Impacts of land use on climate and ecosystem productivity over the Amazon and the South American continent

M Wu1,5, G Schurgers2, A Ahlström1,4, M Rummukainen1,4, P A Miller1, B Smith1 and W May4

1 Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, SE-223 62, Lund, Sweden
2 Department of Geosciences and Natural Resource Management, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen, Denmark
3 Department of Earth System Science, School of Earth, Energy and Environmental Sciences, 10 Stanford University, Stanford, CA 94305, United States of America
4 Centre for Environmental and Climate Research, Lund University, Sölvegatan 37, SE-223 62 Lund, Sweden

Author to whom any correspondence should be addressed.
E-mail: minchao.wu@nateko.lu.se

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Abstract

The Amazon basin is characterized by a strong interplay between the atmosphere and vegetation. Anthropogenic land use and land cover change (LULCC) affects vegetation and the exchange of energy and water with the atmosphere. Here we have assessed potential LULCC impacts on climate and natural vegetation dynamics over South America with a regional Earth system model that also accounts for vegetation dynamics. The biophysical and biogeochemical impacts from LULCC were addressed with two simulations over the CORDEX-South America domain. The results show that LULCC imposes local and remote influences on South American climate. These include significant local warming over the LULCC-affected area, changes in circulation patterns over the Amazon basin during the dry season, and an intensified hydrological cycle over much of the LULCC-affected area during the wet season. These changes affect the natural vegetation productivity which shows contrasting and significant changes between northwestern (around 10% increase) and southeastern (up to 10% decrease) parts of the Amazon basin caused by mesoscale circulation changes during the dry season, and increased productivity in parts of the LULCC-affected areas. We conclude that ongoing deforestation around the fringes of the Amazon could impact pristine forest by changing mesoscale circulation patterns, amplifying the degradation of natural vegetation caused by direct, local impacts of land use activities.

1. Introduction

Studies with climate models show that land use and land cover change (LULCC) over the Amazon basin may generate local, mesoscale and even global influences on climate and ecosystems (Pielke et al 2011, Davidson et al 2012, Lawrence and Vandecar 2015). A wide variety of responses has been simulated in previous studies, depending on locations, scenarios of deforestation, as well as on the modelling approach chosen (Pielke et al 2007, Pielke et al 2011). Studies in which land cover properties have been modified in general circulation models (GCMs) following a ‘scorched Earth’ scenario (e.g. conversion of the entire Amazon basin to grassland) result in a warmer and drier Amazonian climate (Nobre et al 1991, Costa and Foley 2000). Studies based on more realistic deforestation patterns mirroring historical trends tend to show smaller shifts in temperature and rainfall, and may also exhibit contrasting directions of change in different parts of the deforested area or among different models and scenarios (Findell et al 2007, Pitman et al 2009). By modifying biophysical properties of the land surface that affect energy uptake and exchange with the atmosphere, LULCC can affect the local climate, but may also induce teleconnections by affecting large-scale circulation patterns (Chase et al 2000, Werth and Avissar 2002, 2003, Vrugt and Huppes 2004).
In some cases, such an indirect influence on local climate can be larger than the direct, local one induced by biophysical coupling (Findell et al 2009). Due to this complexity in responses, a better understanding of LULCC effects on climate dynamics requires disentangling the effects of local climate drivers from regional or global drivers (Lawrence and Vandecar 2015). Amazonia is an important area for biodiversity and stores considerable amounts of carbon (Malhi et al 2006, Phillips et al 2008), the area is subject to risks posed by the combined effects of rapid deforestation and more frequent or severe droughts (Cox et al 2000, Cox et al 2004, Cox et al 2013, Saatchi et al 2013). Recent studies show that LULCC can significantly influence carbon storage of the Amazon (Sitch et al 2005, Pongratz et al 2009, Brovkin et al 2013), making LULCC in this area critical from a nature conservation and climate change mitigation perspective.

Model resolution may critically affect the simulated influences of land cover changes on hydroclimate (D’Almeida et al 2007). Analyses of LULCC impacts on South American climate have so far mainly been based on GCM simulations. A drawback of these models is their relatively coarse resolution which renders them unable to resolve mesoscale circulation features induced by landscape heterogeneity (Pielke et al 2007). Meso- and regional-scale studies using high resolution models point to small negative (Medvigy et al 2011) or positive (e.g. Correia et al 2008) impacts of deforestation on precipitation over the Amazon region. These earlier studies, however, have focused almost exclusively on the impact of land use on climate, and it is still unclear how deforestation-driven climate changes influence natural ecosystems of the Amazon basin through biophysical feedback.

