Supplementary Material

Long-term Landsat-based monthly burned area for the Brazilian Biomes using Deep Learning

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1. Classification regions

The classification regions were broadly defined based on ecological and land use contexts. For the ecological characteristics, we used an aggregation of the Ecoregions dataset based on edaphoclimatic and morphoclimatic data updated for 2017 [1]. For the land use context, we used the regions with concentration of deforestation and fires based on cumulative area deforested retrieved from MapBiomas Collection 6.0 Land use dataset [2] and Modis MCD64A1 [3]. Using these two criteria, the Amazon was divided in 3 large regions where the first one included the southern portion of the arc of deforestation where 90% of the deforestation and 82% fires in the region took place until 2020. It is also the driest areas of the region, encompassing 14 distinct ecoregions. The second Amazon region includes the Southwestern portion of the basin in Brazil, which is more humid but also with an important deforestation history (7% of the deforestation has affected this region and 10% of the average Amazon annual fire happened in this portion of the Amazon). This region was formed by 10 ecoregions. The third and last region for the Amazon is the least affected by fire and least deforested, it contains another fire pattern due to the presence of large patches of fire prone savannas in the northern portion of the region. It is formed by 12 ecoregions (Figure S1).

The Cerrado was defined into 5 regions based on the grouping of ecoregions produced by Sano et al. [4], and considering the degree of deforestation in different parts of the biome, the different fire pattern, and land use and land cover. The Caatinga biome was divided into 4 regions, considering the level 2 of hydrographic basins defined by the National Water Resources Plan (NWRP), which corresponds to the highest level of detail and considers the similarity in environmental conditions, such as soil type, vegetation and weather [5]. The Atlantic Forest was also divided into 4 regions (i) the region dominated by agriculture fields in the Southern portion of São Paulo State, (ii) the wetlands at the limit of Mato Grosso do Sul and Paraná states, (iii) the mining areas of Minas Gerais state and (iv) the Atlantic Forests in the Northeast region of Brazil [6]. The Pampa biome was divided into 3 regions considering the higher lands dominated by grassland fields and the lower lands with rice production. The Pantanal biome was not divided into any region due to its smaller area and similar conditions in relation to ecological and land use patterns within the biome.

Figure S1. Regions defined for each biome in Brazil used to collect training samples and classify burned areas for MapBiomas Fire Collection 1.

2. Annual Landsat Mosaics

For the classification of burned areas and the distinction between burned and unburned areas, the following spectral bands of each Landsat sensor were selected and used to extract spectral information from the annual quality mosaics (Table S1).

Table S1. Landsat satellites spectral bands used as predictors for burned area classification.

Spectral band	Landsat 5 and 7 (1985 - 2012)		Landsat 8 (2013 - 2020)	
	Band number	Bandwidth (μm)	Band number	Bandwidth (μm)
Red	3	0.63 - 0.69	4	0.64 - 0.67
NIR	4	0.76 - 0.90	5	0.85 - 0.88
$SWIR_1$	5	1.55 - 1.75	6	1.57 - 1.65
$SWIR_2$	7	2.08 - 2.35	7	2.11 - 2.29

The annual quality mosaic was built based on the extraction of spectral information of the pixel with the minimum NBR value from all the available images in a year. The spectral information was used to create a color composite mosaic highlighting the areas affected by fire within the year (Figure S2). The date of the pixel with minimum NBR was used to indicate the month in which the burn scar was detected (Figure S2 B to M).

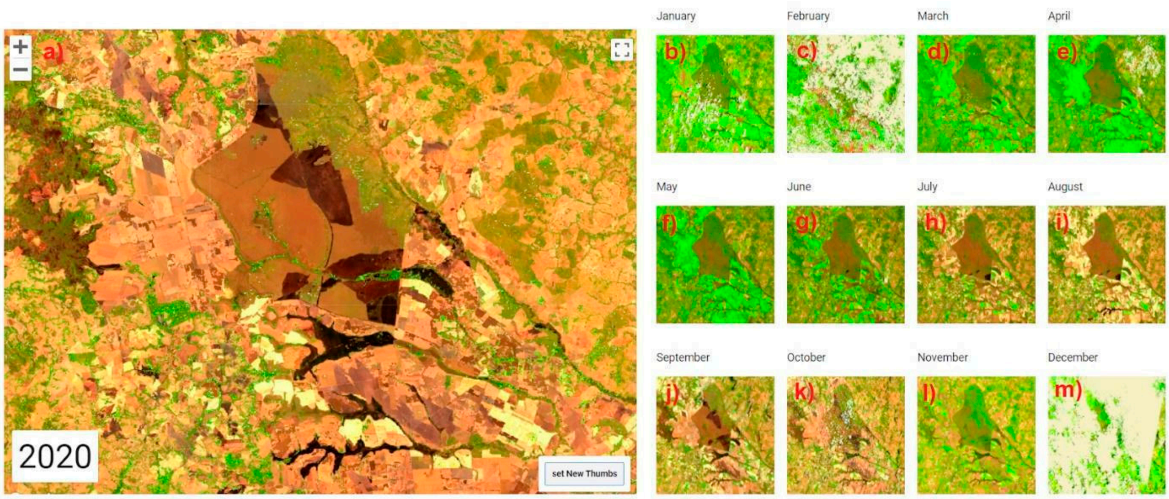

Figure S2. (A) Example of the annual quality mosaic (RGB SWIR-1, NIR, RED) created with spectral information retrieved from the minimum NBR pixels in a year used to perform the burned area classification. Note that this image addresses all the burned areas detected in the monthly mosaics from (B) January to (M) December.

