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Deforestation changes land-atmosphere interactions across South American biomes

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Abstract

South American biomes are increasingly affected by land use/land cover change. However, the climatic impacts of this phenomenon are still not well understood. In this paper, we model vegetation-climate interactions with a focus on four main biomes distributed in four key regions: The Atlantic Forest, the Cerrado, the Dry Chaco, and the Chilean Matorral ecosystems. We applied a three member ensemble al climate model simulation for the period 1981-2010 (30 years) at 25 km resolution over the focus regions to quantify the changes in the regional climate resulting from historical deforestation. The results of computed modelling experiments show significant changes in surface fluxes, temperature and moisture in all regions. For instance, simulated temperature changes were stronger in the Cerrado and the Chilean Matorral with an increase of between 0.7 and 1.4 °C. Changes in the hydrological cycle revealed high regional variability. The results showed consistent significant decreases in relative humidity and soil moisture, and increases in potential evapotranspiration across biomes, yet without conclusive changes in precipitation. These impacts were more significant during the dry season, which resulted to be drier and warmer after deforestation.

Key words: Dry Chaco, Cerrado, deforestation, climate, Chilean Matorral, Atlantic forest, land surface-atmosphere interactions.

1 Introduction

By the year 2000, approximately 55 percent of the Earth's biomes had been converted into pastures, croplands, settlements and other land uses (Ellis et al., 2010). These changes have impacted biotic components of ecosystems such as biodiversity, and also modified land surface-atmosphere interactions through changes in the water and energy balance (Foley et al., 2003). Understanding these processes is important because it can enhance or dampen anthropogenic climate change and therefore increase vulnerability of ecosystems and people to climate variability.

It is well recognised that land use/cover change (LUCC) can affect climate through the absorption or emission of greenhouse gases (biogeochemical impacts) and by modifying the physical properties of land surface (biogeophysical effects). Changes in land use and land cover can lead to changes in surface fluxes of radiation, heat, moisture and momentum that can further impact the

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climate at local to regional scales (Pielke et al., 2002). In terms of radiation changes, LUCC can alter the surface albedo and thereby evapotranspiration processes and partitioning of sensible, latent and ground heat fluxes that can influence near-surface temperature and precipitation (Pielke et al., 2007). In addition, changes in land use/cover can transform vegetative attributes such as roughness, which influences the mixing of air in the boundary layer and surface temperature (Foley et al., 2003). Cumulatively, these modifications of land surface characteristics can impact the climate at a range of spatial and temporal scales (Mahmood et al., 2014; Pielke et al., 2011).

Non-Amazonian South America is considered as one of the least studied regions worldwide in terms of LUCC impacts on the surface climate (Salazar et al., 2015). During the last 500 years, LUCC has resulted in a massive transformation of its biomes, with more than 1 million km^2 (52%) of the Brazilian Cerrado savanna converted to crops and pastures (MMA/IBAMA, 2011) and ~980.000 km^2 (81%) of the Atlantic moist forests transformed into crops, pasture and urbanization (Ribeiro et al., 2009; Salazar et al., 2015). High deforestation rates have also been reported for the forests of the Chilean Matorral and the Dry Chaco of Paraguay, Argentina and southern Brazil, with the later registering the highest global rate of tropical deforestation (Hansen et al., 2013). Increasing evidence from observational and modelling studies shows that this transformation of natural native forests significantly affects the flux of moisture, heat and momentum with subsequent impacts on surface temperature and precipitation (e.g. Beltrán-Przekurat et al., 2012; Loarie et al., 2011; Pongratz et al., 2006). However, high levels of uncertainty remain in relation to the mechanisms and consequences of the influence of deforestation on the climate of non-Amazonian South America.

In this paper we addressed the question "what are the potential impacts of historic deforestation on the mean climate of non-Amazonian South America?". We present results of simulations of a three model ensemble for the period 1981-2010 (30 years) to quantify the changes in the regional climate produced by deforestation of different biomes distributed in four key regions: the Atlantic Forest (tropical and subtropical moist broadleaf forest), Cerrado (tropical and subtropical savanna), Dry Chaco (tropical and subtropical dry broadleaf forest) and the Chilean Matorral (Mediterranean forest), which are considered as the regions most affected by LUCC and where subsequent climate impacts are not well understood.

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2 Methods

2.1 Climate model: CCAM

In this study, we used the Conformal-Cubic Atmospheric Model (CCAM) developed by CSIRO (McGregor, 1996; 2003; 2005a; 2005b; McGregor and Dix, 2008) to model the influence of historic deforestation on the climate of southern South America. CCAM is an hydrostatic full atmospheric Global Circulation Model formulated on a quasi-uniform grid derived by projecting the panels of a cube onto the surface of the Earth (McGregor and Dix, 2008). It can also be employed in a stretched mode by utilising the Schmidt (1977) transformation. In this study, the model was run in stretched mode with about 25 km horizontal resolution from latitude 10-45 S and longitude 30-90 W. This allows for dynamical downscaling where the computational grid is denser over the region of interest, but sparser elsewhere. CCAM contains a comprehensive set of physical parameterizations. It employs the diurnal varying Geophysical Fluid Dynamics Laboratory (GFDL) parameterization for long wave and short wave radiation (Freidenreich and Ramaswamy, 1999; Schwarzkopf and Fels, 1991), with interactive cloud distribution derived in combination with the liquid and water-ice scheme of Rotstayn and Lohmann (2002). In addition, it employs a stability-dependent boundary layer scheme according to Monin-Obukhov similarity theory (McGregor, 1993), the mass-flux cumulus convection (McGregor (2003) and the gravity-wave drag scheme over mountainous terrain (Chouinard et al., 1986) to reduce orographically-related systematic errors.

2.2 Land surface model: CABLE

The coupling between the land surface and the atmosphere is an important component of climate variability. In CCAM, feedbacks between the Earth's surface and the climate are described through the Community Atmosphere Biosphere Land Exchange version 2.0 (CABLE) land surface model. CABLE simulates the exchange of CO_2, radiation, heat, water and momentum fluxes between the land surface and atmosphere, and is composed of five main sub-models: (1) the radiation sub-model estimates the radiation transfer and absorption by both sunlit and shaded leaves and by soil surface in the visible, near infrared and thermal radiation, and also the surface albedo for visible and near infrared radiation (Wang and Leuning, 1998); (2) the surface flux sub-model estimates the coupled transpiration, stomatal conductance, photosynthesis and partitioning of net available energy between latent and sensible heat of sunlit and shaded leaves (Wang and Leuning, 1998). Photosynthesis is calculated for both C3 and C4 plants; (3) the canopy micrometeorology sub-model describes the surface roughness length, zero plane displacement height, and aerodynamic

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resistance from the reference height to the air within the canopy or to the soil surface (Raupach, 1994); (4) the soil and snow sub-models compute the heat and water fluxes within each of the six soil layers and three snowpack layers, snow age, snow density and snow depth, and snow covered surface albedo. Soil moisture is calculated with the Richards' equation and the heat conduction equation is used to obtain soil temperature (Kowalczyk et al., 2006; Wang et al., 2011); and (5) the ecosystem carbon module, which estimates respiration of stem, root and soil organic carbon decomposition (Dickinson et al., 1998).

The fluxes of heat, water and momentum depend on the mean properties of the flow through the use of aerodynamic resistances. Surface temperature is calculated through the energy balance equation and may consist in a combination of surface elements such as vegetation, bare ground, snow and ice. In CABLE, the vegetation is placed above the ground and hence allows for full aerodynamic and radiative interaction between the vegetation and the ground. The total surface fluxes are therefore the sum of the fluxes from the soil to the canopy air space and from the canopy to the atmosphere. This vertical flux is calculated using the Monin-Obukov similarity theory (Kowalczyk et al., 2006; Raupach et al., 1997), where surface roughness is an important factor influencing the friction velocity. A complete description of CABLE including its development history, major features and physics is given by Kowalczyk et al. (2006).

