

Supplementary Information

Observed shifts in regional climate linked to Amazon deforestation

Marcus V. F. Silveira^{1*}; Patrick W. Keys²; Anderson Ruhoff³, Paulo Artaxo⁴, Marcos H. Costa⁵, Liana O. Anderson¹, Marcos Adami¹, Celso von Randow⁶, Luiz E. O. C. Aragão^{1,7}

1 Earth Observation and Geoinformatics Division (DIOTG), National Institute for Space Research (INPE), São José dos Campos, Brazil

2 Department of Earth & Environment, Boston University, Boston, United States of America

3 Institute of Hydraulic Research, Federal University of Rio Grande do Sul (UFRGS), Porto Alegre, Brazil

4 Institute of Physics, University of São Paulo (USP), São Paulo, Brazil

5 Department of Agricultural Engineering, Federal University of Viçosa (UFV), Viçosa, Brazil

6 Earth System Science Coordination, National Institute for Space Research (INPE), São José dos Campos, Brazil

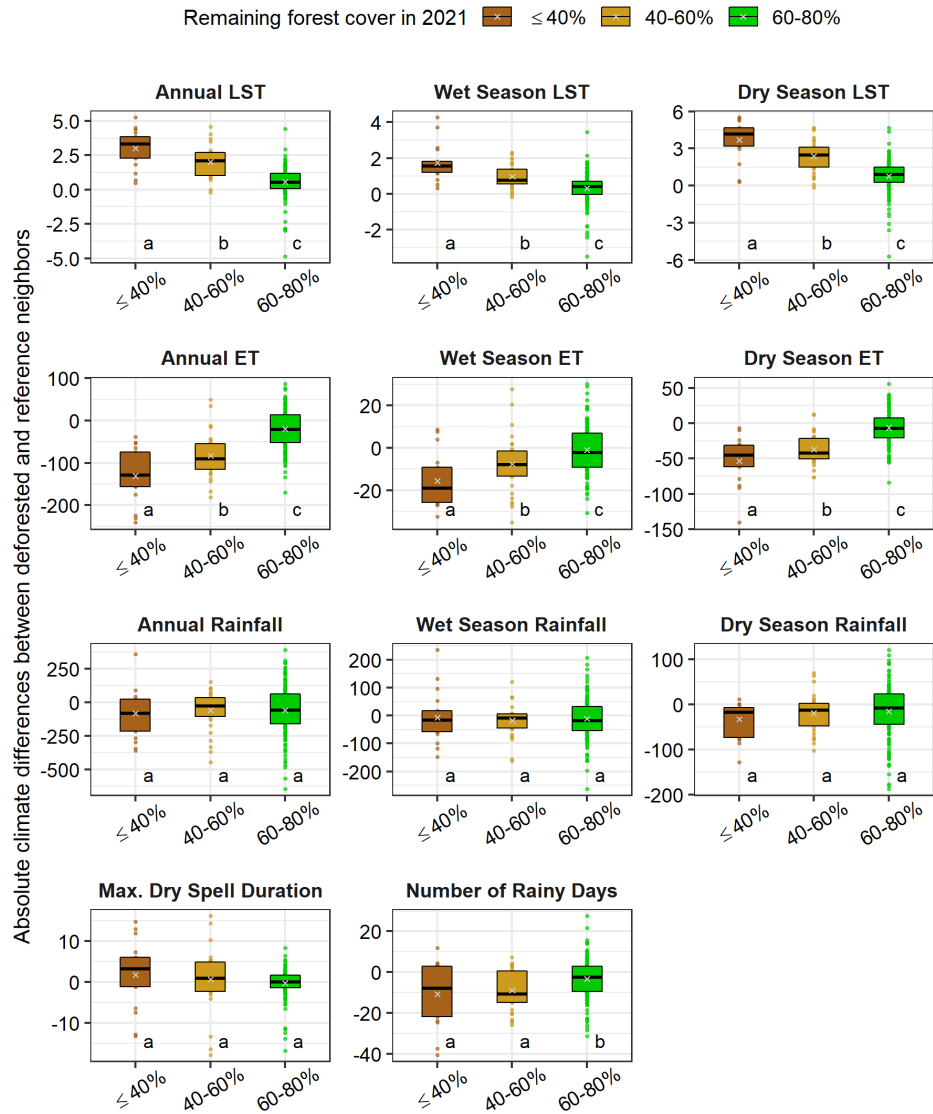
7 University of Exeter, College of Life and Environmental Sciences, Exeter, United Kingdom

