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Influence of climate variability, fire and phosphorus limitation on vegetation structure and dynamics of the Amazon–Cerrado border

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This document provides supplementary information for the publication "Influence of climate variability, fire and phosphorus limitation on vegetation structure and dynamics of the Amazon–Cerrado border" to appear in *Biogeosciences*.

S1. Regional phosphorus database

We used 54 samples of phosphorus content in the soil, of which 52 were obtained via the Mehlich-1 extraction (H_2SO_4, 0.025mol L^{-1} + HCl 0.05mol L^{-1}) 1:10 soil: solution ratio, and two are direct measurements of total phosphorus content (P_{total}) in the soil. In addition to these samples collected in the field, a phosphorus soil map of the Amazon was also used (Quesada et al., 2010).

All 54 samples of P content were provided by researchers from the UNEMAT – State University of Mato Grosso, collected for different vegetation types ranging from sparse physiognomies like *Campo de Murundus*, open flooded field, *Cerrado típico* to more dense forest formations such as *Cerradão*, semideciduous forest, evergreen seasonal forest and gallery forest in the Amazon-Cerrado transition region in the state of Mato Grosso.

The database of Quesada et al. (2010) provides data of physicochemical properties of the soil, and Hedley fractionation data with eight different fractions of phosphorus content in the soil, including: phosphorus extracted by resin (P_{resin}), P_{total} and residual. The location, name of the experimental sites, value of P_{total}, P_{Resin} and clay percent used to establish the relationship between $P_{-Mehlich-1}$ and P_{total} are shown in Table S1.

Based on the Freire (2001) equation, the amount of phosphorus remaining in the soil, i.e., the existing amount of P in the soil (P_{rem}) was estimated for each site, based on their clay content:

$$P_{rem} = 52.44 - 0.9646\ C + 0.005\ C^2 \qquad R^2 = 0.747 \qquad (1)$$

where P_{rem} is expressed in mg L^{-1} and C is the clay content in %. P_{rem} is the P concentration that remains in solution after shaking soil with 0.01 mol L^{-1} $CaCl_2$ containing 60 mg L^{-1} P (Alves and Lavorenti, 2006).

After obtaining of the remaining values (P_{rem}), it was necessary to estimate the phosphorus maximum adsorption capacity (CMAP) of each soil, in order to calculate how much phosphorus each soil is capable of adsorbing.

Based on significative data from several studies (Bognola, 1995; Campello et al., 1994; Fabres, 1986; Gonçalves, 1988; Ker, 1995; Moreira, 1988; Muniz, 1983; Novelino, 1999; Paula, 1993), Neves (2000) proposed Equation (2) to calculate CMAP from P_{rem}:

$$CMAP = 1816.1 - 373.72\ \log P_{rem} \qquad R^2 = 0.751 \qquad (2)$$

where CMAP is expressed in mg kg^{-1} and P_{rem} in mg L^{-1}.

Knowing the CMAP, Neves (2000) also proposed a robust model (Equation 3), which estimates how much the Mehlich-1 extraction is able to removing the P added in each soil sample ($P_{-Mehlich-1}/P_{Adc}$). This relationship was adjusted based on 31 soil samples data from the work of Bahia-Filho (1982), Muniz (1983), Gonçalves (1988) and Novelino (1999);

$$\frac{P_{-Mehlich-1}}{P_{Adc}} = 380.96\ \ CMAP^{-1.2101} \qquad R^2 = 0.734,\ (p<0.001) \qquad (3)$$

where P_{Adc} is the added dose of P in soil expressed in mg kg^{-1}.

Finally, knowing $P_{-Mehlich-1}/P_{Adc}$, $P_{resin}/P_{-Mehlich-1}$ was estimated using the Equation (4) established by Neves (2000) with r=0.899, n=26.

$$\frac{P_{resin}}{P_{-Mehlich-1}} = 0.5553\ \left(\frac{P_{-Mehlich-1}}{P_{Adc}}\right)^{0.6002} \qquad R^2 = 0.808,\ (p<0.001)$$

(4)

where P_{resin} is expressed in mg kg^{-1}.