2.3 Experimental design

2.3.1 Land surface datasets

In order to evaluate the historic impacts of deforestation on the climate of southern South America, we completed two sets of model simulations (3 ensembles each) for the period 1981-2010. The only difference between the simulations was the description of land surface datasets. The first scenario had present (CNTRL) land cover characteristics and the second simulation had natural (NAT) land surface characteristics. For the CNTRL scenario, we upgraded the default land cover map integrated in CABLE (Loveland et al., 2000) by that developed by Friedl et al. (2010) for 2005, also known as Collection 5 MODIS Global Land Cover product or MODIS MCD12Q1 product. This represents a more actualized and accurate description of the land cover in South America. In the NAT scenario, we recreated the original vegetation in four main regions representative of distinct biomes: 1) the Atlantic Forest (tropical and subtropical moist broadleaf forest), 2) Cerrado (tropical and subtropical savanna), 3) Dry Chaco (tropical and subtropical dry broadleaf forest) and 4) Chilean Matorral (mediterranean forest) according to literature (see Table 1) and Olson et al. (2001) biomes and ecoregions boundaries. These regions are considered the most affected by deforestation in non-

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Amazonian South America (Salazar et al., 2015) (Fig. 2). From the CNTRL land cover characteristics, we identified the most complex vegetation types in the MODIS image that agreed with descriptions from literature of natural vegetation types for each one of the regions. We then extrapolated historic native vegetation by replacing current (e.g. crops) by natural (e.g. forest) vegetation types (Table 1). Leaf area index (LAI) for modern land cover was based on that developed by Beijing National University (BNU) for the period 2000-2009 (Yuan et al., 2011). Finally, we inferred the leaf area index of the original vegetation by interpolating the BNU leaf area index of remaining natural vegetation in the MODIS image using a nearest neighbour rule. Outside the study area, land cover and land surface characteristic were set for modern day conditions for all simulations (Fig. 1). For each simulation, we calculated the seasonal averages of surface temperature, precipitation, heat fluxes, evaporation, moisture and wind speed and analysed the statistical difference using bootstrapping at 95% confidence level ($p < 0.05$) where:

$X = \{X_1, X_2, \ldots, X_{n_X}\}$ is the sample of a climate variable from the NAT experiment during period 1981-2010, and $Y = \{Y_1, Y_2, \ldots, Y_{n_Y}\}$ the sample of the same climate variable taken from the CNTRL experiment in the same period.

The null hypothesis (H_o) states that there is no significant difference between the means $\overline{X}$ and $\overline{Y}$ (i.e. deforestation has no significant impact on the selected climate variable).

The alternative hypothesis (H_1) states that there is a significant difference between the means $\overline{X}$ and $\overline{Y}$ (i.e. deforestation has a significant impact on the selected climate variable).

The observed t-statistic is:

$$t_{obs} = \frac{\overline{Y} - \overline{X}}{\sqrt{\frac{\sigma_X^2}{n_X} + \frac{\sigma_Y^2}{n_Y}}}$$

Where ($\overline{X}, \sigma_X, n_X$) and ($\overline{Y}, \sigma_Y, n_Y$) are the mean, standard deviation and sample size of the NAT and CNTRL samples, respectively.

The bootstrap statistic for each sample is computed as:

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$$t^* = \frac{\overline{Y}^* - \overline{X}^*}{\sqrt{\frac{\sigma^2_{X^*}}{n_{X^*}} + \frac{\sigma^2_{Y^*}}{n_{Y^*}}}}$$

Where ($X^*, \sigma_{X^*}, n_{X^*}$) and ($Y^*, \sigma_{Y^*}, n_{Y^*}$) are the mean, standard deviation and sample size of randomly selected bootstrapped samples, respectively. The Achieved Significance Level (ASL) will be the proportion of samples where $|t^*| \geq |t_{obs}|$. The p value is calculated as $p = 1 - \mathrm{ASL}$. The null hypothesis is rejected if $p < 0.05$, indicating a significant change in the climate variable across the two scenarios for the 30-year period. The sample sizes for X and Y were both 90 (3 ensembles over 30 years), with $N = 500$ bootstrap samples conducted to test for statistical significance.

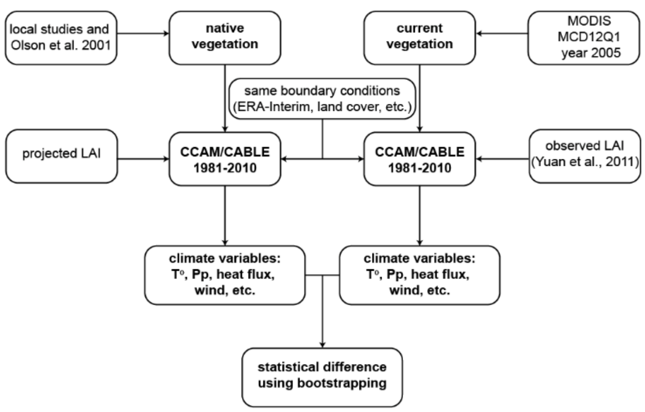

Figure 1. Conceptual model of methods used to identify the impacts of historic deforestation over the climate of non-Amazonian South America (for details see section 2.3.1).

2.3.2 Model experiments

For the modelling experiments, CCAM was driven by ERA-Interim reanalysis (Dee et al., 2011). This reanalysis was chosen in order to reduce the noise and maximize the local signal of deforestation. A recent evaluation of ERA-Interim reanalysis over the central Andes for winter temperature and precipitation showed a good correspondence with the gridded observations from Climate Research Unit (CRU) in terms of interannual variability (Rusticucci et al., 2014). Evaluations of ERA-Interim over different regions have resulted in good agreements with observed surface temperature (Mooney et al., 2011; Wang et al., 2014).

The dynamical downscaling was performed using the scale-selective filter proposed by Thatcher and McGregor (2009). The scale-selective downscaling approach allows consistency between the

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host model and model simulation at larger scales by replacing atmospheric fields at a spectral domain greater than a particular length scale (Radu et al., 2008; Thatcher and McGregor, 2009). This technique allows the model to freely develop regional-scale features consistent with the large-scale ones driven by the reanalysis and results are independent of the domain size (Thatcher and McGregor, 2009). In this study, CCAM used a scale cut-off configuration of about 24°, corrected every 6 hours above 850 hPa (about 1.5 km above the surface), allowing to assess the impact of land cover change on surface climate both near the surface and at scales less than the cut-off.

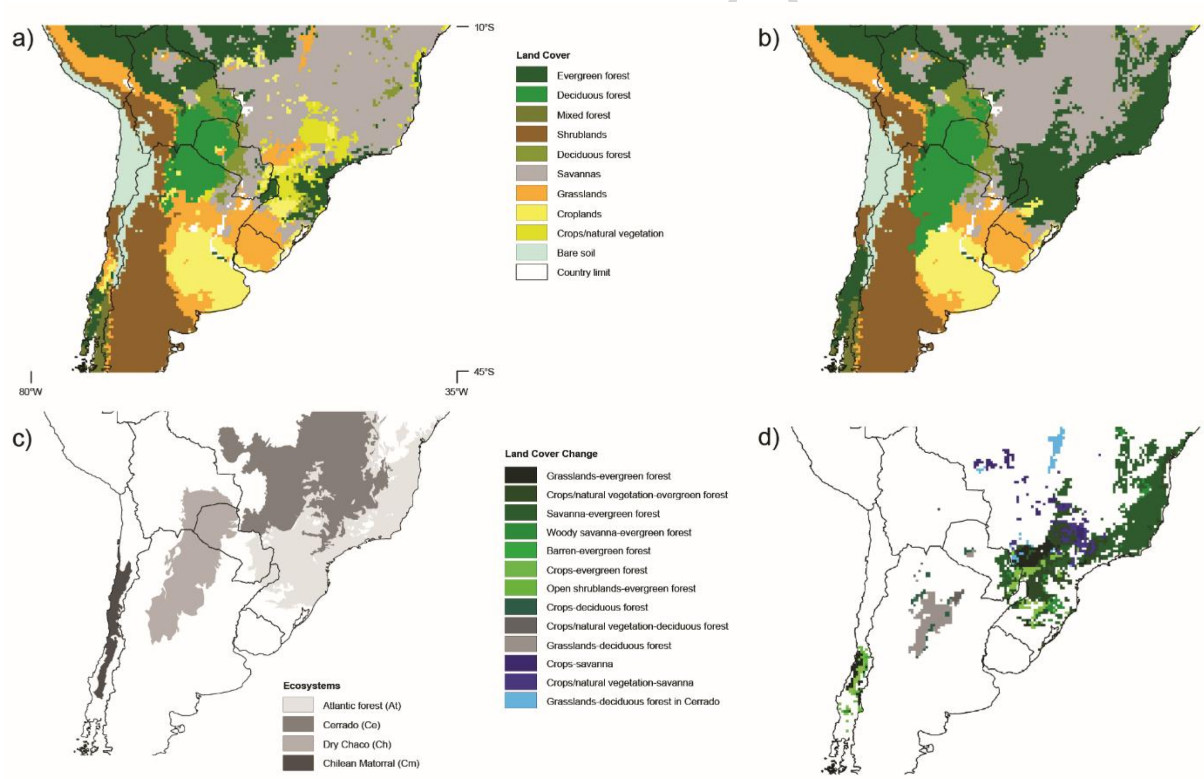

Figure 2. Land cover maps used in modelling experiments. a) Land cover map for CONTROL (CNTRL) experiment taken from MODIS MCD12Q1 for 2005; b) land cover map for NATURAL (NAT) experiment projected according to literature and the Olson et al. (2001) classification for non-Amazonian South America. Cerrado land cover is taken from MMA/IBAMA (2011); c) boundaries of the regions considered in this study; and d) main changes (CNTRL-NAT) in vegetation between experiments. The green colour scale in map d) shows conversions of evergreen forest to other land uses, the grey scale shows conversion from deciduous forest, and the blue colour scale shows conversion of savanna vegetation and deciduous forest in the Cerrado.