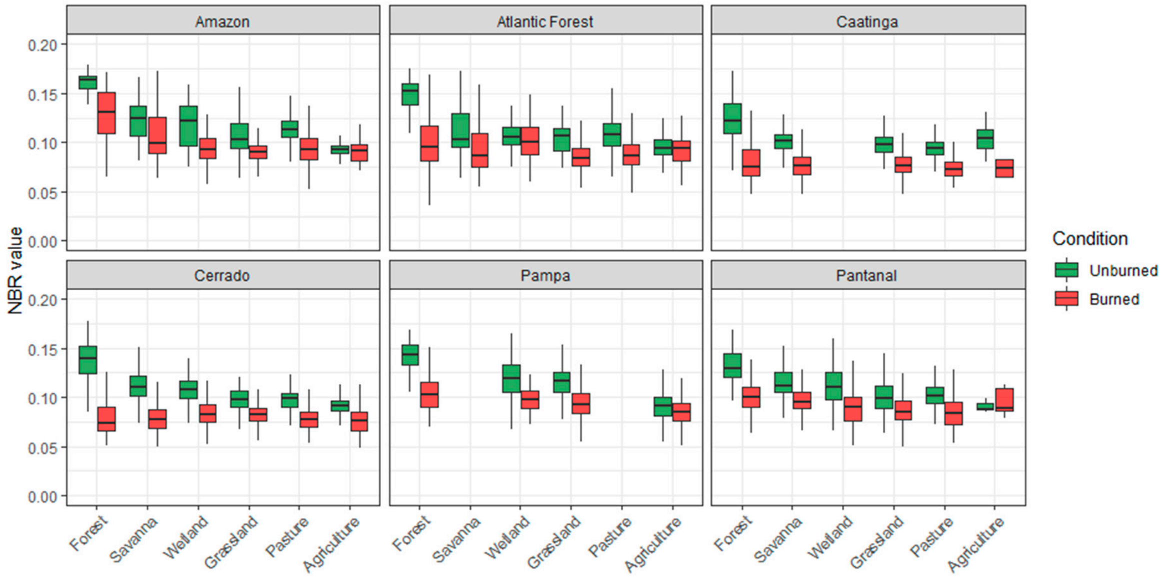

Figure S3. Variation of NBR value extracted from the quality mosaic between burned and unburned areas by land use and cover by biome. Burned (red boxes) represents the immediately post-fire reflectance values, and unburned (green boxes) represents the reflectance value in a specific year.

3. Sampling strategy

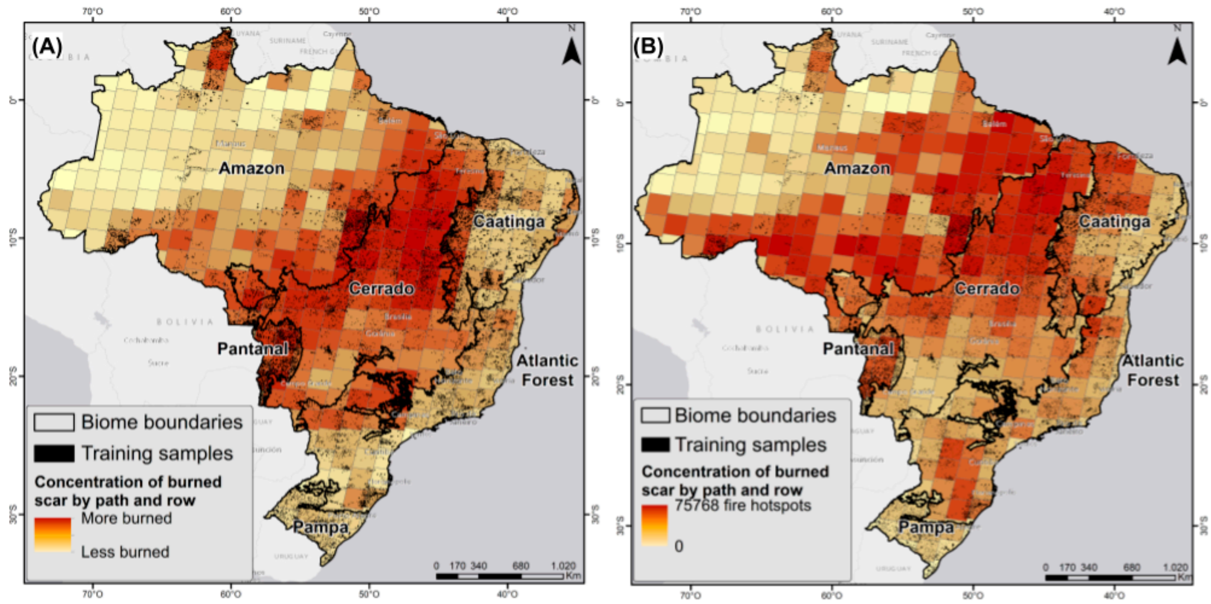

Figure S4. (A) Concentration of burned scar from the MCD64A1 Burned Area from 2000 to 2020 by Landsat path and row; and (B) concentration of active fire pixels from the AQUA_M-T (Sensor MODIS) from 2000 to 2020 by Landsat path and row.