With the P_{resin} values and the ratio estimated by Equation (4), $P_{-Mehlich-1}$ values for all stations in Quesada et al. (2010) were estimated ($P_{\_m1\_est,}$ expressed in mg kg^{-1}). Table 2 shows the estimates obtained by Equations (1), (2), (3) and (4) for the 26 sites in the Amazon.

Obtaining $P_{\_m1\_est}$ values for locations where data for clay content and P_{total} (mg kg^{-1}) were available enabled the development of a linear regression model (Equation 5) that estimates P_{total} from $P_{\_m1\_est}$ (mg kg^{-1}) and C (%) with r = 0.639.

$$P_{total} = 72.4628 + 0.639\ \left(P_{\_m1\_est}\ C\right) \qquad R^2 = 0.408, (p<0.001) \qquad (5)$$

Although the R^2 value is low, the regression is significant at $p<0.01$. The product ($P_{\_m1\_est}$ C) was used to correct the effect of soil clay contribution on $P_{-Mehlich-1}$ values, which tends to remove smaller amounts of P, for high values of clay. Applying the Equation (5) to the observated data, P_{total} was estimated for 54 field samples collected in Mato Grosso. These results are presented in Table S2 and were incorporated to the regional dataset of Quesada et al. (2010). Depending on the spatial distribution of the samples, the average for the P_{total} values was calculated inside each 1° × 1° pixel.

Table S1. Phosphorus samples in P_{resin} and clay fraction of different plots in the Brazilian Amazon from the database Quesada et al. (2010). Estimates used to obtain $P_{Mehlich\text{-}1}$ values for the stations used in this study.

Observation data				Estimated data				
Quesada et al. (2010)								
Plot	P_{resin}	P_{total}	Clay	P_{rem}	CMAP	$\frac{P_{\_Mehlich-1}}{P_{Adc}}$	$\frac{P_{resin}}{P_{\_Mehlich-1}}$	$P_{\_m1\_est}$
ID	mg kg^{-1}	mg kg^{-1}	%	mg L^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
'RIO-12'	3.42	178.96	9.50	43.7	404.2	0.27	1.23	2.79
'ELD-12'	5.34	173.59	20.1	35.1	486.9	0.21	1.40	3.80
'SCR-01'	2.36	65.85	6.88	46.0	384.9	0.28	1.18	1.99
'TIP-05'	9.01	437.32	37.3	23.4	637.6	0.15	1.71	5.27
'JRI-01'	1.30	189.13	80.7	7.15	1081	0.08	2.51	0.52
'JAS-02'	8.79	423.65	29.1	28.6	563.1	0.18	1.56	5.64
'CAX-01'	5.17	115.18	41.8	20.9	680.6	0.14	1.79	2.88
'MBO-01'	3.14	101.38	11.5	42.0	419.1	0.26	1.26	2.49
'BNT-04'	4.82	68.67	57.7	13.4	845.2	0.11	2.10	2.30
'TAP-04'	4.50	192.34	89.3	6.18	1136	0.08	2.60	1.73
'ALP-12'	7.37	86.62	14.0	40.0	437.9	0.24	1.30	5.67
'SUC-02'	4.06	349.81	37.2	23.5	636.7	0.15	1.71	2.38
'AGP-01'	2.99	303.28	42.6	20.4	688.8	0.14	1.81	1.66
'ZAR-03'	4.81	177.19	31.1	27.3	580.7	0.17	1.60	3.01
'TAP-123'	1.65	78.89	66.1	10.5	936.4	0.1	2.26	0.73
'ZAR-04'	7.48	54.15	18.3	36.5	471.8	0.22	1.37	5.45
'JUR-01'	10.6	331.93	36.6	23.8	631.2	0.16	1.70	6.22
'RST-01'	8.29	240.19	25.4	31.2	530.8	0.19	1.49	5.55
'ALF-01'	3.51	118.14	11.4	42.1	418.7	0.26	1.26	2.79
'DOI-01'	7.18	203.19	19.1	35.9	478.5	0.22	1.39	5.18
'SIN-01'	2.58	61.25	9.8	43.5	406.4	0.27	1.23	2.10
'TAM-01'	5.85	343.51	37.8	23.2	641.9	0.15	1.72	3.41
'CUZ-03'	11.5		42.5	20.5	687.4	0.14	1.80	6.35
'CRP-01'	21.8		18.1	36.7	470.1	0.22	1.37	15.9
'HCC-21'	7.34	289.76	25.6	31.0	532.4	0.19	1.50	4.90

Table S2. Phosphorus content data ($P_{-Mehlich-1}$) and clay percentage for the 54 soil samples collected in the Amazon-Cerrado transition region and P_{total} estimates.