In this study, we focused on the climate effects on regions representing a variety of biomes considered the most historically impacted by deforestation (Salazar et al., 2015) and for which there are still little research in relation to LUCC impacts on the regional climate and how these vary

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spatially and seasonally. We did not focus on the effects of specific conversions between different land uses since these interactions have been addressed by other studies in South America (e.g. Beltrán-Przekurat et al., 2012; Pongratz et al., 2006).

Table 1. Main vegetation types for CNTRL and NAT model simulations, and equivalent MODIS classification scheme for four regions of non-Amazonian South America.

Region	CNTRL vegetation	Biome	NAT vegetation according to MODIS MCD12Q1
Atlantic Forest	Crops, grassland, savanna	Tropical and subtropical moist broadleaf forest (Câmara, 2003; Oliveira-Filho and Fontes, 2000)	Evergreen broadleaf forest
Cerrado	Crops, grassland	Tropical and subtropical savanna (Eiten, 1972)	Savanna
Dry Chaco	Crops, grassland	Tropical and subtropical broadleaf dry forest (Pennington et al., 2000; Prado, 1993).	Deciduous forest
Chilean Matorral	Crops, grassland, open shrubland	Mediterranean forest (Luebert and Pliscoff, 2006).	Evergreen broadleaf forest

3 Results

In this section, we describe the changes in the land surface characteristics, heat fluxes, temperature, precipitation and moisture for present day conditions relative to the natural scenario. Mean changes correspond to the variables averaged across ensemble members for each experiment (CNTRL minus NAT). We present results according to dry and wet seasons. In eastern southern South America (Atlantic Forest, Cerrado and Dry Chaco), the dry season corresponds to austral winter (JJA) while in the Chilean Matorral it corresponds to austral summer (DJF). This pattern reverses in the wet season. Complementary variables are shown in Table 1 of the Appendix.

3.1 Change in surface characteristics

The changes in natural vegetation cover were related to changes in LAI, roughness length and albedo. All regions showed a decrease in the LAI for both the dry and wet seasons (Fig. 3). The Atlantic Forest presented the greatest mean decrease with 1.54±1.01 and 1.28±0.99 in the dry and wet season, respectively (Table 2). Here, reductions in LAI were largest when crops and savannas replaced evergreen broadleaf forest (down to 4.5 in the dry season and 4.6 in the wet season (Fig. 3)). The Chilean Matorral registered the second largest decrease in LAI in the dry season associated with the conversion of evergreen broadleaf forest to crops and grasslands used for pastures (1.04±0.58). Similarly, in the Cerrado, the main differences in LAI were in the dry season, particularly in those areas where savannas were replaced by crops (0.84±0.74, Table 2). The Dry Chaco represented the smallest change in mean LAI during the dry season with 0.04±0.07 and only few pixels showed a change (Fig. 3).

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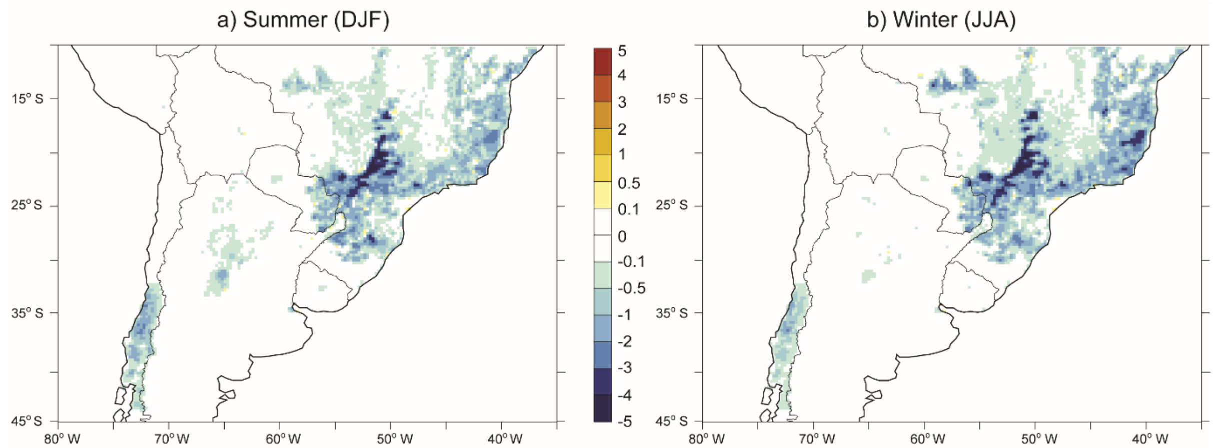

Figure 3. Seasonal changes (CNTRL-NAT) in Leaf Area Index (LAI, dimensionless) for non-Amazonian South America.

Table 2. Mean differences ± standard deviation (CNTRL – NAT) for seasonal leaf area index (LAI), roughness length (Z_o) and albedo (α, dimensionless) in four regions of non-Amazonian South America.

Region	Dry Season			Wet Season		
	LAI	Z_o (m)	α	LAI	Z_o (m)	α
Atlantic Forest	-1.54 ± 1.01	-2.00 ± 0.43	-0.0038 ± 0.01	-1.28 ± 0.99	-1.98 ± 0.40	0.0003 ± 0.01
Cerrado	-0.84 ± 0.74	-0.32 ± 0.47	-0.0073 ± 0.01	-0.60 ± 0.45	-0.30 ± 0.46	-0.003 ± 0.01
Dry Chaco	-0.04 ± 0.07	-1.85 ± 0.51	0.0014 ± 0.002	-0.24 ± 0.29	-1.29 ± 0.34	0.0012 ± 0.003
Chilean Matorral	-1.04 ± 0.58	-1.75 ± 0.72	-0.0078 ± 0.01	-0.64 ± 0.43	-2.09 ± 0.87	0.0143 ± 0.03

The change in LAI was related to a general decrease in roughness length. In CABLE the roughness length depends on the canopy height (35 m for evergreen broadleaf forest and 0.6 m for grass and crops) and LAI. Therefore, changes in vegetation cover were associated with changes in low level winds and heat fluxes (Fig. 7-d and 4, $p < 0.05$). Again, the Atlantic Forest showed the greatest decrease in roughness length with an average of 2±0.43 m in the dry season and 1.98±0.4 m during the wet season. A large reduction in roughness length also occurred in the Chilean Matorral with 1.75±0.72 m in the dry season and 2.09±0.87 m in the wet season. Likewise, in the Dry Chaco the roughness length decreased -1.85 ± 0.51 and -1.29 ± 0.34 in the dry and wet season, respectively. The Cerrado registered the smallest mean reduction in roughness length in both the dry (-0.32 ± 0.47) and wet (0.30±0.46 m) seasons (Table 2). Changes in albedo between the experiments showed contrasting results. While in the Cerrado albedo respectively decreased between 7 and 15% in the dry and wet season, in the Dry Chaco it increased between 6 and 6%. Decreases between 1 and 8%

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were recorded for the Atlantic Forest and the Chilean Matorral in the dry season, while in the wet season albedo decreased between 1 and 16% in the same regions.

3.2 Change in heat fluxes

3.2.1 Dry season

CCAM shows a high contrast in heat fluxes response after deforestation. Because these are closely influenced by variations in the LAI, the geographical extent of changes was concurrent. However, orography and distance from the coast seem to be also important factors in the heat flux response that requires further research. Figure 4 shows the significant changes ($p < 0.05$) in sensible (H) and latent (LH) heat fluxes for non-Amazonian South America. During the dry season, the Cerrado and the Dry Chaco recorded a strong increase in H of about 12 and 15%, respectively. In the Cerrado, significant increments in H were found in western areas where crops and grasslands replaced savanna vegetation, while in the Dry Chaco the main changes occurred where herbaceous vegetation replaced deciduous forests (Fig. 4-a, Table 3). The Atlantic Forest and the Chilean Matorral registered a decrease in H by about 1% in areas previously covered by evergreen forest (Fig. 2-b, 4-a).

Reductions in LH were more consistent than H across all regions, with changes ranging between 3 and 8%. In the Cerrado, changes in LH were conspicuous. These corresponded with reduced LAI and conversion of natural savannas to crops and grasslands (Fig. 3). Likewise, significant decreases in LH were observed in the Chilean Matorral (5%) in areas near the Pacific coast (Fig. 4). Less negative changes in LH were observed for the Atlantic Forest and the Dry Chaco with 3 and 5%, respectively. In the Atlantic Forest, the main reduction was located in the western areas, also concordant with the greatest decrease in LAI and in the second largest changes located in the central region of the Atlantic Forests (Fig. 4-b).