The Landsat annual quality mosaics were used to visually identify and extract burned and unburned training samples to compose the classification spectral library. The proportion of the samples collected and the number of the samples collected in different years are presented in Figure S5.

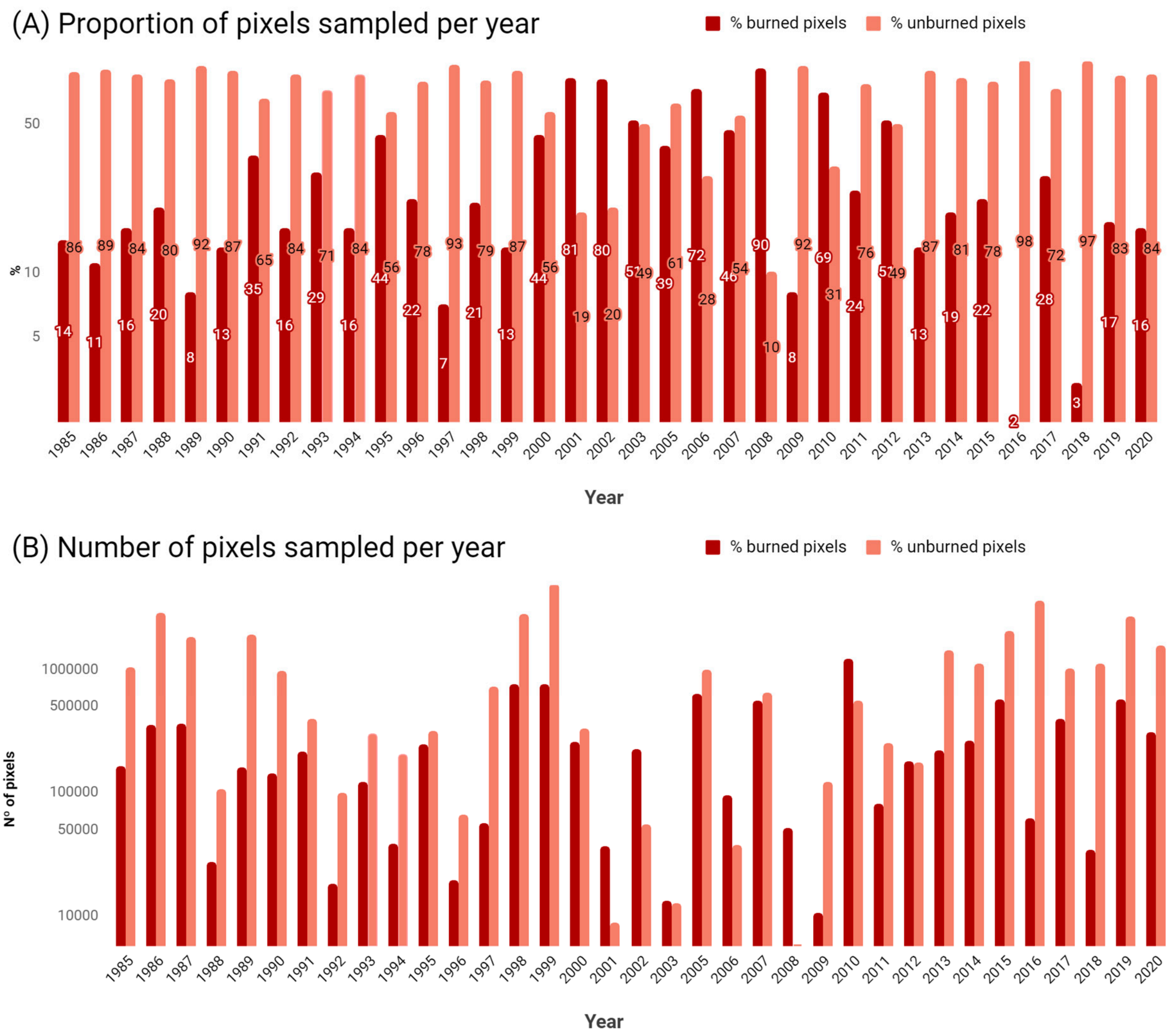

Figure S5. (A) Proportion of burned and unburned training pixels sampled by year; and (B) Number of burned and unburned training pixels sampled by year.

4. Deep learning model

The model structure used for burned area classification was the Multi-Layer Perceptron Network (MLPN), which consists of several layers of interconnected computational units, where each node (neuron) in one layer is connected to a node in the next layer [7,8]. The layers are divided in three: input, hidden, and output layers (Figure S6).