Location				Physiognomy	Clay	$P_{-Mehlich-1}$	$P_{\_total}$
Latitude	**Longitude**	**n**	**pixel**		**%**	**mg dm^{-3}**	**mg dm^{-3}**
-15.55	-50.10	1	1	*Cerrado rupestre*[a]	30.6	0.89	89.87
-15.54	-50.10	2	1	*Cerrado típico*[b]	34.7	0.2	76.9
-14.17	-51.76	3	2	*Cerrado ralo*[c]	21.06	2.28	103.14
-14.17	-51.77	4	2	*Cerrado ralo*[c]	29.97	1.3	97.36
-14.15	-51.76	5	2	*Cerrado típico*[b]	40.53	2.93	148.35
-14.16	-51.77	6	2	*Cerrado típico*[b]	35.41	1.11	97.58
-14.71	-52.35	7	3	*Cerrado típico*[b]	35.84	3	141.17
-14.71	-52.35	8	3	*Cerrado típico*[b]	48.16	0.84	98.31
-14.71	-52.35	9	3	*Cerrado típico*[b]	49.33	0.42	85.7
-14.82	-52.17	10	3	Semi deciduous Forest	21.5	3.18	116.15
-14.71	-52.35	11	3	*Cerrado típico*[b]	17.28	0.34	76.22
-14.71	-52.35	12	3	*Cerrado típico*[b]	17.71	0.13	73.93
-14.70	-52.35	13	3	*Cerradão*[d]	21.04	0.26	75.96
-14.70	-52.35	14	3	*Cerradão*[d]	24.35	0.1	73.96
-14.69	-52.35	15	3	*Cerradão*[d]	21.03	5.46	145.83
-14.69	-52.35	16	3	*Cerradão*[d]	33.53	3.8	153.88
-14.69	-52.35	17	3	*Cerradão*[d]	40.47	1.9	121.6
-14.69	-52.35	18	3	*Cerradão*[d]	44.03	0.8	94.97
-14.69	-52.35	19	3	*Cerradão*[d]	45.24	0.3	81.13
-14.72	-52.36	20	3	Gallery Forest	15.02	0.87	80.81
-14.72	-52.36	21	3	Gallery Forest	10.45	6.94	118.8
-14.72	-52.36	22	3	Gallery Forest [f]	11.65	1.71	85.19
-13.10	-53.39	23	4	Riparian Forest [f]	43	26	786.86
-13.10	-53.39	24	4	Riparian Forest [f]	49	18	636.06
-13.00	-50.25	25	5	*Cerrado rupestre*[a]	4.44	2.44	79.39
-12.38	-50.93	26	6	*Campo de Murundus*[g]	39.33	2.3	130.27
-12.36	-50.93	27	6	*Campo de Murundus*[g]	29.52	3.3	134.71
-12.56	-50.92	28	6	*Campo de Murundus*[g]	22	3.3	118.85
-12.04	-50.73	29	6	*Campo de Murundus*[g]	38.48	0.7	89.67
-12.57	-50.91	30	6	*Campo de Murundus*[g]	39.11	1.7	114.95
-12.62	-50.82	31	6	*Campo de Murundus*[g]	25.56	2.4	111.66
-12.43	-50.72	32	6	*Campo de Murundus*[g]	29.11	2.3	115.25
-12.23	-50.77	33	6	*Campo de Murundus*[g]	30.77	2.3	117.69
-12.38	-50.94	34	6	*Campo de Murundus*[g]	37.46	5.2	196.93
-12.38	-50.94	35	6	*Campo de Murundus*[g]	39.34	4	173.02
-12.38	-50.93	36	6	open field [f]	32.45	1.6	105.64

Table S2 (continued).