*Correspondence: marcus.silveira@inpe.br

Supplementary Table 1. The distribution of climate differences between deforested cells from each deforestation group ($\leq 40\%$, 40-60%, 60-80% forest cover) versus reference neighboring cells (forest cover $>80\%$) was compared against the distribution of climate differences between reference versus reference neighboring cells. This table shows the p-values for the Two-Sample Kolmogorov-Smirnov test (KS-test), to test for differences in distribution, and the Welch's t-test, to test for differences in the mean of distributions. In the first columns for KS and Welch's t-tests, the distribution of climate differences between reference versus reference neighbors included only reference cells that were also neighboring deforested grid cells within a 3x3 window. In the second columns, we compared the original distribution of deforested versus reference neighbors against 1000 distributions of randomly sampled reference versus reference neighbors across the Amazon (these reference cells were not necessarily neighboring the selected deforested cells). We then computed the 95% confidence interval for the p-values of these 1000 comparisons. Statistical comparisons that are not significantly different at the 0.05 level are highlighted in bold.

Climate variable	Deforestation group vs. reference (forest cover $>80\%$)	KS-test	95% CI for KS-test with subsampling	Welch's t-test	95% CI for Welch's t-test with subsampling
Annual LST	$\leq 40\%$	$< .001$	$< .001$	$< .001$	$< .001$
	40-60%	$< .001$	$< .001$	$< .001$	$< .001$
	60-80%	$< .001$	$< .001$	0.012	$< .001$
Wet Season LST	$\leq 40\%$	$< .001$	$< .001$	$< .001$	$< .001$
	40-60%	$< .001$	$< .001$	$< .001$	$< .001$
	60-80%	$< .001$	$< .001$	0.017	$< .001$
Dry Season LST	$\leq 40\%$	$< .001$	$< .001$	$< .001$	$< .001$
	40-60%	$< .001$	$< .001$	$< .001$	$< .001$
	60-80%	$< .001$	$< .001$	$< .001$	$< .001$
Annual ET	$\leq 40\%$	$< .001$	$< .001$	$< .001$	$< .001$
	40-60%	$< .001$	$< .001$	$< .001$	$< .001$
	60-80%	$< .001$	$< .001$	0.043	$< .001$
Wet Season ET	$\leq 40\%$	$< .001$	$< .001$	$< .001$	$< .001$
	40-60%	0.003	$< .001$	0.009	.004 - .004
	60-80%	0.108	.001 - .002	0.583	.184 - .208
Dry Season ET	$\leq 40\%$	$< .001$	$< .001$	$< .001$	$< .001$
	40-60%	$< .001$	$< .001$	$< .001$	$< .001$
	60-80%	0.234	$< .001$	0.847	.013 - .016
Annual rainfall	up to 40%	0.186	.187 - .200	0.121	.117 - .125
	40-60%	0.253	.625 - .650	0.118	.123 - .137
	60-80%	0.037	.003 - .004	0.01	.024 - .031
Wet season rainfall	$\leq 40\%$	0.293	.189 - .203	0.869	.781 - .798
	40-60%	0.068	.124 - .140	0.208	.198 - .216
	60-80%	0.053	.047 - .057	0.186	.211 - .239
Dry season rainfall	$\leq 40\%$	0.007	.011 - .013	0.004	.008 - .009
	40-60%	0.069	.158 - .174	0.031	.076 - .086
	60-80%	0.037	.093 - .106	0.008	.047 - .059
Max. dry spell	$\leq 40\%$	0.004	.003 - .004	0.486	.377 - .384