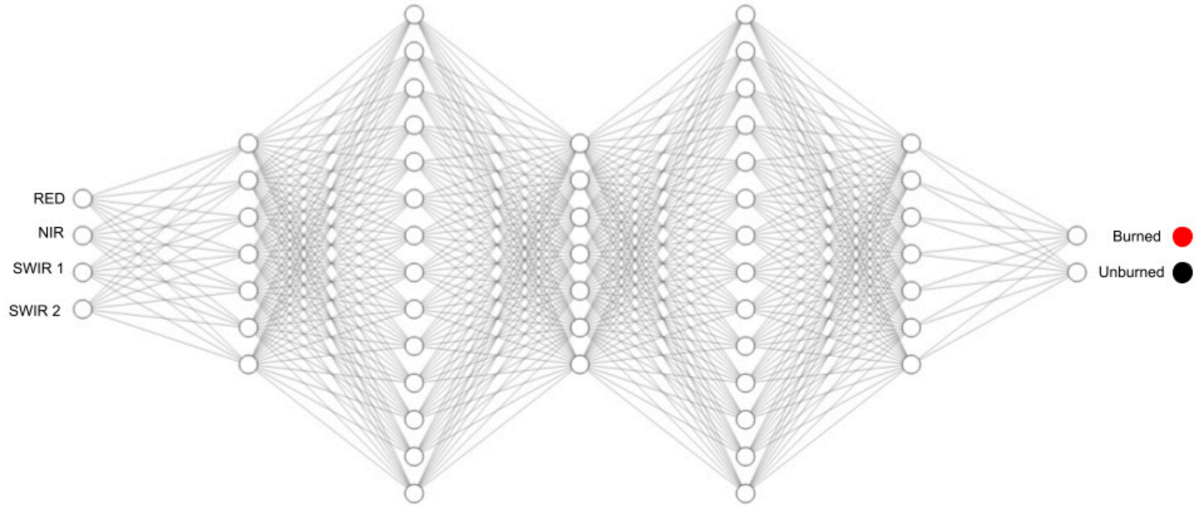

Figure S6. Architecture of the Multi-Layer Perceptron Network, where the input layers are the spectral bands (RED, NIR, SWIR1 and SWIR2) and the output layers are the classes burned and unburned.

Table S2. List of Google Earth Engine scripts used for the construction of annual quality mosaics, the collection of training samples, the classification of burned area, and the MapBiomas Collection 1 burned area dataset.

	Script link
Construction of annual mosaics	https://code.earthengine.google.com/7f87f9da175eabfce854538d2ee0365f
Training samples collection	https://code.earthengine.google.com/f2f1948e67fcea98ca731874a178ffa3
Burned area classification	projects/mapbiomas-workspace/public/collection6/mapbiomas-fire-collection1-annual-burned-coverage-1
Annual burned area maps	https://code.earthengine.google.com/b7acee0bff17a6bf2d1136695ed399bc

5. Post Classification

Table S3. Classes of land use and cover used to mask and remove the committed errors of burned area mapping from the classification results by biome.

Biome	Water	Urban Area	Rocky Outcrop	Rice	Soybeans	Other Temporary Crops
Amazon	X	X	X			
Caatinga	X		X			
Cerrado	X	X				
Atlantic Forest	X	X		X		
Pampa	X	X		X		X
Pantanal	X				X	X

6. Validation

For the validation of the burned area maps, samples were collected for each Biome in 2007, 2001 and 2019 (Table S4).

Table S4. Total sampling units (grid cells of 2 x 2 km) by biome and year used for validation.

Year	Amazon	Caatinga	Cerrado	Atlantic Forest	Pampa	Pantanal	Total
2007	370	370	370	370	352	364	2196
2011	370	370	370	370	342	361	2183
2019	370	370	370	370	337	366	2183

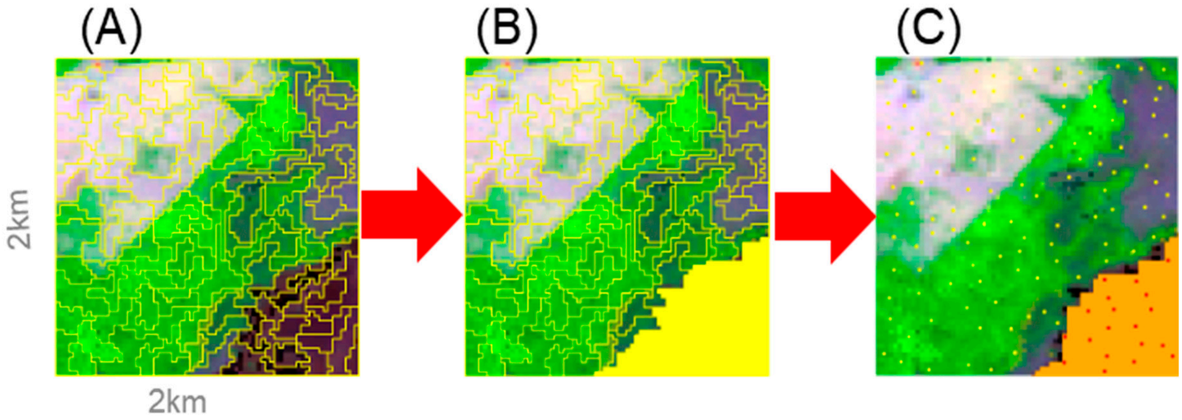

Figure S7. Strategy used to create the validation sampling dataset. (A) in a grid of 2 x 2 km we run a segmentation routine, (B) the burned segments were selected manually and classified as burned (yellow polygon) and unburned; and (C) a centroid of each polygon was created and used to generate the final validation dataset.

A confusion matrix with the accuracy of burned area was produced by aggregating the accuracy from the biomes for all the three years validated (Table S5, S6 and S7), generating producer's and user's accuracy, and commission and omission errors. Because burned area is considered a rare class on the map when compared to unburned areas, we applied a weight to reduce the disparities among the size of burned and unburned areas.

Table S5. Confusion for the classification of burned area in Brazil for the year 2007 with user's accuracy, producer's accuracy, commission and omission errors.