These changes in the partitioning of sensible and latent heat are represented by changes in the Bowen ratio, which showed consistent increments across all regions. They indicate that, despite small reductions of H in the Atlantic Forest and the Chilean Matorral, declines in LH were greater in magnitude and hence, with current vegetation, more energy is used in heating the surface rather than in evapo-transpirative cooling. The last recorded the largest increase in the Bowen ration during the dry season with 0.35±0.54, followed by the Cerrado with 0.19± 0.24 and the Dry Chaco with 0.06±0.29. For the Atlantic Forest, the Bowen ratio increased by 0.06±0.31, mainly due to the reductions in LH.

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Table 3. Mean differences ± standard deviation (CNTRL – NAT) for seasonal sensible (H) and latent (LH) heat fluxes, and proportional changes for Bowen ratio (β=H/LH, dimensionless) averaged for each region of non-Amazonian South America.

Region	Dry Season			Wet Season		
	H (w/m^2)	LH (w/m^2)	β	H (w/m^2)	LH (w/m^2)	β
Atlantic Forest	-0.18 ± 1.2	-1.45 ± 1.4	0.06± 0.31	-2.09 ± 1.5	0.56 ± 1.6	-0.04 ± 0.08
Cerrado	3.82 ± 1.3	-4.21 ± 1.7	0.19± 0.24	-0.83 ± 0.6	1.91 ± 1.4	-0.01 ± 0.02
Dry Chaco	1.48 ± 1.1	-1.13 ± 1.3	0.06± 0.29	-0.41 ± 2.4	1.30 ± 2.5	-0.01 ± 0.13
Chilean Matorral	-1.83 ± 2.3	-2.82 ± 2.1	0.35 ± 0.54	2.94 ± 0.7	-4.31 ± 0.8	-0.004 ± 0.11

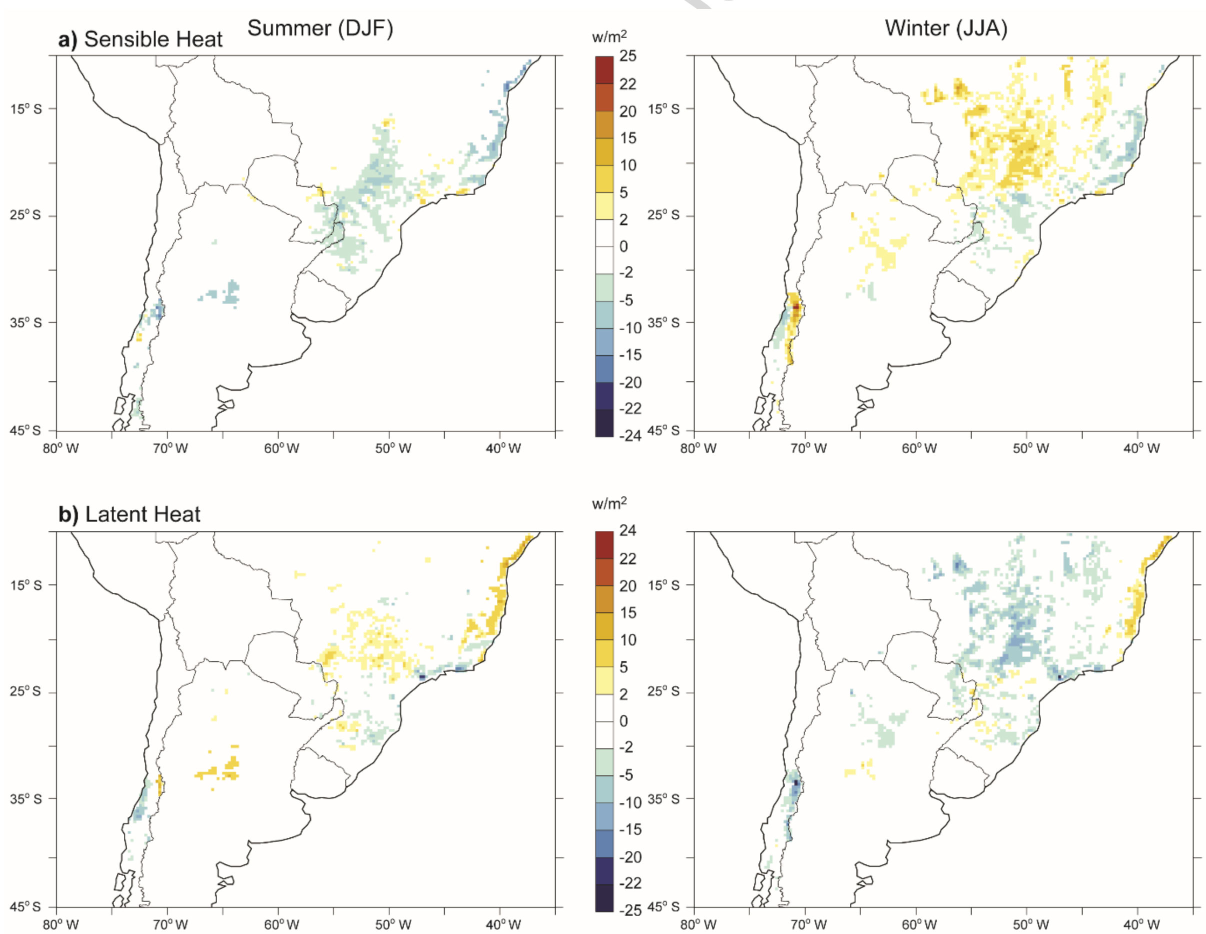

Figure 4. Differences in the seasonal means (CNTRL-NAT) for sensible (H) and latent heat flux (LH) across non-Amazonian South America. Differences are expressed as w/m^2. In the Chilean Matorral, the summer and winter correspond to the dry and wet season, respectively. This pattern is opposite for the Atlantic Forest, Cerrado and Dry Chaco. Only pixels that are statistically significant at a 95% confidence level are shown.

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3.2.2 Wet season

During the wet season, changes in heat fluxes generally showed the opposite trend to the dry season and were less in magnitude and more variable (expressed by the larger standard deviation). The only exception was the Chilean Matorral (in winter) which recorded a significant increase in sensible heat (37%) and the greatest seasonal mean reduction in latent heat (12%). In eastern South America, results showed a decrease in sensible heat (H), with the Atlantic Forest and the Cerrado showing the greatest reductions with 7 and 6%, respectively. These reductions corresponded with areas experiencing the greatest changes in LAI where herbaceous vegetation replaced evergreen forest and natural savannas. In the Atlantic Forest, a reduction in sensible heat was recorded near the coast, while in the Cerrado, changes located in the easternmost areas (Fig. 4-a, Summer). The Dry Chaco registered the smallest decrease in sensible heat for the wet season with significant changes located in the southernmost areas of the region (Fig. 4-a, Summer).

In eastern South America (Atlantic Forest, Cerrado and Dry Chaco), changes in latent heat flux (LH) showed the opposite pattern of H in areas where natural vegetation was converted to herbaceous vegetation (crops/grasslands). Yet the increments were less in magnitude compared to H, ranging between 1 and 2%. The Cerrado showed the greatest increment in LH, while in both the Atlantic Forest and the Dry Chaco, positive mean changes of +1% were recorded, particularly in coastal areas in the first and in the southernmost tip of the Dry Chaco (Fig. 4-b, Summer). For these regions, the Bowen ratio tends to decrease during the wet season. These decreases indicate that more energy was used for evapo-transpirative cooling rather than heating the planetary boundary layer. The Atlantic Forest registered the greatest reduction trend in the Bowen ratio with 0.04±0.08, followed by the Cerrado and the Dry Chaco with 0.01±0.02 and 0.01±0.13 w/m^2, respectively. By contrast, during the wet season (winter), the Chilean Matorral showed a positive change in the Bowen ratio by about 0.004±0.11. Yet this change was highly variable (Table 3).

3.3 Change in surface temperature

3.3.1 Dry season

According to CCAM, deforestation resulted in significant differences ($p < 0.05$) in average surface temperatures in all regions (Fig. 5). These changes were prominent in the dry season for both eastern and western southern South America. The Chilean Matorral showed the greatest mean increase in surface temperature in the dry season with 1.42±0.17 °C (Fig. 5). A significant warming of up to 4 °C occurred in central areas, particularly where crops and grasslands replaced evergreen

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forest. The conversion of natural savannas in the Cerrado resulted in a warming increase of 0.68±0.17 °C that was also coincident with strong reductions in the LAI. The Atlantic Forest also showed significant increase in surface temperature corresponding to areas with the highest reductions in LAI. A mean temperature increase of 0.52±0.16 °C was observed when evergreen broadleaf forest was replaced with herbaceous (crops, grasslands and savannas) vegetation. There was a warming reaching up to 2 °C in the westernmost areas of the Atlantic Forest, and coincident with the greatest reductions in LAI (Fig. 3 and 5). On the contrary, the Dry Chaco showed a cooling in surface temperature by 0.01±0.24 °C in the hilly areas of Sierras de Córdoba, although this was less significant and highly variable compared to other regions.