In this study, we employ a regional Earth system model to assess impacts of recent past anthropogenic land cover change on climate and natural vegetation dynamics over the Amazon forest region and South America as a whole. By accounting for interactions between the vegetated land surface and the atmosphere, we can evaluate the impact of deforestation and other land cover shifts on regional climate patterns and variability, and the impacts of changing climate patterns on natural ecosystem structure and function.

2. Methods and Data

2.1. The regional Earth system model

The coupled dynamics of the land surface and atmosphere over the South American study area were simulated with RCA-GUESS (Smith et al 2011), a regional Earth system model that couples the Rossby Centre regional climate model RCA4 (Kjellström et al 2005, Samuelsson et al 2011) to LPI-GUESS, an individual-based ecosystem model that combines an individual-based representation of vegetation structure and dynamics with process-based physiology and biogeochemistry (Smith et al 2001, Smith et al 2014).

RCA4 represents surface heterogeneity such as complex topography and incorporates a multi-level representation for the lowest atmospheric layers above and below the forest canopy (Samuelsson et al 2011). Open land and forest tiles of the land surface carry separate energy balances (Samuelsson et al 2006). In each tile, the soil is divided into three layers for soil moisture, with a maximum depth defined by a rooting depth prescribed for each tile. Root extraction depends on an exponential root distribution, and accounts for water uptake compensation for dry soil conditions, i.e. an adapted water uptake efficiency for each soil layer according to the changes in soil moisture availability. Soil water conditions influence vegetation surface resistances, thus controlling evapotranspiration and energy fluxes. A detailed description of the physical land surface representation can be found in Samuelsson et al (2006).

Vegetation in LPI-GUESS is characterized as local neighborhoods (patches) of individuals belonging to different plant functional types (PFTs; table S1 available at stacks.iop.org/ERL/12/054016/mmedia), co-occurring and competing for light, space and soil resources. PFTs encapsulate the differential functional responses of potentially occurring species in terms of growth form, bioclimatic distribution, phenology, physiology and life-history characteristics. Vegetation development is affected by allometric growth, competition for light and soil resources among individuals, stochastic disturbances, establishment and mortality. The simulated vegetation structure affects land surface properties (albedo and roughness length, as well as the water vapor exchanges with the atmosphere) by returning updated forest and open land tile fractions and leaf area index (LAI) to RCA4. The coupling scheme between the vegetation and physical model components is described by Smith et al (2011).

RCA-GUESS has been shown to simulate realistic biophysical dynamics in applications to Europe (Wranneney et al 2010, Smith et al 2011), the Arctic (Zhang et al 2014) and Africa (Wu et al 2016).

2.2. Experiment design

RCA-GUESS was run over the South American domain of the Coordinated Regional Climate Downscaling Experiments (CORDEX, Giorgi et al 2009, Jones et al 2011) on a horizontal grid with a resolution of 0.44° × 0.44° (figure 1). In order to capture important circulation patterns, including potential shifts in the Inter-Tropical Convergence Zone, the South American Easterly trade wind and Southern Atlantic trade winds, the simulation domain was chosen to cover the whole South American continent. In order to isolate the biophysical effects of LULCC, two experiments were conducted, which are described further down. Both were forced with atmospheric conditions typical of 1950 and 2005.
fields and sea-surface temperature (SST) as lateral and lower boundary conditions derived from ECMWF re-analysis (ERA-Interim) (Berrisford et al 2009). Transient historical radiative forcing (i.e. atmospheric greenhouse gas concentrations) was used for RCA4. The vegetation sub-model LPJ-GUESS was forced at the same resolution as RCA4, set up with eleven PFTs representing the compositional diversity of South American vegetation including tropical evergreen and drought-deciduous trees, temperate evergreen and deciduous trees and C₃ and C₄ herbaceous vegetation (‘grass’) following (Smith et al 2014), adapted for the present study by increasing the respiration coefficient (table S1) of tropical PFTs to match the carbon-use efficiency (CUE, i.e. ratio of net to gross primary production) suggested by a recent meta-analysis of tropical forest carbon dynamics (Anderson-Teixeira et al 2016). Fire disturbance (Thonicke et al 2001) and nitrogen (N) limitation (Smith et al 2014) were included, applying N deposition following Lamarque et al (2010). Transient historical CO₂ concentration values were used to force LPJ-GUESS. The model was initialized with a two-stage spinup following Wramneby et al (2010).