Location				Physiognomy	Clay	$P_{-Mehlich-1}$	$P_{\_total}$
Latitude	**Longitude**	**n**	**pixel**		**%**	**mg dm^{-3}**	**mg dm^{-3}**
-12.38	-50.93	37	6	open field [f]	20.78	2	99.02
-12.36	-50.93	38	6	open field [f]	17.08	1.6	89.93
-12.04	-50.73	39	6	open field [f]	22.83	0.8	84.13
-12.57	-50.91	40	6	open field [f]	24.95	0.7	83.62
-12.62	-50.82	41	6	open field [f]	20.77	2.2	101.66
-12.43	-50.72	42	6	open field [f]	19.55	1.6	92.45
-12.23	-50.77	43	6	open field [f]	27.03	1.9	105.28
-12.38	-50.94	44	6	open field [f]	29.93	3.1	131.75
-12.38	-50.94	45	6	open field [f]	30.75	0.9	90.15
-12.83	-52.35	46	7	Seasonal Evergreen Forest	49	-	**141.54**
-12.81	-51.85	47	8	Seasonal Evergreen Forest	16	-	**117.03**
-11.18	-50.23	48	9	*Cerrado denso*[h]	3.96	2.71	79.32
-11.18	-50.23	49	9	*Cerradão*[d]	4.16	1.66	76.88
-11.17	-50.23	50	9	*Cerrado típico*[b]	3.56	1.45	75.76
-11.86	-50.72	51	10	open field [f]	41.63	2	125.67
-11.86	-50.72	52	10	*Campo de Murundus* [g]	47.65	2.8	157.72
-9.11	-54.23	53	11	*Cerrado rupestre*[a]	4.56	4.17	84.61
-9.79	-50.43	54	12	Semi deciduous Forest	18.36	2.04	96.4

[a]**Cerrado rupestre**: a tree-shrub vegetation that grows in areas of accentuated topography with many rock outcrops and shallow soils, where individual trees establish themselves in clefts in the rocks so that their densities will vary as a function of the specific conditions of each site (Ribeiro and Walter, 2008).

[b]**Cerrado típico**: a vegetation of trees and shrubs fairly regular and usually not more tall (approximately 4m) (Ribeiro and Walter, 2008).

[c]**Cerrado ralo**: a vegetation that is more open than *Cerrado típico*; the trees not exceeding 2 to 3 meters in height, covering from 5 to 20% of the soil (Ribeiro and Walter, 2008).

[d]**Cerradão**: a dense and tall woodland formation (Ribeiro and Walter, 2008).

[g]**Campo de Murundus**: a typical landscape of Central Brazil characterized by countless rounded earth mounds (the '*murundus*'), which are covered by woody '*Cerrado*' vegetation and are found scattered over a grass-covered surface (the 'campo') (Ribeiro and Walter, 2008).

[h]**Cerrado denso:** this vegetation is more dense than *Cerrado típico*; the trees exceeding 2 to 3 meters in height, and covered with a woody cover ranging from 10 to 60% (Ribeiro and Walter, 2008).

S2. Difference between the global P_{total} map and regional P_{total} map (PG-PR)

The spatial difference of the soil phosphorus content between the global P_{total} map (PG) and the regional map (PR) showed that global data underestimates the P_{total} values in some Amazon-Cerrado transition areas, mainly in western Amazonia. PG overestimations are observed in northern Amazonia and in most of the Cerrado biome area. The differences between the absolute values of total phosphorus at a spatial resolution of 1° × 1° varied in the range of ±180 mg kg^{-1}, with an average of 24.19 mg kg^{-1} (Figure S1).