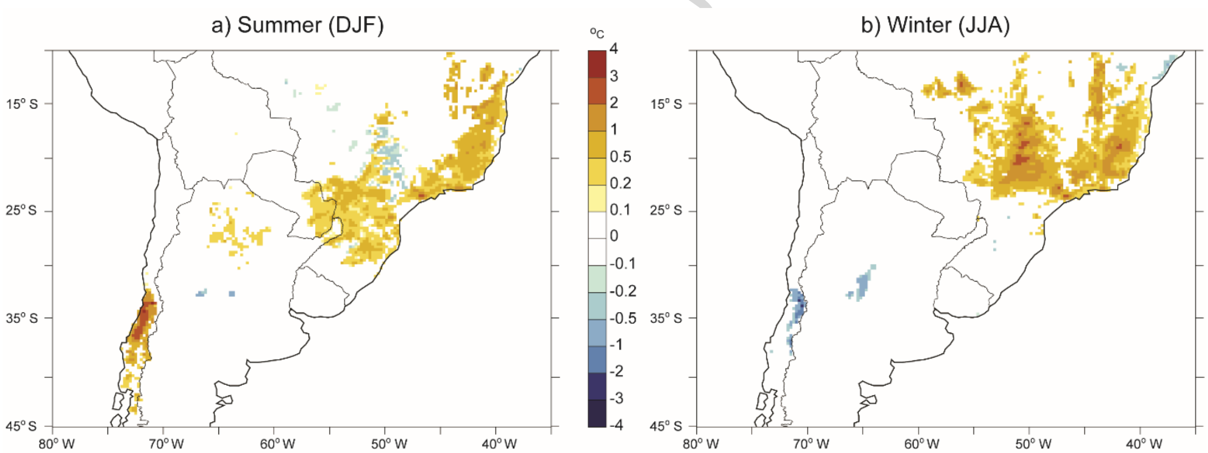

Figure 5. Significant differences of seasonal mean (CNTRL-NAT) for surface temperature (°C) across non-Amazonian South America. In eastern southern South America (Atlantic Forest, Cerrado and Dry Chaco) the dry season corresponds to austral winter (JJA) while in the Chilean Matorral corresponds to austral summer (DJF). This pattern reverses in the wet season. Only pixels that are statistically significant at a 95% confidence level are shown.

3.3.2 Wet season

During the wet season, the Atlantic Forest showed a significant warming of 0.5±0.12 °C in surface temperature which coincided with areas of highest deforestation (Fig. 5-a). Similarly, the Dry Chaco experienced a significant warming of 0.2±0.19 °C, particularly in the northern areas (Fig. 5). However, it also showed a decrease in surface temperature in southern hilly areas where deciduous forests were replaced by grasslands and crops (Fig. 5). Likewise, for the Cerrado a slight cooling in surface temperature of 0.02±0.09 °C was recorded, particularly in those areas adjacent to the Atlantic Forest and was coincident with a replacement of savanna vegetation by crops. The Chilean

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Matorral also experienced a cooling in surface temperature of 0.37±0.18 °C, particularly near the Andes foothills.

Table 4. Mean differences ± standard deviation (CNTRL – NAT) for seasonal surface temperature and precipitation in four regions of non-Amazonian South America.

Region	Dry Season		Wet Season	
	Temperature (C°)	Precipitation (mm/month)	Temperature (C°)	Precipitation (mm/month)
Atlantic Forest	0.52 ± 0.16	-1.75 ± 3.39	0.5 ± 0.12	5.69 ± 6.40
Cerrado	0.68 ± 0.17	-0.49 ± 1.39	-0.02 ± 0.09	-0.35 ± 6.40
Dry Chaco	-0.01 ± 0.24	-0.96 ± 1.32	0.2 ± 0.19	1.55 ± 8.62
Chilean Matorral	1.42 ± 0.17	-0.47 ± 1.52	-0.37 ± 0.18	-2.58 ± 11.16

3.4 Change in precipitation and moisture

3.4.1 Precipitation

Figure 6 shows the mean differences in total precipitation for each of non-Amazonian South America. In general, modelled changes in precipitation showed a low significance due to the high variability of the rainfall response, particularly during the wet season (Fig. 6-a).

Dry Season

All regions showed a mean decrease in total precipitation during the dry season (Fig. 6-a). The Dry Chaco had the greatest reduction in precipitation with the current land cover conditions having 10% less rain relative to the natural vegetation conditions. These reductions were concentrated in the northern area of deforestation (Fig. 6-a). Similarly, both the Atlantic Forest and the Cerrado showed a rainfall reduction of approximately 5%. However, only a small number of pixels were significant. Positive significant changes were observed in the northern coastal areas of Atlantic Forest, whilst the Cerrado did not record major significant changes (Fig. 6-a). The same pattern was present in the Chilean Matorral which showed a mean reduction in rainfall of 3%, but this was not significant.

A somewhat similar pattern was observed for convective precipitation, with the Atlantic Forest showing a significant increase of 27% in coastal and hilly areas (Table 4, Fig. 6-b). The Cerrado and the Dry Chaco showed a reduction of 6% while the Chilean Matorral showed a reduction of 2%. These changes were not significant.

Wet Season

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Changes in rainfall were more significant during the wet season (Fig. 6). The Atlantic Forest showed a significant increase in rainfall of 4%. A small but significant increase of 1% was observed in the southern extremity of the Dry Chaco. Similarly, a small significant reduction of 0.2% was observed in parts of the Cerrado. The Chilean Matorral did not experience significant changes during the wet season.

Changes in convective precipitation during the wet season followed a similar pattern of total rainfall, but over a larger area (Fig. 6-b). The increase in convective precipitation was the greatest in the Atlantic Forest with a mean increase of 10% after deforestation. Smaller both positive and negative changes were recorded for the Cerrado and the Dry Chaco (Fig. 6-b).

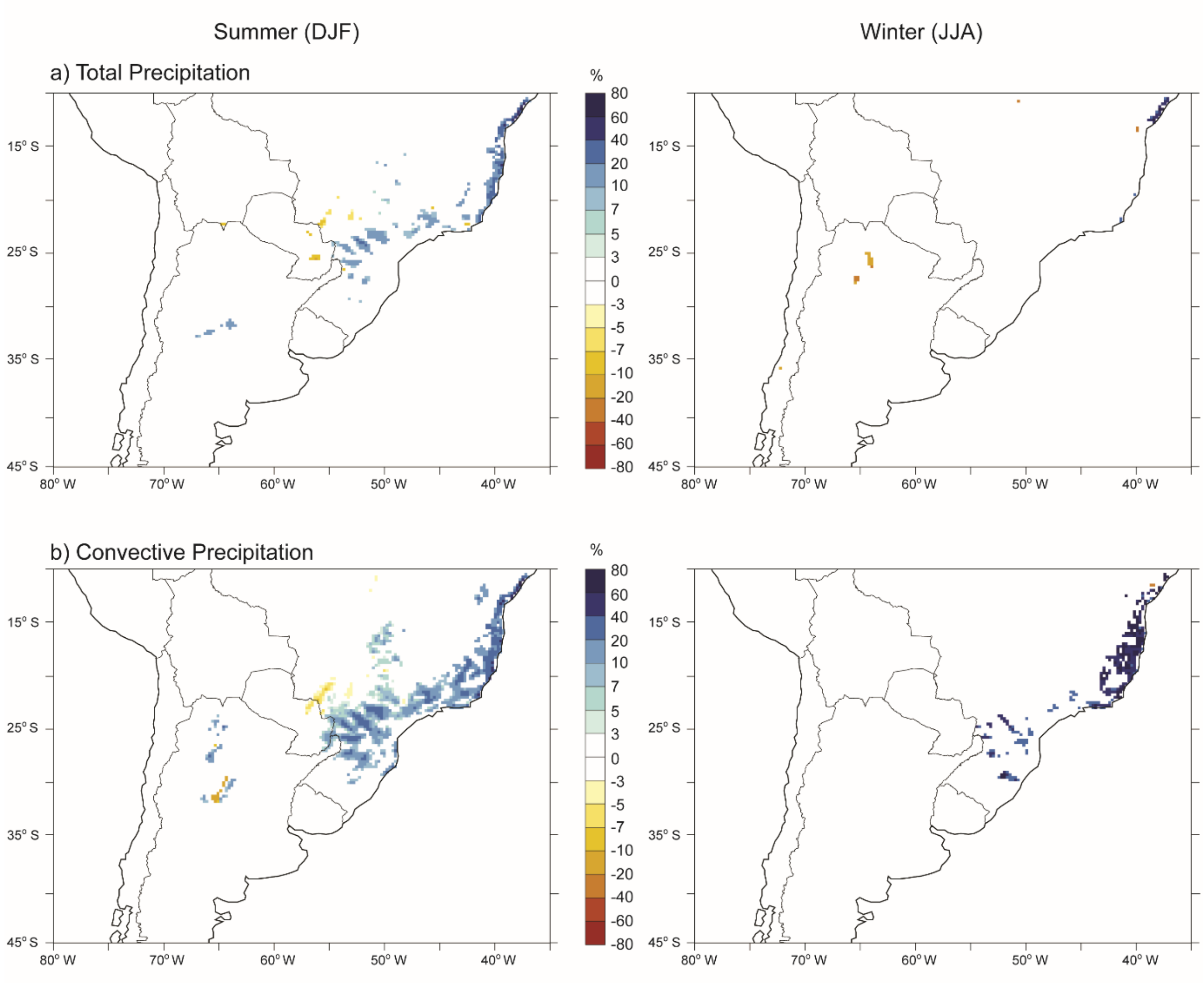

Figure 6. Mean changes in: a) total precipitation (%) and b) convective precipitation (%) between CNTRL and NAT experiments for non-Amazonian South America. The areas shown are those significant at 95% confidence level ($p < 0.05$).

