THE INFLUENCE OF FOREST COVER CHANGE ON DECADAL LAND SURFACE TEMPERATURE CHANGES IN THE BRAZILIAN AMAZON

Marcus V. F. Silveira[1], *Luiz E. O. C. Aragão*[1,2], *Celso von Randow*[3]

[1]Remote Sensing Program (PGSER), Earth Observation and Geoinformatics Division (DIOTG), National Institute for Space Research (INPE) – São José dos Campos, Brazil; marcus.silveira@inpe.br,
[2]College of Life and Environmental Sciences, University of Exeter, Exeter, United Kingdom; luiz.aragao@inpe.br,
[3]Earth System Sciences Centre, National Institute for Space Research (INPE) – São José dos Campos, Brazil;
celso.vonrandow@inpe.br

ABSTRACT

Deforestation disrupts ecosystem services provided by forests at a regional scale, such as surface temperature regulation. This study evaluated how changes in land surface temperature (LST) from 2003 to 2021 across the Brazilian Amazon varied according to the rate of forest cover change and the amount of regional forest cover. To do so, we used LST data from MODIS, land cover data from MapBiomas, and divided the Amazon region into grid cells of 0.5° spatial resolution. We observed a gradual rise in the incidence and intensity of decadal LST warming as the rate of forest loss increased. The influence of deforestation on LST warming was remarkable in areas where the initial forest cover was greater than 40% and forest cover loss was greater than 0.5 percentage points per year on average. Our findings provide supporting information for forest restoration and conservation initiatives aiming for climate change adaptation.

***Key words* —** Deforestation, climate change, Amazonia, LST, ecosystem services.

1. INTRODUCTION

Global surface temperature in the last two decades (2001-2020) was 0.99 ºC warmer than in 1850-1900, mostly due to human-induced greenhouse gas emissions [1]. At regional scales, human-induced land-use/land cover change can also play an important role in surface temperature changes, moderating or amplifying the effects from global warming [1]. Large-scale tropical deforestation, for instance, can increase regional surface temperature by reducing latent heat (from evapotranspiration) and increasing sensible heat fluxes from earth's surface to the atmosphere [2].

In the Brazilian Amazon, where forest cover is currently 12% lower than in 1985 [3], studies have been showing an increase in the annual mean land surface temperature in the order of 0.44-1.25 ºC at local scales due to deforestation [4,5]. However, large-scale observational assessments of changes in land surface temperature (LST) across the Amazon and the link to deforestation are still incipient. Critical points still lacking clarification include identifying where LST has warmed with more intensity, and how the intensity of LST changes varied with the intensity of forest loss and the amount of forest cover in a region.

Observational evidence from these points can help to indicate where and how forest restoration and conservation projects can be more successful for climate change adaptation strategies. They can also help to improve the ability of regional models in projecting deforestation impacts on climate.

The objective of this study was to evaluate how forest cover and forest loss influenced changes in land surface temperature across the Brazilian Amazon from 2003 to 2021. First, we provided a spatially-explicit quantification of land surface temperature changes across the Brazilian Amazon territory. Next, we assessed the variability of changes in land surface temperature according to the intensity of forest loss and the initial amount of forest cover.

2. MATERIAL AND METHODS

2.1. Study area

Our study focused on the *Amazonia sensu lato* [6] limits of Brazil. This region covers the entire lowland rainforest biome within the Brazilian Amazon. We divided the study area into grid cells of 0.5° spatial resolution (~55 km) to use these cells as samples sharing the same spatial scale in our analyses.

2.2. Remote sensing products

We used land surface temperature (LST) data from the Moderate Imaging Resolution Spectrometer (MODIS) MYD11A1 Version 6.1 product derived from the Aqua satellite. This product provides daily LST estimates with 1 km spatial resolution based on thermal infrared observations under clear-sky conditions. We selected only daytime LST estimates with the highest level of accuracy as flagged by the product (LST error ≤ 1 K) [7]. The Aqua satellite crosses the equator approximately at 1:30 pm in its daytime passage, providing observations closer to the maximum daily temperature compared to the Terra satellite, which crosses the equator around 10:30 am.

For forest cover data we used the annual classification provided by MapBiomas Collection 7 [3], which has 30 m spatial resolution, selecting only pixels classified as Forest Formation.

For each grid cell of our study area and each year of our time series, we computed the percentage of the area covered with forests and the annual mean daytime LST.