		Reference Data			
		Burned	**Unburned**	**Total**	**Weight**
2007 Classification	**Burned**	8041	811	8852	0,03241
	Unburned	1773	262473	264246	0,96759
	Total	9814	263284	273098	
	Burned	248077,39	25020,61	273098	
	Unburned	54699,81	271265,61	325965	
	Total	302777,20	296286,22	**86,69**	
	Producer´s accuracy	**81,93**			
	Omission error (%)	**18,07**			
	User´s accuracy	**90,84**			
	Commission error (%)	**9,16**			

Table S6. Confusion for the classification of burned area in Brazil for the year 2011 with user's accuracy, producer's accuracy, commission and omission errors.

		Reference Data			
		Burned	**Unburned**	**Total**	**Weight**
2011 Classification	**Burned**	5933	398	6331	0,02389
	Unburned	1118	257588	258706	0,97611
	Total	7051	257986	265037	
	Burned	248375,38	16661,62	265037	
	Unburned	46803,25	263891,64	310695	
	Total	295178,63	280553,26	88,98	
	Producer´s accuracy	**84,14**			
	Omission error (%)	**15,86**			
	User´s accuracy	**93,71**			
	Commission error (%)	**6,29**			

Table S7. Confusion for the classification of burned area in Brazil for the year 2019 with user's accuracy, producer's accuracy, commission and omission errors.

		Reference Data			
		Burned	**Unburned**	**Total**	**Weight**
2019 Classification	**Burned**	11703	610	12313	0,04763
	Unburned	1401	244791	246192	0,95237
	Total	13104	245401	258505	
	Burned	245698,37	12806,63	258505	
	Unburned	29413,26	257033,93	286447	
	Total	275111,63	269840,56	92,25	
	Producer´s accuracy	**89,31**			
	Omission error (%)	**10,69**			
	User´s accuracy	**95,05**			
	Commission error (%)	**4,95**			

Table S8. Comparisons between mapping burned areas in individual scenes and the annual quality mosaic for 15 Landsat Path/Row sorted in the Amazon and border of Cerrado for the year 2015.

Landsat Path/row	MapBiomas Fire annual quality mosaic mapping (km²)	Landsat Individual scenes mapping (km²)	Comparison between Individual scenes burned area mapping and quality mosaic	
			Mapped only in individual scenes (km²)	Coincident mapping (km²)
232/57	3.477	3.507	30	3.477
232/58	2.658	2.658		2.658
225/59	1.233	1.237	4	1.233
225/60	425	428	4	425
222/61	1.271	1.327	57	1.271
226/61	61	72	11	61
222/62	1.643	1.732	89	1.643
226/62	35	35	-	35
227/65	936	951	15	936
001/66	555	559	4	555
226/67	387	387	-	387
229/67	886	900	14	886
002/67	561	574	13	561
224/68	4.855	4.855	-	4.855
231/68	140	140	-	140
Total	**19.123**	**19.363**	**240**	**19.123**

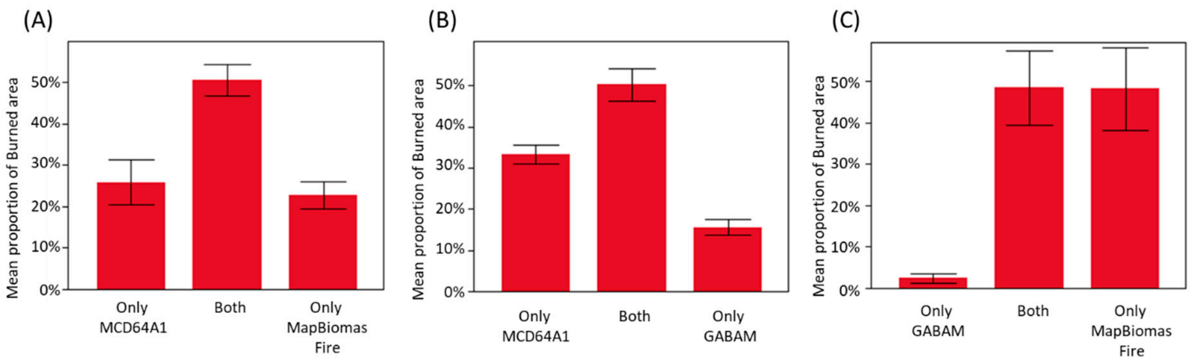

Figure S8. Mean proportion of area burned retrieved from the spatial comparison between Modis MCD64A1 burned area product [3], MapBiomas Fire Collection 1 burned area (this dataset), and GABAM burned area [9] for the year 2005, 2010, 2018. (A) mean burned area mapped only in MCD64A, mean burned area coincident in both MCD64A1 and MapBiomas Fire, and mean burned area mapped only in MapBiomas Fire; (B) mean burned area mapped only with MCD64A1, mean burned area coincident in both MCD64A1 and GABAM, and mean burned area mapped only in GABAM; (C) mean burned area mapped only in GABAM, mean burned area coincident in both GABAM and MapBiomas Fire, and mean burned area mapped only in MapBiomas Fire.

7. Annual variability of burned area by biome

Table S9 Annual burned area (km²) by biome from 1985 to 2020.