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3.4.2 Changes in atmospheric and soil moisture

Dry Season

Changes in precipitation were accompanied by a significant decrease in atmospheric moisture and were concurrent to areas of deforestation. These reductions were strongest where forests were converted to herbaceous vegetation. The Cerrado showed the greatest reductions of 8% in evapotranspiration, which located in those areas of reduced precipitation (Fig. 7-a). Evapotranspiration in the Chilean Matorral decreased by 5%, mostly in areas were herbaceous vegetation replaced evergreen forest (Fig. 7-a). Smaller reductions were recorded for the Atlantic Forest (3%) and the Dry Chaco (4%). With the exception of the Atlantic Forest, which recorded an increase in average plant respiration CO_2 flux, all regions registered a reduction in respiration of between 3 and 30%, indicating that decreased evapotranspiration is strongly influence by plant respiration during the dry season (Fig. 7-f). Changes in evapotranspiration were observed following the same pattern of changes in latent heat.

Spatial and temporal variations in evapotranspiration were accompanied by a reduction in relative humidity. CCAM showed significant decreases in humidity throughout non-Amazonian South America (Fig. 7-b). These were evident in areas with significant changes in surface temperature. The Atlantic Forest and the Cerrado registered the greatest mean reductions of 6%, with maximum reaching 22% coinciding with areas experiencing the greatest reductions in LAI (Fig. 3 and 8-b). The Chilean Matorral experienced a mean 2% mean reduction in relative humidity after conversion of forest to herbaceous vegetation. The Dry Chaco experienced a 2% reduction in relative humidity although southern hilly areas showed a small increase (Fig. 7-b).

The Atlantic Forest showed the greatest increase in potential evaporation (Fig. 7-a). Mean increases of 202% were recorded, though with positive changes up to fifteen fold in its eastern areas. Significant changes were also observed in the Chilean Matorral, which registered mean growths of 99% in potential evaporation during the dry season. Mean increases of 94% were recorded in the Cerrado, while the Dry Chaco registered a registered a smaller increase compared to the other regions. These changes in potential evaporation are associated to significant changes soil moisture, which showed reductions across all regions (Fig. 7-d, e).

The Cerrado registered the largest reduction in soil moisture of 11%, followed by the Atlantic Forest (6%) and the Chilean Matorral (4%), whilst a reduction of 1% was observed in the Dry Chaco during the dry season. These changes in soil moisture were associated with a significant reduction in evapotranspiration (Fig. 7-a, Table 1 in Appendix), which registered strong negative

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changes after deforestation. The changes were significant for all regions and as expected were correlated with variations in latent heat.

Wet Season

Increments in evapotranspiration were observed across eastern South America, though these ranged from 1-2%. For the Cerrado and the Dry Chaco, this change matched significant reductions of 26-32% in average plant respiration CO_2 flux, which indicates that most of increased evapotranspiration came from evaporation rather than transpiration (Fig. 7-a, d). The Chilean Matorral recorded a mean reduction of 12% in evapotranspiration without mean changes in average plant respiration CO_2 flux (Appendix, Table 1)

The Atlantic Forest experienced significant reductions of about 6% in relative humidity. By contrast, humidity did not show a significant change for the Cerrado (Fig. 7-b). Changes in relative humidity in the Dry Chaco were larger than in the dry season, with mean changes of -5% corresponding with deforested areas (Fig. 7-b). The Chilean Matorral showed a reduction of 3% with a slight increase observed in the northern Matorral.

Similar to the dry season, the wet season potential evaporation significantly increased over all regions with the Atlantic Forest showing the greatest mean increase of 88%, followed by the Cerrado (42%) and the Dry Chaco (32%). The Chilean Matorral recorded the smallest increase of 3% in potential evaporation during the wet season. As for the dry season, soil moisture decreased by 1-3% in most regions. By contrast, the Chilean Matorral showed an increase of 1% in soil moisture corresponding with areas of decreased potential evaporation and increased evapotranspiration, mostly in the Andes foothills (Fig. 7-a).

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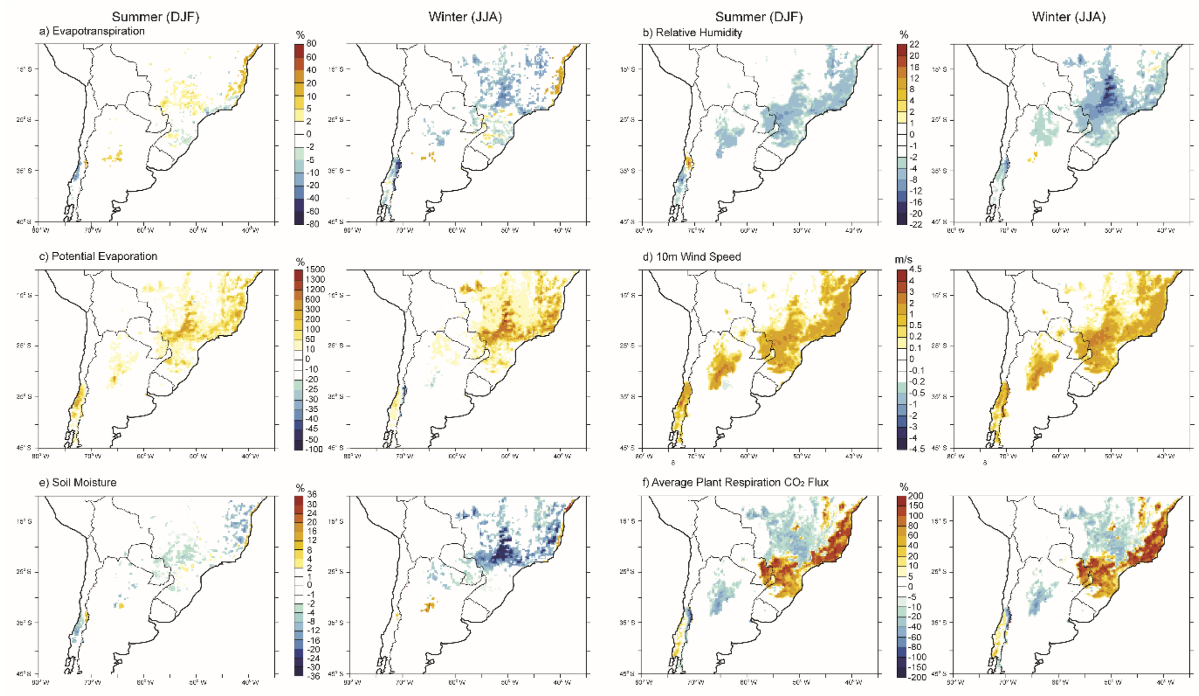

Figure 7. Seasonal significant changes for a) evapotranspiration (%), b) surface relative humidity (%), c) potential evaporation (%), d) 10 m wind speed (m/s), e) top level soil moisture (%); and f) average plant respiration CO_2 flux (%). Summer (DJF) corresponds to the dry season in the Chilean Matorral and the wet season in eastern South America (Atlantic Forest, Cerrado and Dry Chaco). This pattern changes in winter (JJA). Only pixels that are statistically significant at a 95% confidence level are shown.

4 Discussion

4.1 Key findings

Overall, the results support the alternative hypothesis that deforestation has significant impacts on the land–atmosphere interactions in non-Amazonian South America. However, there was considerable spatial and seasonal variability of the climate response, with changes in surface temperature and precipitation varying across regions and seasons in the 30 years of analysis. The key findings of our study are: i) deforestation has modified key characteristics of the non-Amazonia land surface that affect surface-atmosphere coupling. For different biomes distributed in four key regions, we estimated reductions in the leaf area index of between 6 and 48% and reductions in roughness length of between 70 and 89%; ii) effects on heat fluxes and surface temperature show high intra-regional and seasonal variability. In the Atlantic Forest and Chilean Matorral sensible and latent fluxes tend to decrease during the dry season. Temperature variation manifests through a change of between -0.01 °C and +1.42 °C during the dry season and between -0.37 °C and +0.5 °C

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during the wet season. Temperature increase in the Atlantic Forest, Cerrado and Chilean Matorral were significant; iii) changes in precipitation showed low significance and high variability, indicating that other factors independent of forest cover control total precipitation. Though the combination of changes in roughness length and hilly areas seems to play a role in precipitation; and iv) deforestation has a significant impact on atmospheric and soil moisture in both seasons as expressed by a decrease of between 2 and 6% in relative humidity, an increase of 1 to 202% in potential evapotranspiration and a reduction of 1 to 6% in soil moisture. All these changes are more significant during the dry season, which tends to be drier and warmer after deforestation.