The first stage initialized the vegetation component with an uncoupled 500 year spinup driven by CRU TS3.1 (Harris et al 2014), followed by a coupled run for 1980–2009 with ERA-Interim boundary conditions. The second stage forced the vegetation component with the climate generated from the first stage’s coupled period for another uncoupled 500 year spinup, in order to bring the vegetation sub-component to equilibrium before the start of the two experimental runs.

Potential Natural Vegetation (PNV) run: After the spinup, the coupled RCA-GUESS was run for 1980–2005 with ERA-Interim boundary conditions and without land use, to simulate natural vegetation conditions.

Land Use (LU) run: An LU simulation was conducted with the same setup as the PNV run, starting with the simulated PNV state at 1980. However, in this case, historical LULCC forcing was applied from the Harmonized Global Land Use database (Hurtt et al 2006), regridded to the RCA-GUESS resolution of 0.44° × 0.44°. Cropland and pasture fractions from the Hurtt dataset were aggregated to provide initial fraction for the open land tile in RCA-GUESS. Only C₃ and C₄ herbaceous PFTs were permitted to grow in the open land tile.

To isolate the effects of anthropogenic land cover change (mainly deforestation) on regional climate and vegetation, the differences between the LU and PNV simulations were analyzed as averages for the period 1996 to 2005. The first 15 years (1980–1995) are thereby excluded, to avoid transient changes in the climate following the transition between PNV and LU to dominate the analysis. Four areas are in focus in this study (figure 1). The Amazonian arc of deforestation over the Cerrado (area A, figure 1(a)) and the temperate grassland centred on northeastern Argentina (area B, figure 1(a)) are the two most

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**Figure 1.** Land use fraction (a), and the comparison between observation-based estimates and simulated results for annual mean leaf area index (LAI) (b); LAI3g from Zhu et al (2013), (c); simulated and aboveground biomass (AGB). (e) Liu et al 2015, (f) simulated averaged over the analysis period. Differences between LU and PNV experiments are displayed for LAI (d) and AGB. Four areas used in the analysis are displayed in (a): area A and B with intensive LU were selected for assessing LULCC-induced local climate changes, and the Northwestern and Southeastern parts of the Amazon basin for assessing further ecosystem impact analysis.
intensive LULCC areas. They are in focus in our analysis of local impacts on climate. Changes in circulation and ecosystem productivity were analysed for the Amazon basin, divided into northwestern (NW) and southeastern (SE) parts (figure 1(a)). To assist the analyses of the LULCC-induced climate changes and their impacts on ecosystem productivity over the Amazon basin, we employed the Mann–Whitney U test based on the simulated yearly dry season or wet season means in the defined analysis period to indicate significant spatial changes to climate (figure 3) and ecosystem productivity (figure 5). In addition, linear partial correlation was used to analyze the factorial effects on net primary productivity (NPP) (figure 5), based on the sets of multi-year monthly LULCC-induced changes in climate drivers and NPP during the analysis period for all grid points.

### 2.3. Evaluation Data

Relevant RCA-GUESS output was evaluated with observation-based datasets over the analysis period. Observed LAI was obtained from the GIMMS-AVHRR and MODIS-based LAI3g product (Zhu et al. 2013). Aoveground biomass (AGB) originates from the harmonized satellite-based vegetation optical depth (VOD) data derived from passive microwave satellite sensors (Liu et al. 2015). Simulated temperature and precipitation were compared with the mean and range of corresponding climate variables from four historical climate datasets: CRU TS3.21 (Harris et al. 2014), CRUNCEP v5 (Wei et al. 2014), Princeton V2 (Sheffield et al. 2006) and WFDEI GPCC (Weedon et al. 2011).

### 3. Results

#### 3.1. Model evaluation

The simulated pattern of LAI is generally close to the LAI3g product (figure 1(b) and (c)). The model overestimates LAI around the southern margins of the Amazon forest area and over the Andes mountain range by up to 1.5, and underestimates LAI in southern Brazil by up to 1. The simulated pattern of AGB is also close to the observation (figures 1(e) and (f)), indicating an adequate distribution of forest presence and structure. The spatial bias patterns are generally similar to those for LAI.