	Annual area burned (km²)						
Years	Cerrado	Amazon	Pantanal	Caatinga	Atlantic Forest	Pampa	Brazil
1985	94,044	49,641	7,836	2,122	4,281	64	157,989
1986	86,100	44,254	12,181	6,114	6,317	59	155,024
1987	110,652	81,080	7,397	7,230	3,842	93	210,294
1988	113,873	73,468	11,943	3,430	5,191	154	208,059
1989	41,405	35,142	3,022	2,869	2,198	95	84,731
1990	56,853	43,600	6,161	4,793	2,768	143	114,318
1991	37,474	50,770	10,037	2,285	1,860	77	102,504
1992	39,159	49,085	3,083	6,042	909	34	98,311
1993	68,889	57,047	16,201	5,385	7,984	115	155,621
1994	73,596	53,936	6,355	4,100	5,147	59	143,194
1995	55,509	83,528	10,002	3,608	3,348	111	156,105
1996	72,443	68,797	8,691	3,330	3,238	190	156,689
1997	57,852	83,244	3,868	5,968	4,640	106	155,678
1998	118,613	89,624	5,481	4,880	2,645	52	221,295
1999	67,678	89,572	24,404	3,428	5,961	84	191,128
2000	49,150	66,301	5,118	3,200	3,020	169	126,958
2001	78,533	73,680	12,663	5,765	4,265	240	175,145
2002	79,654	85,315	15,662	4,491	3,517	164	188,803
2003	47,957	75,382	2,832	4,762	6,043	164	137,140
2004	62,999	98,274	6,496	5,616	2,146	102	175,633
2005	58,567	113,683	14,872	4,754	1,973	69	193,918
2006	34,332	77,987	2,469	486	2,516	55	119,845
2007	110,067	109,853	8,220	4,442	2,366	57	235,005
2008	47,913	80,394	4,213	4,296	2,414	40	139,270
2009	23,943	50,463	5,913	2,383	1,874	55	84,632
2010	108,470	82,741	6,476	3,360	2,974	46	204,066
2011	31,881	40,512	2,189	399	3,269	22	78,272
2012	94,233	44,726	8,929	5,977	2,219	78	156,161
2013	42,972	23,893	2,556	2,039	1,211	41	72,712
2014	75,737	44,669	1,598	2,770	2,115	36	126,926
2015	81,782	65,523	4,085	5,169	1,843	80	158,483
2016	66,299	45,524	7,381	3,594	2,307	88	125,194
2017	81,368	65,972	5,354	2,487	2,446	64	157,691
2018	38,227	35,406	1,603	3,111	1,433	60	79,840
2019	72,191	53,711	11,710	5,092	2,629	142	145,477
2020	61,586	51,489	22,922	4,044	2,096	120	142,257

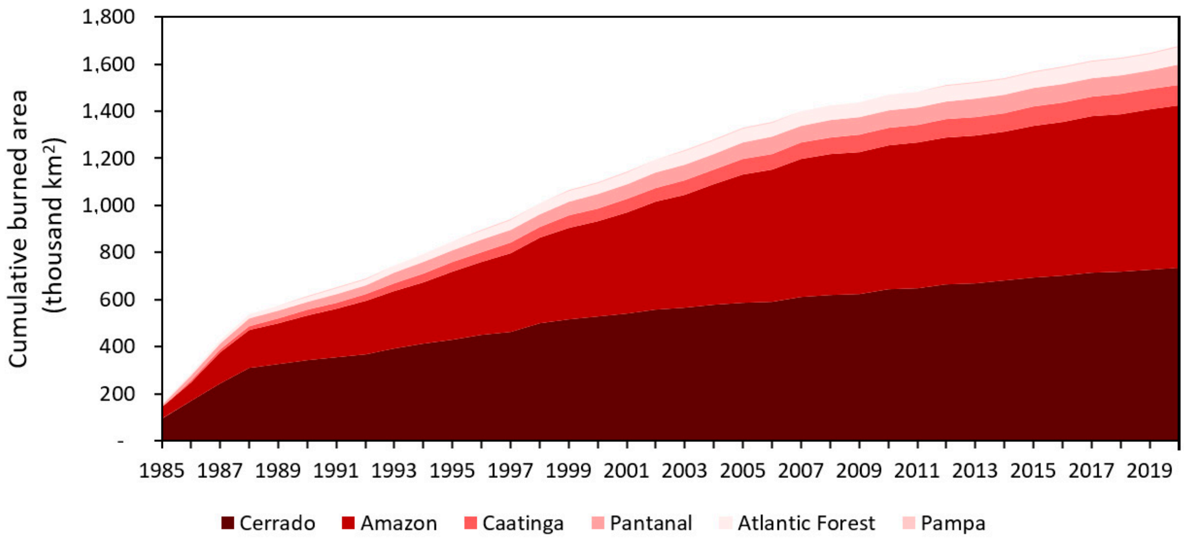

Figure S9. Cumulative burned area by biome from 1985 to 2020.