2.3. Analysis

We computed the slope of the 2003-2021 time series of forest cover and mean LST for each grid cell, based on the Theil-Sen estimator. This nonparametric method computes the median slope of all pairs of points in the time series, thus indicating the average rate of change per unit of time. Because we are working with annual values and forest cover as a percentage, Sen's slopes in this case indicate the average rate of change as percentage points (pp) per year. Negative slopes of forest cover change indicate forest loss over time, whereas positive slopes indicate forest gains. LST slopes were initially computed from annual values but multiplied by 10 to indicate the average rate of change in ºC per decade. Additionally, we used the Mann-Kendall test to assess the significance at the 0.1 level of monotonic increasing or decreasing trends in the time series.

To understand the influence of forest cover change on LST changes, we divided our grid cells into groups according to intervals of change in forest cover, quantifying the percentage of cells with significant positive, significant negative, or non-significant trends in LST in each group. We selected only cells with a significant trend in forest cover for this analysis. We also tested for differences in the magnitude of LST warming in each group, based on pairwise Mann–Whitney *U* tests at the 0.05 significance level. P-values were adjusted with the False Discovery Rate (FDR) method. To understand how the relationship between LST change and forest cover change varied based on the amount of regional forest cover, we divided the cells with both significant positive trends in LST and significant trends in forest cover into groups according to intervals of forest cover at the beginning of the time series. For each group we performed linear regressions with the LST slope as the dependent variable and the forest cover change slope as the explanatory variable.

3. RESULTS

We found that annual mean daytime land surface temperature (LST) has been increasing on average by 0.4 ºC per decade across the Brazilian Amazon since 2003, reaching a maximum of 2.3 ºC decade^{-1} in some areas. About 42% of the territory had significant positive trends in LST at the 0.1 level, 57% had non-significant LST trends, and only 0.27% had significant negative trends. From 2003 to 2021, the mean forest cover percentage changed from 79% to 72% in areas with significant positive LST trends, from 40% to 39% in areas with significant negative LST trends, and from 78% to 77% in areas with non-significant LST trends.

Significant positive LST trends were mostly prevalent in southern Brazilian Amazon, mainly in northern Rondônia state, where annual mean LST has been increasing by more than 1.5 ºC per decade on average. In northern Mato Grosso state and some areas in southern Pará state, LST increases of more than 1 ºC decade^{-1} were also widespread (Figure 1).

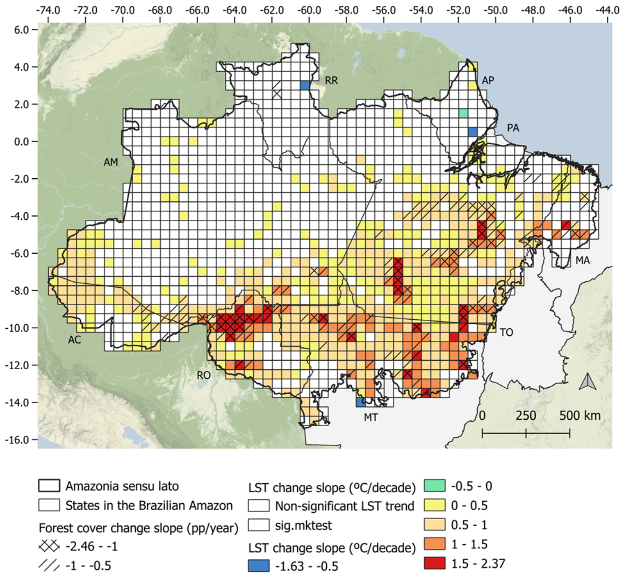

Figure 1. Average rate of change (ºC/decade) in annual mean daytime land surface temperature (LST) in the Brazilian Amazon from 2003 to 2021. Blank cells had non-significant trends in LST at the 0.1 level based on the Mann-Kendall test. Hashed cells indicate areas where forest cover decreased on average by more than 0.5 percentage points year^{-1}.

With respect to forest cover trends, areas where forest cover decreased by more than -1 percentage points (pp) per year were prevalent in northern Rondônia and across Pará (Figure 1). Other locations in which forest cover decreased more than -0.5 pp year^{-1} on average include northern Mato Grosso, Maranhão, and eastern Acre states.

The greater the magnitude of forest loss, the greater was the incidence of areas with significant positive LST trends. In areas where forest cover decreased on average by 0 to -0.05 per year, only 27% of grid cells had significant positive LST trends. Where forest cover decreased in the order of -0.25 to -0.5 pp year^{-1} on average, 69% of cells had significant positive LST trends, in contrast to 97% of cells in areas where forest cover decreased more than -1 pp year^{-1}. Although not as prevalent as areas with forest loss, there were some areas with gains in forest cover up to 0.5 pp year^{-1} on average. In these areas, over 73% of cells had non-significant LST trends and only 27% had significant positive trends.