4.2 Contribution

This study differs from previous studies in three main aspects. First, we estimate natural vegetation for regions whose boundaries approach the original extent of natural communities prior to major LUCC (Olson et al., 2001). This compares to the modelled historical vegetation maps that, though they describe the global distribution of main vegetation types, they do not accurately describe natural vegetation in South America (e.g. Ramankutty and Foley, 1999). Second, we include those areas recognized as the most impacted by deforestation and least studied in terms of related climatic impacts. Finally, we used the CCAM model at 25 km spatial resolution using the ERA-Interim reanalysis (Dee et al., 2011) in combination with changes in vegetation cover and land surface characteristics. This approach allowed us to show significant regional and seasonal differences in the climate response to deforestation. In particular, we found variations across biomes, the potential influence of topography on the effect of deforestation for the Atlantic Forest and the Chilean Matorral, and the less sensitivity of rainfall compared to surface temperature for both the dry and wet season. In this regard, natural vegetation cover is more important to the hydrological cycle when the water is limited. Results from this study are in line with observations that show changes in vegetation cover have an important influence on the surface temperature and is particularly relevant in semi-arid regions where small changes in vegetation can have significant impacts on surface temperature and hence the water cycle (Mildrexler et al., 2011; Oyama and Nobre, 2004).

The results of this study are conditional on a number of limitations. First, the land cover map that shows present vegetation cover is developed for 2005 and does not capture recent LUCC processes such as those described by Hansen et al. (2013). Another limitation is the ability of surface models such as CABLE to accurately describe the diversity of functional vegetation types and land uses at regional scales. In addition, the lack of observation of fluxes and other prognosis variables at the same spatial and temporal scale of the model predictions makes it difficult to validate the results

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(Wang et al., 2011). This is particularly important for South America, which has been consistently described as a region that lacks of enough observation platforms to validate climate models projections (Magrin, 2014). In the following sections, we discuss the main findings and explain the underlying mechanisms for each of the regions addressed in this work.

4.3 Atlantic Forest

Changes in land-atmosphere interactions for the Atlantic Forest were spatially concurrent with deforestation. In general, results in the dry season were more robust and less variable compared to the wet season. During the dry season, variations in surface temperature can be explained by a reduced cooling capacity through sensible and latent heat fluxes, which finally warms the surface. Increased surface and soil temperature could also have strong influences on modelled moisture fluxes in the Atlantic Forest for both seasons. In the dry season, deforestation significantly decreases atmospheric and soil moisture. Strong increments in 10 m wind speed also influence moisture dynamics by transporting the moisture from the evaporating surfaces, which in turn increases potential evaporation.

The only previous study relating deforestation and the surface climate was conducted by Webb et al. (2005). The authors used weather station data in the state of São Paulo to identify links between deforestation and precipitation. Though they did not find significant relationships between forest cover and total rainfall, forest cover was positively related to the number of rain days. In our study, associations between deforestation and precipitation were more evident. However, the link is rather complex and it appears that distance from the coast and orography are key factors explaining the modelled precipitation patterns after deforestation. During the wet season (summer), the change in precipitation occurs in pixels located mainly near the Atlantic coast and at high elevations. Our results agree with those from Webb et al. (2005) indicating that distance to the coast in combination with elevation may exert strong influences on the precipitation pattern of the Atlantic Forest. As shown in Figure 8, there is a high proportion of significant pixels presenting an increased precipitation in the first 100 km from the coastline, with the next peak occurring at the highest elevation level (700 m) and decreasing towards the interior where the number of significant pixels showing a decreased precipitation seems to increase. These factors may act in combination with deforestation to significantly decrease surface roughness and increases 10 m easterly winds speed (Fig. 7-d), which boosts the moisture transport from the coast to the Atlantic Plateau where increased condensation occurs. The complex interactions between orography, deforestation and

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precipitation still remain as an understudied field in vegetation climate feedbacks studies and more work needs to be done to elucidate these interactions in the Atlantic Forest.

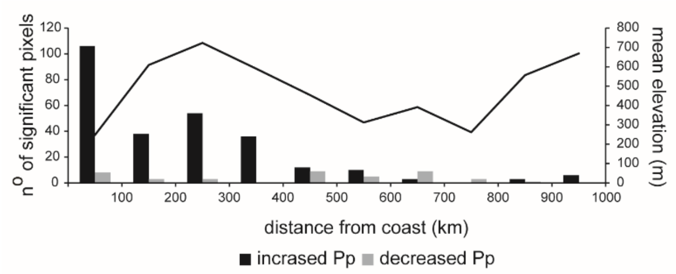

Figure 8. Number of significant pixels ($p < 0.05$) in relation to distance from the coast and elevation in the Atlantic Forest during the wet season (DJF). Bars represent number of significant pixels for increased (black) and decreased (grey) precipitation (Pp) after deforestation. The line refers to elevation taken from the CCAM model output expressed as the mean elevation for each distance range.

4.4 The Cerrado

Small differences in surface roughness in the Cerrado are explained by small differences in canopy height between crops/grassland and savannas or the low proportion (10%) of forests in savanna type biomes considered in CABLE. Consequently, small significant differences emerge in heat and moisture fluxes, particularly during the wet season, though these differences are more conspicuous during the dry season. Here, the increase in temperature and heat fluxes was accompanied by a decrease in total precipitation and changes in soil moisture, humidity, convection, and a general decrease in atmospheric moisture content (Fig 7). Compared to the Atlantic Forest, coastal influences are less important and even low changes in the leaf area index can trigger significant atmospheric responses on the surface. This suggests that changes in latent heat fluxes can drive main atmospheric alterations to deforestation in the Cerrado. The overall result is a drier atmosphere and a more intense dry season.

These results agree with others studies in the Cerrado using other climate and surface models. For instance, Georgescu et al. (2013) modelled a warming after conversion of natural vegetation to sugarcane and a decrease in evapotranspiration and rainfall. Also, Lee et al. (2011), using an atmospheric model, found that climatic consequences of LUCC in the Cerrado occurs primarily during the dry season and are expressed through mean changes in surface temperature of about +0.7 °C during the dry season (in agreement with our results) and a drier atmosphere that according to the authors would stimulate more intense and frequent droughts in the Cerrado. This trend in temperature and moisture change from modelling approaches is confirmed by observations

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conducted by Loarie et al. (2011) using satellite images over the entire Cerrado. The authors measured a mean increase of 1.55 °C and an evapotranspiration change of -0.6 mm/day when natural vegetation was converted to crops/pastures. This temperature response was mostly influenced by evapotranspiration rather than albedo changes. In our study, though mean albedo decreases for the Cerrado in both seasons, the mean increment in surface temperature during the dry season confirms the results from modelling and observations in terms of the higher relative importance of evapotranspiration on the surface temperature. As shown here, small changes in land cover can significantly affect the surface climate in the Cerrado.

4.5 Dry Chaco

In the Dry Chaco, the magnitude and spatial extent of the changes in surface characteristics is not as high as the Cerrado and Atlantic Forest. Differences in LAI are almost absent during the dry season and very low during the wet season. Therefore, variations in surface temperature in both periods are the lowest in non-Amazonian South America. The temperature during the wet season appears to be more sensitive to changes in vegetation than the dry season, possible because in the Dry Chaco deciduousness occurs during the last and no major changes in the leaf area index (Fig. 3). Under the current land cover conditions, the difference between soil and surface temperature was 0° C implying that surface temperature approaches soil temperature after deforestation, affecting evapotranspiration rates and relative humidity. Though differences in latent and sensible heat fluxes were not significant, average plant respiration CO_2 flux for the Dry Chaco decreased 28% during the wet season, which indicates that increased evapotranspiration is mostly driven by increased soil evaporation than plant transpiration. During the dry season, differences between the sensible and latent heat fluxes become significant but absolute differences are less than 5 w/m^2 and no major increments in surface temperature were observed despite a 14% increase in the Bowen ratio. By contrast, surface temperature decreases in the southern tip of the Dry Chaco, which is consistent with increments in latent heat flux, relative humidity and soil moisture. The possible mechanism that explains these increments in moisture and ultimate precipitation in this area could be related to increased northerly and westerly 10 m wind speed carrying moisture from deforested areas (Fig. 7-d) that finally condenses in the hilly areas of the southern Dry Chaco.