duration	40-60%	0.016	.008 - .009	0.848	.635 - .650
	60-80%	0.819	.479 - .512	0.112	.539 - .573
Number of rainy days	≤ 40%	0.03	.013 - .014	0.024	.014 - .014
	40-60%	< 0.001	< .001	< .001	< .001
	60-80%	0.18	.008 - .010	0.042	.006 - 0.008

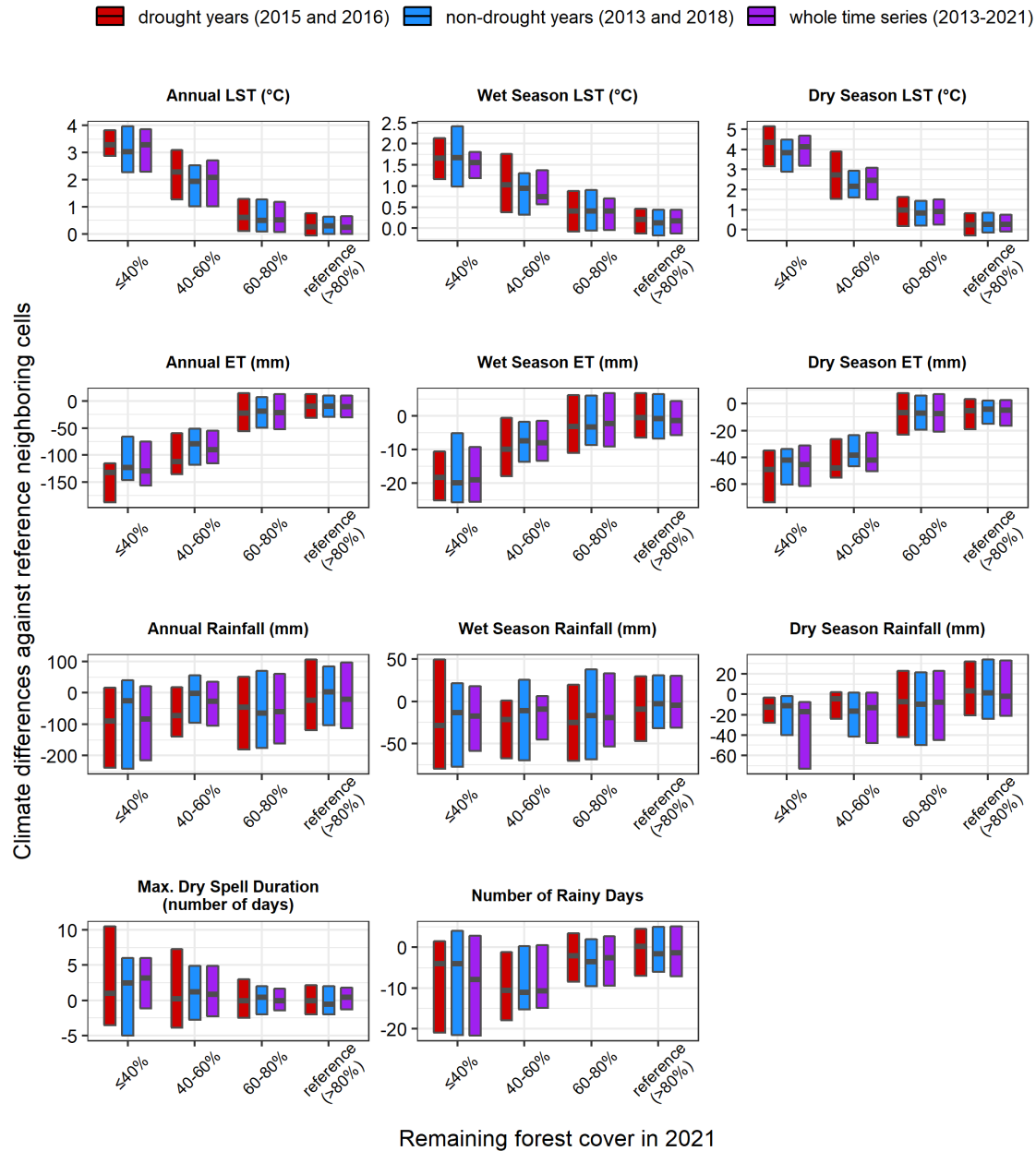


Supplementary Figure 1. Absolute climate differences between deforested cells and their reference neighboring cells. Values indicate the absolute difference in climate averages during 2013-2021 between deforested cells against their reference neighboring cells. Deforested cells were grouped by their remaining forest cover in 2021. Forest cover in reference cells was >80%. Upper and lower boundaries of each box indicate the third and first quartile of distributions. Horizontal lines indicate the median and cross marks the mean. Points show values beyond the first and third quartiles. Letters at the bottom represent the comparison among deforestation groups based on pairwise Welch's t-test at the 0.05 level. Number of samples: 17 for ≤40% forest cover versus reference, 30 for 40-60% forest cover versus reference, 163 for 60-80% forest cover versus reference, and 148 for reference versus reference.

Supplementary Table 2. The distribution of climate differences between deforested cells from each deforestation group ($\leq 40\%$, 40-60%, 60-80% forest cover) versus reference neighboring cells (forest cover $>80\%$) was compared against the distribution of climate differences between reference versus reference neighboring cells. This table shows the p-values for the Two-Sample Kolmogorov-Smirnov test (KS-test), to test for differences in distribution, and the Welch's t-test, to test for differences in the mean of distributions. These tests were performed considering climate averages during different time intervals to evaluate the influence of interannual climate variability in the comparison of climate averages. Statistical comparisons that are not significantly different at the 0.05 level are highlighted in bold.