Differences in simulated LAI and AGB between the two simulations (figure 1(d, g)) reflect the imposed land use pattern (figure 1(a)), but also show impacts of LULCC-induced climate change on AGB over areas of the Amazon basin where anthropogenic impacts of land cover are locally negligible, suggesting remote influences (see section 3.3).

The simulated surface temperature and precipitation generally depict seasonal dynamics and annual mean quantities comparable to the observed values (figure 2). For the simulated temperature, the LU simulation captures the observed annual mean and seasonal variation for area A and SE Amazon more accurately than the PNV simulation (figures 2(a) and (d)). For the simulated precipitation, the differences between the two simulations are minor, except for the area A, where LU simulation yields higher precipitation during January-March (figure 2(e)) with a smaller deviation from the observed annual mean. The results for Area B and NW Amazon show comparable seasonality but both underestimate the observations most of the year. Relatively large biases are found for May-September for NW Amazon (figure 2(g)), despite the high absolute values.

#### 3.2. Land use impacts on climate

The impact of land use on climate, determined from the difference between the LU and the PNV simulations, was primarily caused by differences in the local properties of the natural versus LULCC-affected vegetation to account for energy and mass exchanges, and its consequences for surface atmospheric mixing.
transpiration and local-to-mesoscale circulation. At the southeastern margin of the Amazon (area A), this resulted in two distinctly different patterns of LULCC-induced changes for the wet and the dry seasons (defined here as October-April and May-September, respectively; figures 2(a) and (e); figure 3). Further south (area B), where seasonal variations are characterized by temperature and not by hydrology, the changes are more consistent through the year (figures 2(b) and (f); figure 3).

During the dry season, LULCC generally imposes a warming effect over nearly the entire continent, with the most pronounced impact (up to +2.2 °C) along the southeastern edge of the Amazon basin (figure 3(a)). This warming is primarily caused by a decrease in evapotranspiration (~18 mm month⁻¹, figure S1(a)), which is determined by soil water availability (figure S1(e)) and the difference in soil water extraction of forested and grassland vegetation, although decrease in cloudiness is also relevant (figure S2(a)). The decreased evapotranspiration over the deforested land surface is partly associated with vegetation rooting depth and its influence on soil water availability. Herbaceous vegetation (simulated in the open land tile) has a shallower rooting depth than forest, limiting water access at depth and leading to an earlier soil moisture deficit compared to deep rooted forest vegetation (Gash and Nobre 1997). Differences in surface roughness amplify the pattern via impacts on turbulence and evapotranspiration. The shallower soil layer for the open land tends to dry out faster with higher surface wind speeds (figure S3(a)) under a warming than the soil layer for the forest tile, as is evident from negligible soil moisture changes and less intra-season variability for the latter, despite similar LULCC-induced warming (figure S1(g,h)).

The land-use induced warming described above dominates the continental-scale changes (figure 3(a), but land use also results in a higher albedo of land use areas compared to forest, which generally leads to a decrease in surface energy absorption (figure S4). In our experiments, the albedo cooling effect is generally smaller than the warming from reduced evapotranspiration, except for the southern
part of South America (figure 3(a)), where albedo changes dominate the temperature change, resulting in a net cooling effect. An increase in land surface temperature changes the temperature profile in the planetary boundary layer (PBL) and results in a larger vertical temperature gradient that promotes convection. However, increased temperature leads to neither marked changes in atmospheric humidity (not shown) nor changes in moisture flux convergence (MFC) (figure 4(a)), due to the constraining influence of the decreased soil water content (figure S1(e)). As a result, changes in precipitation are negligible (figure 3(c)). A warmer climate with little change in precipitation induced by land use in the dry season is consistent with previous GCM (e.g. Costa and Pires 2010) and RCM studies (e.g. Correia et al 2008), and is also evident from satellite-based observations (Negri et al 2004). Negri et al (2004) analyzed infrared satellite data of August and September over southwestern Brazil and found that deforested areas generally have much higher temperature, exceeding that of adjacent forest by up to +5 °C in the middle of the day, while increases of cloudiness and rainfall occurrence are limited.