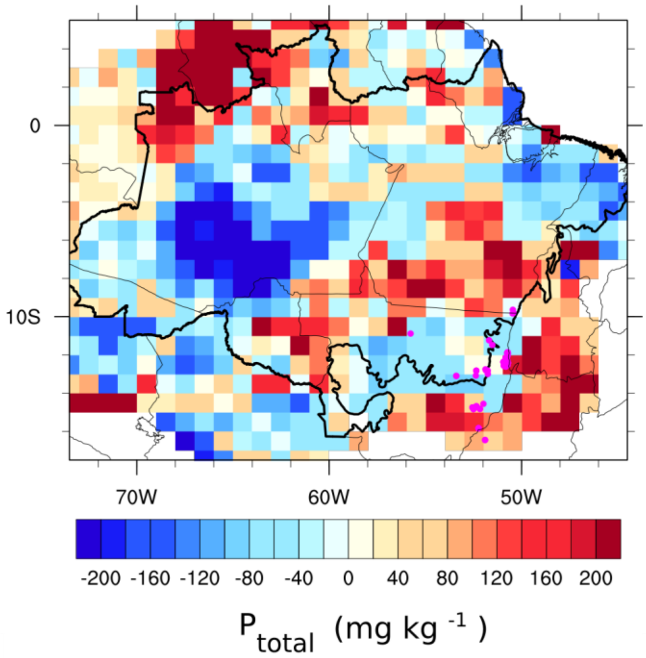

Figure S1. Difference between the global P_{total} map (Yang et al., 2013) and regional P_{total} map (PG-PR) in mg kg^{-1}. The thick black line delimits the Amazon and Cerrado biomes.

S3. Spatial variability of precipitation and temperature from CRU databases

The seasonality of precipitation for Amazon and Cerrado biomes used in this study is shown in Figure S2. The dry season duration is larger in the Cerrado domain (Figure S2a) than in the Amazonia domain (Figure S2b). In the Cerrado, dry season comprise a period of about 6 months with little or no rain.

Spatial variability of precipitation and temperature are shown in Figures S3 and S4, respectively. These figures plot the difference between the average of the last 10 years of CV (1999-2008) and average climate CA (1961-1990). highlighting the spatial variability of these climate variable throughout the study area. When comparing the interannual climate variability with the average climate, it is possible to observe that precipitation decreases (Figure S3) and temperature increases up to 1.5°C (Figure S4) in central Cerrado in October, November, December and January. The lower precipitation associated with higher temperatures in central Cerrado can explain a low biomass, low LAI vegetation and savanna existence without fire disturbance. Note that this is a 10-year subset of the CV database. The actual year-to-year variations present much more intense amplitudes.