Other studies from the Dry Chaco describe similar patterns of temperature and precipitation response after deforestation. For example, Houspanossian et al. (2013), using satellite data, portray a mean diurnal temperature difference of +2.5 °C between dry forests and crops in the Dry Chaco, despite a 50% higher albedo of crops compared to forests. Similarly, the modelling study of

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Canziani and Carbajal Benitez (2012) found increments in surface temperature < 1 °C in deforested areas and beyond, without significant changes in precipitation. Even though LUCC climate feedbacks studies in the Dry Chaco are very scarce, the available evidence suggests that the near surface atmosphere is sensitive to the loss of natural vegetation with main changes expressed through modifications of surface characteristics and consequently partitioning of the available energy between sensible and latent heat fluxes, which together affect surface temperature and moisture recycling, yet without impacts on local precipitation. Because the extensive ongoing process of deforestation of the Dry Chaco, more research needs to be conducted to account for the potential climatic impacts of historic and future deforestation.

4.6 Chilean Matorral

Differences in surface characteristics in the Chilean Matorral are the second largest in non-Amazonian South America (after the Atlantic Forest) and the consequences for the surface climate are also high in magnitude, especially during the dry season. The region registers the greatest increment in surface temperature and the greatest decrease in mean precipitation (yet not significant). For the first, since heat fluxes decrease, in combination with a strong reduction in roughness length, a weaker coupling between the canopy and air temperature arises. This reduces the surface capacity to cool down through sensible and latent heat, which finally increases surface temperature significantly.

Although seasonal precipitation change after deforestation is not significant in the Chilean Matorral, the increase in moisture flux seems to be enforced in the foothills of the Andes Mountains. The mechanism related to this could be the same as the Atlantic Forest in terms of the importance of orography in the moisture transport. Precipitation in Chile is strongly influenced by zonal winds carrying moisture from the Pacific Ocean (Garreaud et al., 2009; Viale and Garreaud, 2015) and deforestation weakens the local influence of vegetation on the climate by increasing surface wind speed (because of a reduced roughness length) strengths the ocean influence that transport moisture up to the Andes and could explain the increased latent heat flux, increased soil moisture, and decreased temperature in those areas.

As in other regions of non-Amazonian South America, the process of deforestation in the Chilean Matorral increase overall dryness, predominantly during the dry season. Because this region is semi-arid and therefore sensitive to droughts and desertification, it can be argued that the loss of natural vegetation has increased the drying and potentially desertification process through significant changes in the hydrological cycle including surface temperature, evaporation rates, soil

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moisture content and atmospheric humidity. The strong increments in surface temperature projected by CCAM in the Chilean Matorral highlights the potential importance of surface vegetation over this scalar, which is higher compared to the increments without considering deforestation processes (Rosenbüth et al., 1997). Recent studies have described a drying trend in south-central Chile. For instance, Falvey and Garreaud (2009) analysed observational data to characterize the spatial pattern of surface temperature change in coastal and continental Chile. In the Central Valley, a region coincident with the Chilean Matorral, the authors report a temperature change of 0.18±0.14 °C/decade in the period 1979-2006. We report a temperature change of 1.42±0.17 °C considering only land cover change. Because deforestation can be a rapid and extensive process, the subsequent effect over surface temperature can be noticeable within a decade. This is important because it suggests that vegetation management in the Chilean Matorral could be a key factor that could dampen or enhance the local effects of global warming. However, the only previous study relating vegetation change with subsequent changes on the lower atmosphere focused on the impacts of irrigated agriculture in the northernmost extremity of Central Chile (Montecinos et al., 2008). Our study is the first attempting to identify the climatic impacts of historic deforestation at a local/regional scale in the Chilean Matorral and hence more research needs to be conducted to confirm the results presented here.

5 Summary and Conclusions

We have addressed the main impacts of deforestation on the surface climate of four regions of non-Amazonian South America representative of distinct biomes. These regions, particularly the Atlantic Forest and the Chilean Matorral, have been subjected to intensive pressures since the arrival of the first European settlers and are currently the most affected in relation to their original extent (Salazar et al., 2015). The replacement of natural vegetation by grasslands and crops has affected surface characteristics, the exchange of heat and ultimately the surface temperature and precipitation. The main findings can be summarized as follows:

1. Historic deforestation influences the partitioning of surface energy into sensible and latent heat flux. Changes in these fluxes are significant and more pronounced during the dry season in all biomes and are characterised by strong increases in sensible heat flux. During the wet season deforestation results in a decrease of the Bowen ratio because available energy is transferred to the near surface atmosphere through latent heat flux more than sensible heat flux. However, this water vapour transfer comes mainly from soil evaporation rather than photosynthetic transpiration, as shown by a general decrease in average plant CO_2 flux for the Cerrado, Dry

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Chaco and Chilean Matorral. In addition, increase in evapotranspiration during the wet season indicates that soil moisture is rapidly transferred into the atmosphere through latent heat flux, yet this moisture flux is still less than increased potential evaporation. After deforestation, there is a decrease in the vegetation control of water infiltration into the soils that decreases overall soil water retention. Hence, in the wet season there is less moisture on the soil after vegetation change. This pattern is many levels of magnitude greater during the dry season. Here, the Bowen ratio increases in the Cerrado, the Dry Chaco and the Chilean Matorral, with the first and the second showing the greatest increments.

2. Deforestation-climate interactions in non-Amazonian South America are complex. This complexity is added by the variety of vegetation types, the orographic effect of the Brazilian Plateau and the Andes, which is important in atmospheric circulation at a continental level. According to this study, surface climate interactions in the Atlantic Forest seem to be strongly influenced by orography and Atlantic Ocean vicinity. Similarly, our results suggest that the Chilean Matorral is strongly influenced by the proximity of both the Pacific Ocean and the Andes Mountains. However, the climatic changes in the Cerrado and the Dry Chaco depend more in evapotranspirative factors, due to their continentally. However, the impacts of historic deforestation on precipitation, as shown by the results, indicate that precipitation is partially influenced but not governed by changes in forest cover.

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APENDIX

Table 1. Mean differences (CNTRL-NAT, 3 ensembles each) of key variables in non-Amazonian South America. Values are expressed in original units as mean ± standard deviation. Soil moisture was converted to litre (m^3x1000) to facilitate representation. Means and standard deviation of sensible and latent heat fluxes are shown in Table 2 of the main text.

Ecosystems/variables	Atlantic Forest		Cerrado		Dry Chaco		Chilean Matorral	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
Evapotranspiration (mm/year)	7.08±20.02	-18.22±17.11	23.93±16.97	-52.79±21.08	16.31±31.36	-14.16±15.94	-35.42±26.75	-54.08±10.01
Potential evaporation (w/m^2)	31.13±3.10	98.87±4.60	13.47±1.62	132.12±9.19	48.88±13.62	1.18±8.68	340.94±10.35	0.96±1.75
Relative humidity (pp*)	-5±0.47	-4.81±0.75	-1.35±0.27	-4.56±1.19	-3.68±1.09	-1.31±1.00	-1.29±0.72	-3.13±0.44
Soil temperature (°C)	1.35±0.13	0.80±0.17	-0.03±0.10	0.76±0.19	0.93±0.21	0.04±0.24	1.87±0.18	-0.22±0.17
Soil moisture (lt/lt)	-4.94±4.21	-14.17±5.10	-3.61±2.54	-20.27±5.39	-5.97±6.56	-2.06±7.78	-6.19±2.56	2.37±5.11
10m wind speed (m/s)	1.40±0.03	1.45±0.03	0.33±0.03	0.44±0.03	1.50±0.03	1.40±0.02	1.30±0.02	1.20±0.04
Net radiation (w/m^2)	-1.29±1.44	-1.71±2.04	1.49±1.59	0.48±2.16	1.89±0.98	0.10±1.14	-3.99±1.49	-2.95±1.58
Ground storage (w/m^2)	0.01±0.43	-0.07±0.46	-0.19±0.08	0.31±0.08	0.10±1.24	-0.05±0.3	0.29±1.21	-0.75±0.62
Bowen ratio (w/m^2)	-0.03±0.06	0.05±0.18	-0.01±0.03	0.16±0.13	-0.01±0.02	0.05±0.04	0.27±0.44	0.03±0.05
Plant respiration CO_2 flux ($gC/m^2/s$)	1.2E-05±8.9E-07	8.8E-06±7.2E-07	-1.2E-05±1.2E-06	-9.4E-06±1.2E-06	-5.7E-06±7E-07	-1.7E-06±4.2E-07	-3.4E-07±8.4E-07	1.8E-08±3.3E-07

*pp=percentage points

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Highlights

- Modelling study of the climatic impacts of deforestation across South American biomes
- Significant increase in surface temperature between 0.7 and 1.4 °C
- Dry season is drier and wormer after deforestation in all biomes
- Deforestation significantly changes land surface-atmosphere interactions

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