For the Amazon basin, the dry season does not show distinct changes in precipitation or temperature, but cloud cover changes occur, with contrasting patterns between the NW and SE Amazon basin (figure S2(a)). This is likely caused by changes in circulation as seen in the southward low-level wind advection from the Amazon basin (figure S3(c,e)) which is related to soil moisture-induced changes in temperature contrast between the Amazon basin and the deforested area. The decrease in mean sea level pressure (figure S3(e)) during the dry season enhances the pressure contrast between the Atlantic and the Amazon basin, resulting in the strengthening of the Atlantic trade winds over the northern edge of the Amazon basin, continuing further south towards the Southern Amazon deforestation area (area A, figure S3(e)). As a result, while the moisture flux is reduced over the NW Amazon, it increases over the SE part.

During the wet season, LULCC continues to impose a warming effect over the deforested areas, but with a slightly lower warming than during the dry season over the tropics (area A) and a somewhat higher warming over the subtropics (area B) (figure 3(b)). For the LULCC area over the tropics, the generally high soil moisture content allows for evaporative cooling and reduces the temperature contrast between the forest and LULCC areas. The increase in evapotranspiration (up to 22 mm month\(^{-1}\)) for area A is not only temperature-driven, but also associated with enhanced surface wind speeds (figure S3(b)) related to LULCC-induced changes in surface roughness. This in turn promotes vertical mixing and a larger moisture flux convergence (figure 4(b)). Contrasting behaviour is found for the LULCC area over the subtropics, where the generally low soil moisture content becomes even lower, resulting in decreased evaporation and strengthened warming compared to the tropics.

For area B, an increase in temperature during the wet season does not result in a more vigorous hydrological cycle, as it is constrained by the low soil moisture content. Instead, evapotranspiration is reduced (figure S1(b)) and the MFC and precipitation decrease (figure 3(d), figure 4(b)).

3.3. Impacts on natural vegetation

The LULCC-induced changes in temperature, precipitation and cloudiness affect the functioning of plants and ecosystems, potentially inducing changes in the composition and structure of the natural vegetation as well. Our simulations exhibit changes in NPP that differ by season. The most significant changes are
found for the dry season (figure 5(a)): An increase in NPP over the deforested area A, and contrasting responses for the NW Amazon (increased NPP) and SE Amazon (decreased NPP). For the wet season (figure 5(b)), no such pattern is evident.

Area A presents a year-round increase in natural vegetation productivity, which is larger for the dry season than for the wet season. During the dry season, the reduced cloudiness (figure S2(a)) increases photosynthetically active radiation (PAR), which promotes photosynthesis and increases productivity. During the wet season, the effects of increased precipitation were dampened by increased cloudiness, so NPP changes are small.

For the Amazon basin, two contrasting responses of NPP were found for the NW and SE Amazon. During May-July (dry season) in NW Amazon, PAR effects dominate the response: the partial correlation coefficient of NPP with PAR increases to +0.78 (figure 5(c)), reflecting a strong positive dependency of productivity on radiation uptake, and the PAR differences for these months are large in the NW Amazon (figure S5(f-h)), while the temperature effects are weaker and control by soil water content is minor. The increase in PAR over NW Amazon with increased NPP coincides with a local decrease in cloudiness (figure S2(a)) while temperature generally remains around 24 °C (not shown). At the end of the dry season (August-September) for SE Amazon, the importance of temperature and soil water content increase. The negative effect of temperature on NPP strengthens and peaks in September (R decreases up to −0.6, figure 5(d)). The SE Amazon becomes less productive (up to −10% changes in NPP for September, figure S5(e)) when local temperatures increase from 26 °C to 27.5 °C. During the wet season over the Amazon basin, changes in NPP become more heterogeneous (figure 5(b)) and are strongly controlled by both PAR and temperature (figure 5(c)), with PAR as the dominant driver through the year.

For area B, changes in natural vegetation NPP are minor, primarily because of the low fraction of natural vegetation in this area, but also because precipitation changes are small.

4. Discussion

Studies with GCMs have shown widely diverging impacts of deforestation on South American climate, with one notable point of disagreement being the sign of the overall temperature change for South America in response to land use changes (Findell et al. 2007, Pitman et al. 2009). Differences between the implementation of LULCC effects (variations in classes of land cover, spatial and temporal resolution), vegetation dynamics and land surface biophysical processes (Pitman et al. 2009, Brovkin et al. 2013) explain these divergences.