Climate variable	Forest cover range	Whole time series (2013-2021)		Extreme drought years (2015 and 2016)		Non-drought years (2013 and 2018)	
		KS-test	Welch's t-test	KS-test	Welch's t-test	KS-test	Welch's t-test
Annual LST	$\leq 40\%$	< .001	< .001	< .001	< .001	<.001	<.001
	40-60%	< .001	< .001	< .001	< .001	<.001	<.001
	60-80%	< .001	0.012	< .001	0.006	<.001	0.015
Wet Season LST	$\leq 40\%$	< .001	< .001	< .001	< .001	<.001	<.001
	40-60%	< .001	< .001	< .001	< .001	<.001	<.001
	60-80%	< .001	0.017	< .001	0.032	<.001	0.004
Dry Season LST	up to 40%	< .001	< .001	< .001	< .001	<.001	<.001
	40-60%	< .001	< .001	< .001	< .001	<.001	<.001
	60-80%	< .001	< .001	< .001	<.001	<.001	<.0001
Annual ET	$\leq 40\%$	< .001	< .001	< .001	< .001	<.001	<.001
	40-60%	< .001	< .001	< .001	< .001	<.001	<.001
	60-80%	< .001	0.043	0.003	0.023	0.005	0.023
Wet Season ET	$\leq 40\%$	< .001	< .001	< .001	<.001	<.001	<.001
	40-60%	0.003	0.009	0.002	0.008	<.001	0.01
	60-80%	0.108	0.583	0.021	0.214	0.026	0.148
Dry Season ET	$\leq 40\%$	< .001	< .001	< .001	< .001	<.001	<.001
	40-60%	< .001	< .001	< .001	< .001	<.001	<.001
	60-80%	0.234	0.847	0.256	0.552	0.423	0.741
Annual rainfall	$\leq 40\%$	0.186	0.121	0.162	0.059	0.261	0.164
	40-60%	0.253	0.118	0.085	0.019	0.865	0.295
	60-80%	0.037	0.01	0.158	0.04	0.001	0.004
Wet season rainfall	$\leq 40\%$	0.293	0.869	0.231	0.659	0.391	0.92
	40-60%	0.068	0.208	0.131	0.025	0.049	0.48
	60-80%	0.053	0.186	0.012	0.05	0.003	0.085
Dry season rainfall	$\leq 40\%$	0.007	0.004	0.033	0.036	0.002	0.01
	40-60%	0.069	0.031	0.014	0.132	0.007	0.002
	60-80%	0.037	0.008	0.074	0.013	0.015	0.003

