar et al.*, 2016], it is crucial to account for interconnectivity of the Amazon forests when evaluating the effect of forest loss.

4. Conclusion

We simulated the effect of Amazon deforestation on water fluxes (evapotranspiration, atmospheric moisture transport, and rainfall) and forest resilience using a statistical model relying on observation-based hydro-climate and vegetation data. Our results indicate that resilience of the southwestern Amazon forest will be systematically eroded, regardless of the deforestation rate. This suggests that this region will become more vulnerable to environmental perturbations such as fire, logging, or extreme drought events, which provides feed back on each other and might trigger large forest degradation [*Brando et al.*, 2014]. This region is already vulnerable to such perturbations, as shown by satellite observations of the canopy structure that recovered slowly after the intense drought in 2005 [*Saatchi et al.*, 2013], as well as of fire activities related to dry periods in the last decades [*Morton et al.*, 2013]. *Boisier et al.* [2015] constrained climate simulations with observations and suggest that Amazonian dry season will be intensified by the end of the century. Combined with further deforestation, this might shift the southwestern Amazon forest toward a drier bioclimatic equilibrium with less tree cover. The risk of such a vegetation shift might be even higher if deforestation occurs both in the Amazon region and in Central Brazil [*Pires and Costa*, 2013].

Walker et al. [2009] suggested that large-scale Amazon deforestation outside protected areas will not have dramatic ecological consequences for the remaining forest in the Brazilian Amazon (Legal Amazonia). However, our results suggest that the most impacted forest regions might be located in Bolivia and Peru. In addition, deforestation will likely lead to strong rainfall reduction over the subtropical La Plata basin, covering southern Brazil, Bolivia, northern Argentina, Paraguay, and Uruguay. Therefore, moisture recycling should be considered as a key ecosystem service from Amazon forests to large parts of South America and Amazon forest management strategies should be established at international levels.

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