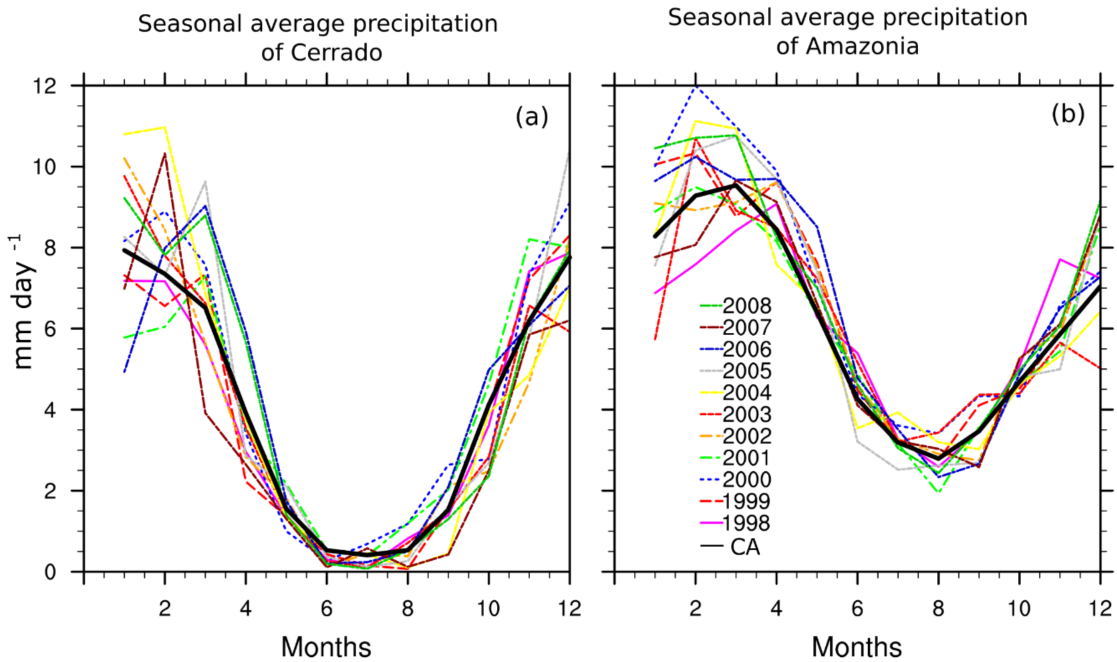

Figure S2. Seasonal precipitation of Amazon and Cerrado domains for average climate (CA) - black line - and the last ten years of interannual- climate variability (CV) – color lines.

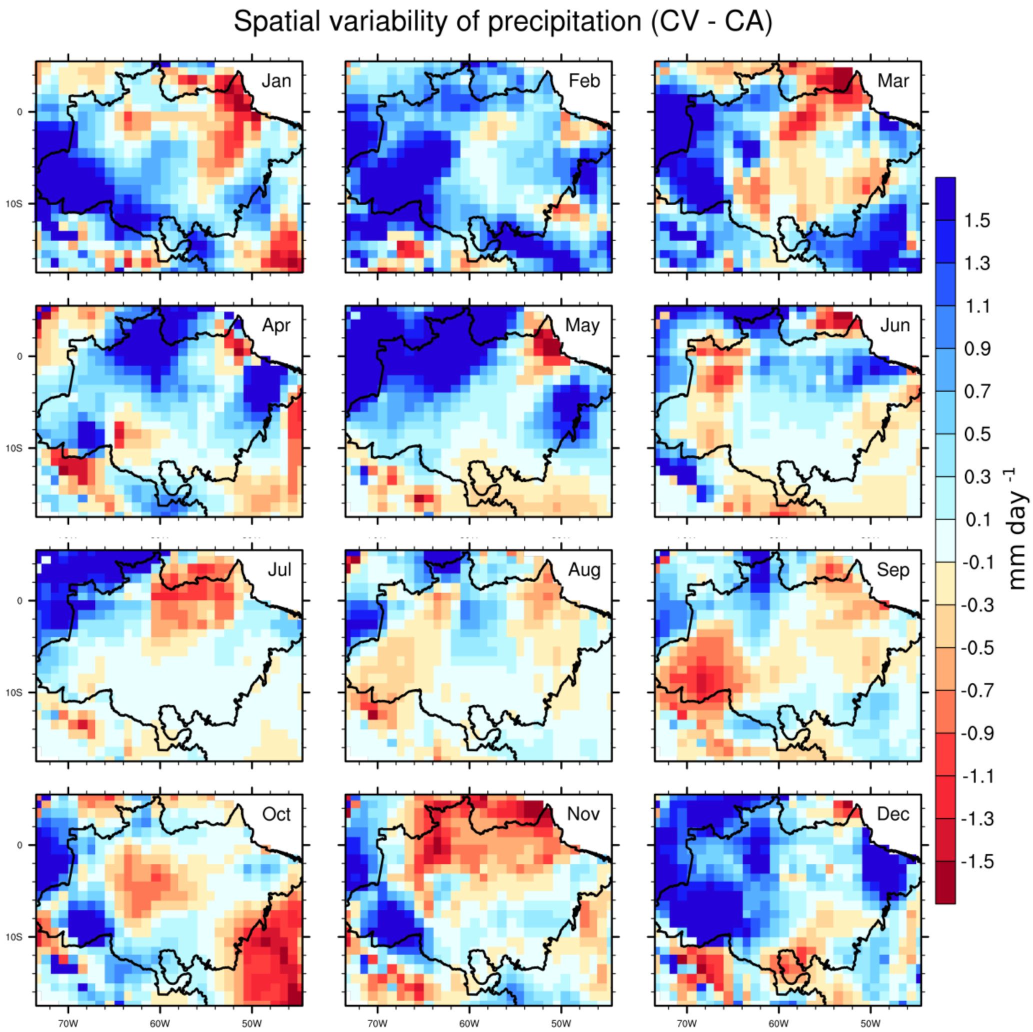

Figure S3. Spatial variability of precipitation for the study area considering the average of the last 10 years of CV (1999-2008) and average climate CA (1961-1990).