Max. dry spell duration	≤ 40%	0.004	0.486	0.04	0.629	0.146	0.321
	40-60%	0.016	0.848	0.041	0.569	0.07	0.606
	60-80%	0.819	0.112	0.92	0.681	0.748	0.154
Number of rainy days	≤ 40%	0.03	0.024	0.026	0.023	0.022	0.037
	40-60%	< 0.001	< .001	0.001	<.001	<.001	<.001
	60-80%	0.18	0.042	0.575	0.132	0.005	0.019

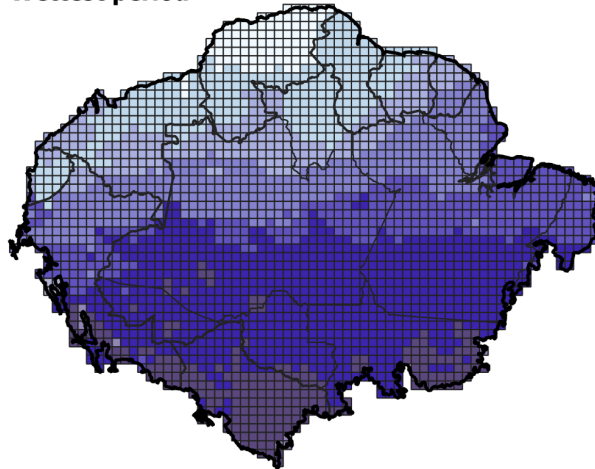


Supplementary Figure 2. Differences in the average of climate variables for grid cells in each forest cover range versus their neighboring reference grid cells (forest cover>80%). Climate differences were computed at different time intervals: drought years (2015 and 2016), non-drought years (2014 and 2018), and the whole time series (2013 to 2018). For boxplots in the reference category, reference grid cells were compared against their reference neighbors. Horizontal lines in the boxplots indicate the median, and the upper and lower boundaries show the first and third quartiles.

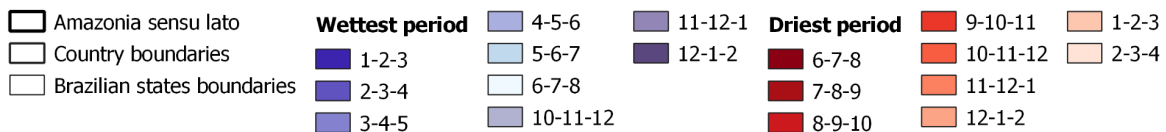
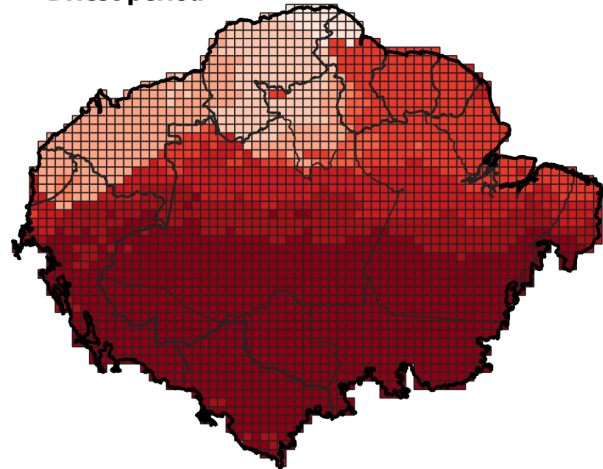
Supplementary Table 3. From the total number of grid cells that are highly deforested (forest cover <60%) and their neighboring highly forested (forest cover >80%) cells, the corresponding percentage of cells whose climate averages during 2013-2021 are within thresholds found for savannas across the Amazon. The climate envelope of savannas was determined as follows: annual land surface temperature (LST) $\geq 32^{\circ}\text{C}$, wet season LST $\geq 31^{\circ}\text{C}$, dry season LST $\geq 31^{\circ}\text{C}$ (based on the 5th percentile of the savanna distribution), annual evapotranspiration (ET) ≤ 1189 , dry season ET ≤ 309 , annual rainfall ≤ 2338 , wet season rainfall ≤ 972 , dry season rainfall ≤ 192 , number of rainy days ≤ 145 (based on the 95th percentile of the savanna distribution). Total number of highly deforested cells: 27. Total number of highly forested cells: 38.