Considering only areas with significant positive LST trends, the greatest increases in LST were generally found in areas with the greatest decreases in forest cover. The mean increase in annual mean daytime LST was 1.55 ºC decade^{-1} where forest cover decreased by -1 to -2.5 pp year^{-1}, 0.97 ºC decade^{-1} where forest cover decreased by -0.5 to -1 pp year^{-1}, and 0.49 ºC decade^{-1} where forest cover decreased only up to -0.05 pp year^{-1}. In areas where forest cover increased from 0.05 to 0.5 pp year^{-1}, LST warming was not statistically different from those where forest cover decreased up to -0.5 pp year (Figure 2a).

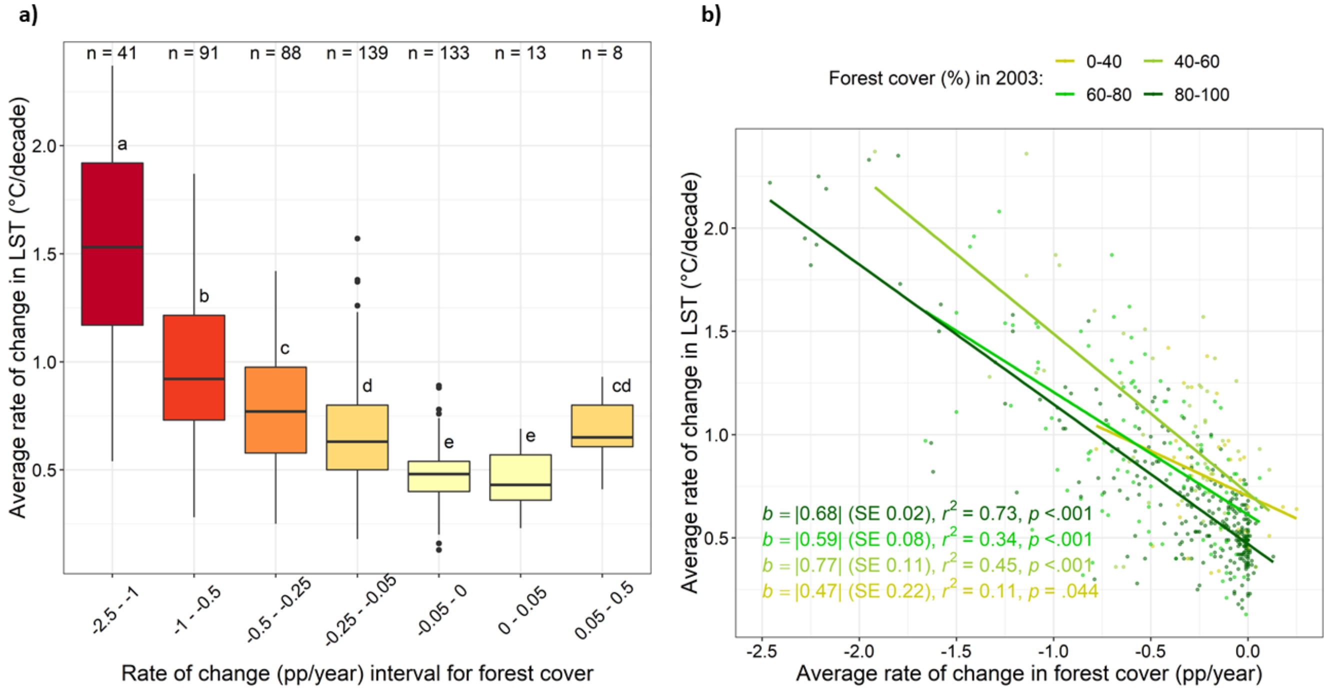

Figure 2. a) Distribution of Sen's slopes of annual mean daytime land surface temperature (LST) for groups of grid cells in the Brazilian Amazon divided by intervals of forest cover change slopes (percentage point/year) during 2003-2021. Negative forest cover change slopes indicate forest loss, and positive slopes indicate gains in forest cover. Letters above the boxplots indicate statistical differences among groups, based on pairwise Mann-Whitney *U* tests at the 0.05 significance level. b) Fitted linear regression lines of LST slopes as the dependent variable and forest cover change slopes as the explanatory variable. Grid cells were grouped by the initial range of forest cover in the time series.