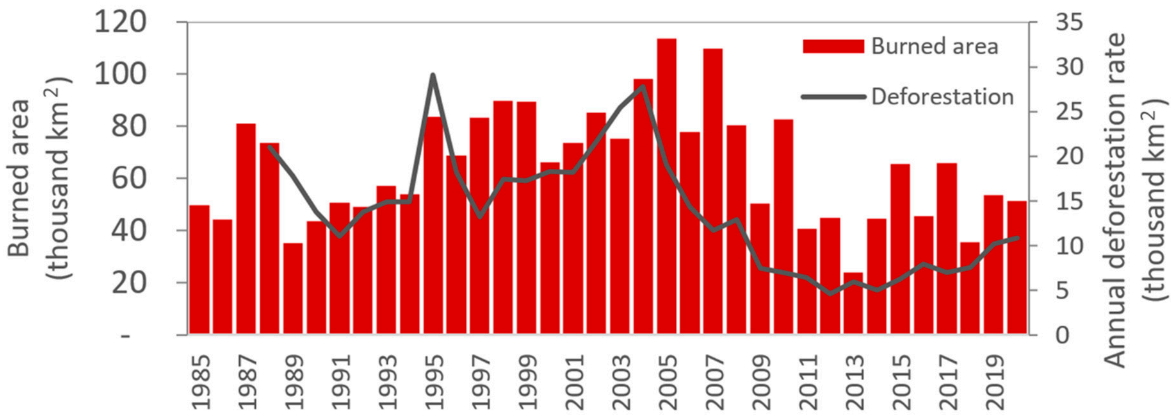

Figure S10. Distribution of annual burned area from MapBiomas Fire Collection 1 and annual deforestation rate from Prodes- INPE [10] for the Amazon biome.

8. Monthly burned area by biome

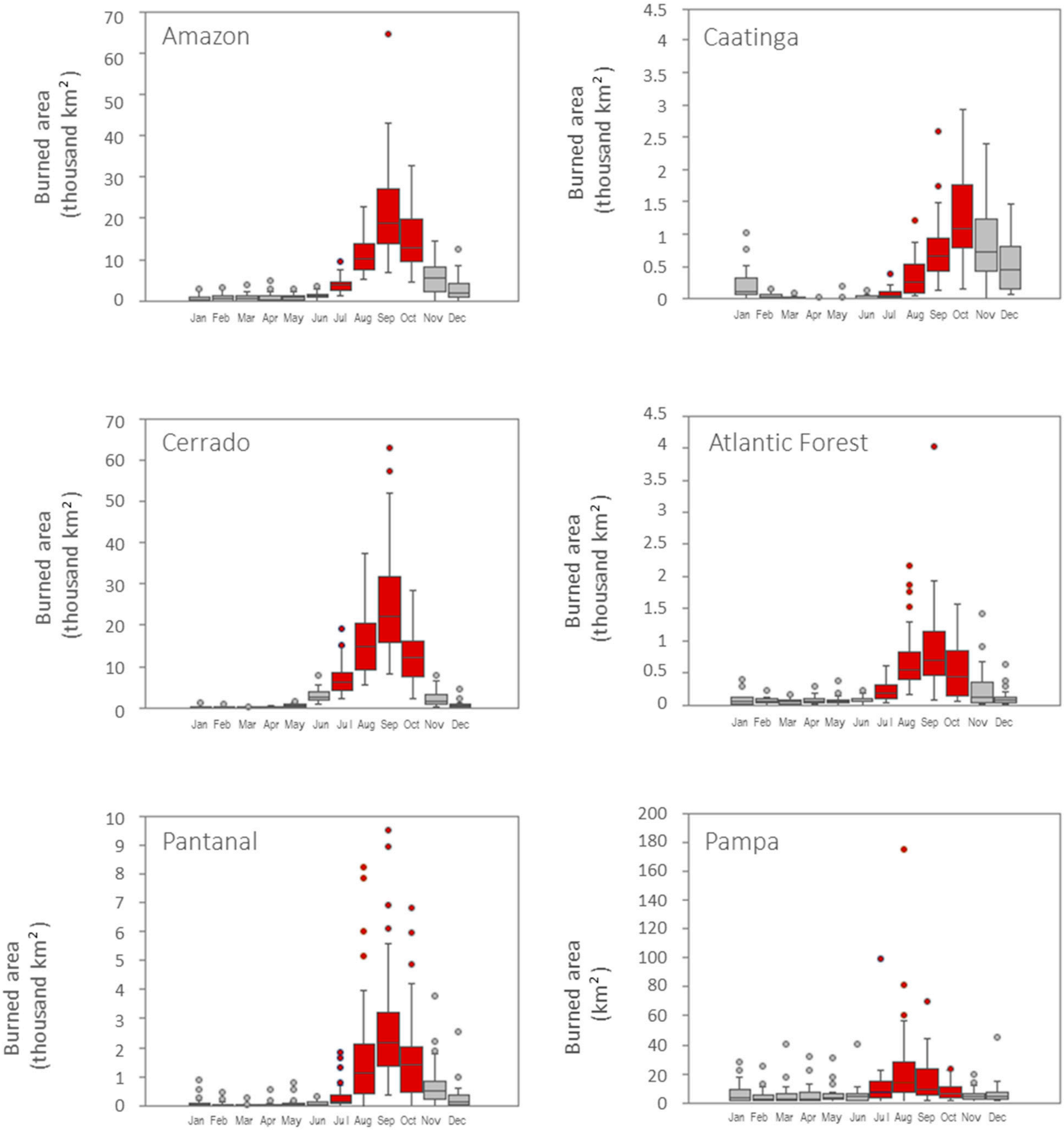

Figure S11. Seasonal patterns of fire events occurred within Brazil's biomes, considering variation in burned area per month, in the period (1985-2020). In red the fire season months from July to October.