Variable	Percentage (%) of cells in the climate envelope of savannas	
	Highly deforested regions	Highly forested regions
Annual LST	66.67	15.79
Wet season LST	59.26	0
Dry season LST	92.59	68.42
Annual ET	77.78	44.74
Dry season ET	62.96	36.84
Annual rainfall	62.96	52.63
Wet season rainfall	55.56	31.58
Dry season rainfall	70.37	55.26
Number of rainy days	48.15	39.47

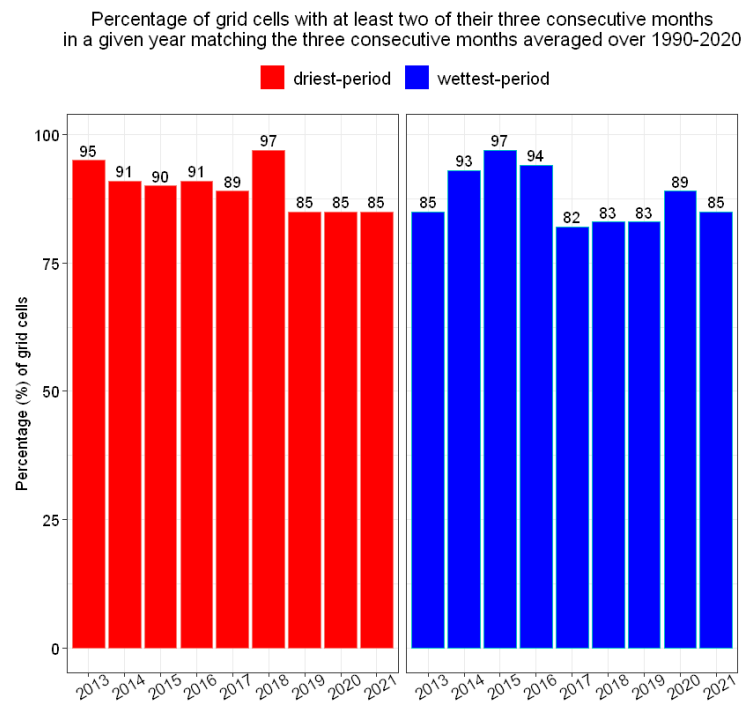
Wettest period



Driest period



Supplementary Figure 3. Spatial variation across the Amazon for the three consecutive wettest and driest months in each 0.5° grid cell based on the mean rainfall during 1990-2020. We computed the mean monthly rainfall over 1990-2020 according to CHIRPS data for each grid cell and identified the three consecutive wettest and driest months to define the wet and dry season, respectively. Months in the legend are represented by their corresponding numbers according to the Gregorian calendar.



Supplementary Figure 4. Percentage of grid cells (out of a 204 total) having at least two of their three consecutive wettest and driest months, for each year during 2013 to 2021, matching the wettest and driest months defined for each grid cell based on their rainfall climatology from 1990-2020.