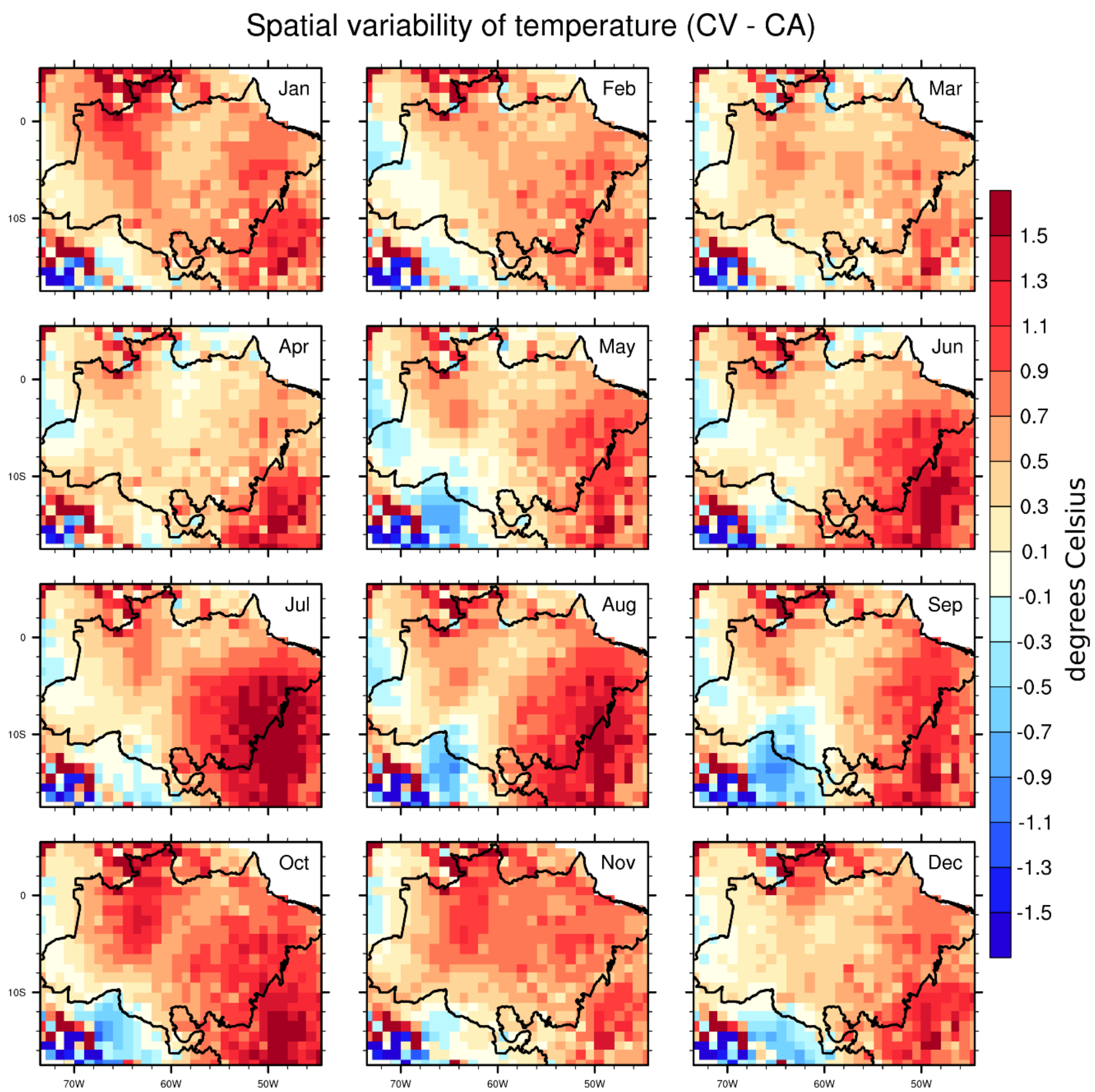

Figure S4. Spatial variability of temperatures for the study area considering the average of the last 10 years of CV (1999-2008) and average climate CA (1961-1990).

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