In areas where the initial forest cover was up to 40%, the intensity of LST warming was weekly dependent on the intensity of forest cover loss (r^2 = 0.11, p =.044). The magnitude of forest loss explained one third to less than half of the variation in the intensity of LST warming where the initial forest cover ranged from 40% to 80%, and 73% of the variation where the initial forest cover ranged from 80-100% (Figure 2b). In areas with more than 80% of forest cover, for every 1% increase in the average rate of forest loss per year, there was a 0.68 ºC average increase in LST per decade, based on the absolute value of the regression coefficient. Among all groups of cells divided by the initial range in forest cover, the intensity of LST warming was generally the lowest where the initial forest cover ranged from 80-100%. In this group, the mean LST increase was 0.62 ºC decade^{-1}, whereas in the other forest cover groups it ranged from 0.73 ºC (in the 0-40% group) to 0.96 ºC (in the 40-60% group) decade^{-1}.

4. DISCUSSION

In this study we demonstrated, through different approaches, how deforestation had a major contribution to drive changes in annual mean daytime land surface temperature (LST) across the Brazilian Amazon during the last two decades. However, our findings suggest that the influence of deforestation at a regional scale was remarkable only in areas with more than 40% of initial forest cover, and when the percentage of forest cover decreased more than 0.5 percentage points per year on average.

When forests are not the dominant land cover in a region, changes in the energy fluxes as a result of deforestation may have secondary importance to alter LST regionally when there are also ongoing changes in the dominant land cover. Although we did not explore differences in landscape composition in this study, pasturelands have been historically the major substitute of forests in the Brazilian Amazon, but losing area to soybean expansion in the southern part of the region during the last two decades [8]. As shown by [5], croplands are on average 1 ºC warmer than pasturelands. As a result, pasture to cropland transitions can be a major driving force to LST increases in regions where forest cover is less than 40%.

Although the majority of areas with forest gains had non-significant changes in LST, a minor portion presented significant LST increases in the same order of magnitude as areas losing forest cover up to 0.5 pp year^{-1} on average. It is likely that, for the observed rates of regional forest gain, drivers of LST warming other than deforestation could have offset or surpassed the cooling effect of reforestation from increased evapotranspiration. Some of these other potential drivers of LST warming include the decreased surface albedo from forest cover gain and increases in downward solar or thermal radiation.

Further research can explore quantitatively the influence of these other drivers to the observed LST warming in the Amazon, in contrast to that of deforestation. If we attempt to isolate the influence of deforestation on annual mean LST by subtracting the average LST increase in highly deforested areas from that in areas where forest cover remained nearly unaltered (0 to -0.05 pp change per year on average), our findings suggest that deforestation led to an average 1 ºC regional increase in annual mean LST per decade where forest cover decreased more than 1 pp per year on average.

Increases in daytime temperature at the soil plus canopy surface, as evaluated in this study, were previously shown to present a good relationship with increases in the maximum 2 m surface air temperature in Brazil, though the rates of change tend to be slightly positively biased [9]. This coupled warming of land and air surface temperature can drive an increase in evapotranspiration due to the increased atmospheric evaporative demand, decreasing soil moisture and increasing drought severity as a result [1]. As we showed an increased dependence of the intensity of LST warming on deforestation according to how extensive was the amount of regional forest cover, the intensification of deforestation into Amazon's forest frontiers can contribute to decrease the resilience of remaining forests in these regions, making them more vulnerable to extreme drought events and wildfires in a long-term.

5. CONCLUSION

This study indicated that the northern portion of Rondônia and Mato Grosso states are the main regions in the Brazilian Amazon with the highest increases in annual mean land surface temperature during the last two decades. These are therefore the regions where forest restoration projects aiming for climate change adaptation could be mostly necessary. We did not observe a colling effect in Amazon's reforested areas at a regional scale. Although our findings demand further exploration, they suggest initially that large-scale forest restoration projects should seek larger rates of forest gain in a long-term if they intend to provide forest cooling benefits at a regional scale. Nonetheless, our findings provide strong evidence for the major influence of deforestation on land surface warming in the Amazon, with an overall increase in the incidence and intensity of land surface warming as the rate of forest loss increased. This contribution of deforestation is strong when the regional forest cover is greater than 40%, and becomes clearly distinguishable from that of other potential drivers of surface warming when the percentage of forest cover decreased more than 0.5 percentage points per year on average. Our findings stress the importance of safeguarding Amazon's remaining forests from illegal deforestation to avoid the amplification of negative climate impacts from global warming and the loss of forest resilience at a regional level.

6. ACKNOWLEDGMENTS

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