In our study, the simulated changes in climate were moderate over the Amazon basin and were mainly linked to land cover changes around the margins of the Amazon basin and savannah areas to the South. These land cover changes induced changes in the circulation and moisture transport, as well as cloud cover over the Amazon.

Previous studies of LULCC impacts using GCMs (Findell et al. 2007, Pitman et al. 2009) show rather weak climate changes when realistic LULCC scenarios are applied. RCMs with horizontal resolution of
25–40 km (e.g. Correia et al. 2008, Salazar et al. 2016) show much more pronounced LULCC effects. RCM studies over the Amazon consistently simulate significant warming (1.5°C to 2°C) during the dry season, which is in line with satellite-based observations of forested-deforested contrasts (Negri et al. 2004, Loarie et al. 2011). This is also evident in our study. Similar to Correia et al. (2008), we find that circulation changes are induced by the enhanced temperature gradient between the forested and deforested areas. Correia et al. (2008) simulated also an enhanced hydrological cycle during the wet season over the deforested area, which agrees with both our study and an idealized modelling study by García-Carreras et al. (2011). As a result, rainfall is re-partitioned latitudinally with increases to the North and South, and decreases for the central part of the Amazon basin (figure 3(c) and (d); Walker et al. 2009). It should be noted, however, that while regional climate change studies with RCMs can have distinct added value compared to GCM studies (Rummukainen 2016), the horizontal resolution applied in this study (0.44° × 0.44°, roughly 50 × 50 km) does not explicitly resolve lower mesoscale circulation, and studies with higher resolution are still needed to resolve landscape-scale topography-driven processes.

The LULCC-induced impact on Amazonian natural vegetation depends not only on the strength of land-atmosphere interactions, but also on the sensitivity of vegetation productivity to variations in climatic drivers. For the tropical (area A) and temperate (area B) LULCC areas, ecosystem productivity is primarily influenced by seasonal variations in temperature and soil water content. For the northern part of the Amazon basin, where forest is generally well hydrated and dry season length is relatively short, forests are resistant to seasonal droughts, and ecosystem productivity is mainly constrained by radiation (Wright 1996). Our results are consistent with an observed strong correlation in the seasonal pattern of radiation and phenology (Myneni et al. 2007). We find a positive correlation between NPP and PAR for this area, despite the relatively low soil moisture content in the beginning of the dry season. Changes in soil moisture content do not explain changes in NPP during this period. We interpret this as a remote effect of LULCC changes.

In contrast, ecosystems of the southern Amazon basin exhibit lower resilience to climate change (Hirotá et al. 2011). Our results exhibit temperature changes not only locally, but also in adjacent forests during the dry season. In addition to soil moisture content during the end of the dry season, the warming imposes a negative effect on NPP. This could be caused by enhanced autotrophic respiration and/or by inhibited photosynthesis due to increased temperature (Larcher 2003, Sitch et al. 2003). For tropical rainforest, the optimal temperature range for photosynthesis is assumed to be 25°C–30°C in our study (table S1). This implies that inhibition of photosynthesis because of high temperature is not important since temperatures following warming usually stay in the range of 26°C–27.5°C. As changes in PAR are moderate for the SE Amazon (figure S5(f-j)), we surmise that enhanced autotrophic respiration is the primary reason for the simulated decline of NPP in this area.

5. Conclusion

Our results indicate that LULCC imposes important local and remote influences on South American climate and vegetation. LULCC causes significant local warming, but also changes the mesoscale circulation during the dry season, and results in an intensified hydrological cycle over major parts of the LULCC areas during the wet season. The response of the natural vegetation to the LULCC-induced changes in climatic conditions is particularly strong during the dry season, enhancing NPP at the deforested southern edge of the Amazon. Moreover, remote effects were simulated for the northwestern part of the Amazon (increased NPP) and southeastern part (decreased NPP). The LULCC-induced impacts on Amazonian productivity found in our study may improve the understanding of Amazonian ecosystem resilience under large-scale deforestation, and add to previously identified influences from human activities on the southern edge of the Amazon basin, such as forest clearing with fires (Aragão and Shimabukuro 2010), biomass-burning-derived aerosol impacts on clouds and precipitation (Lin et al. 2006) and forest fragmentation effects on ecosystem stability (Laurance et al. 2002). Further investigations are required to address the likely and possible impacts of LULCC on climate and ecosystems under future climate change, including effects on dry season length, extreme events, vegetation dieback and ecosystem productivity.

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