9. Fire frequency

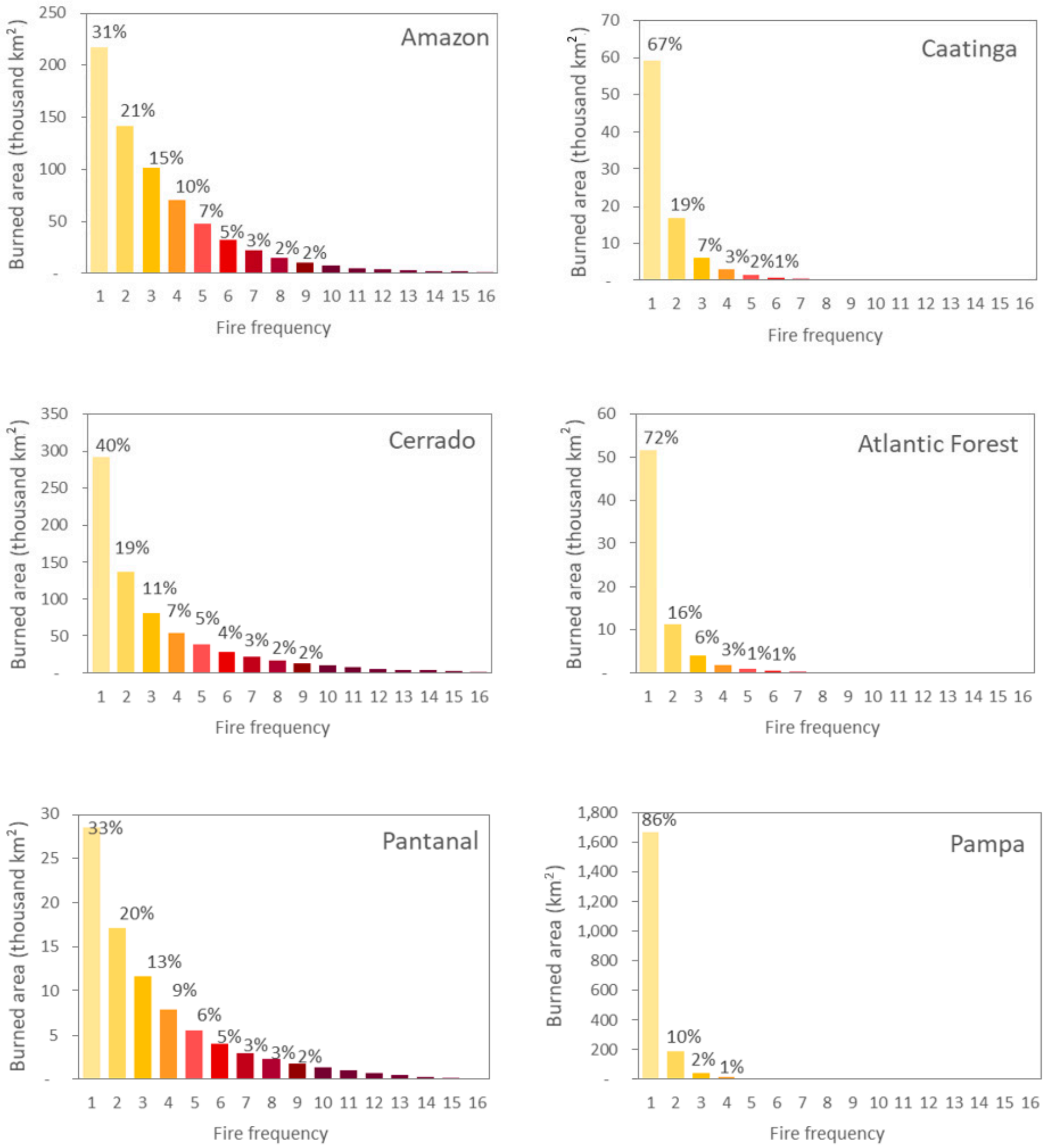

Figure S12. Frequency pattern of the burned area between the years 1985 to 2020 by Brazilian biome, and their respective proportion of burned area.

10. Burned area by land cover and land use

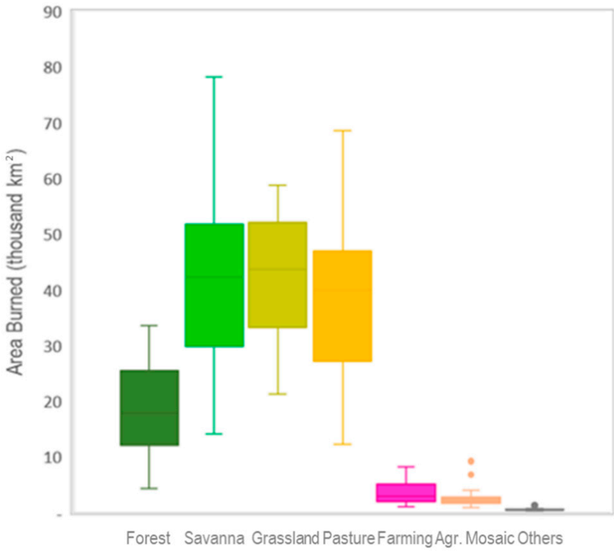

Figure S13. Variance on burned area by land cover and use for Brazil between 1985 and 2020.

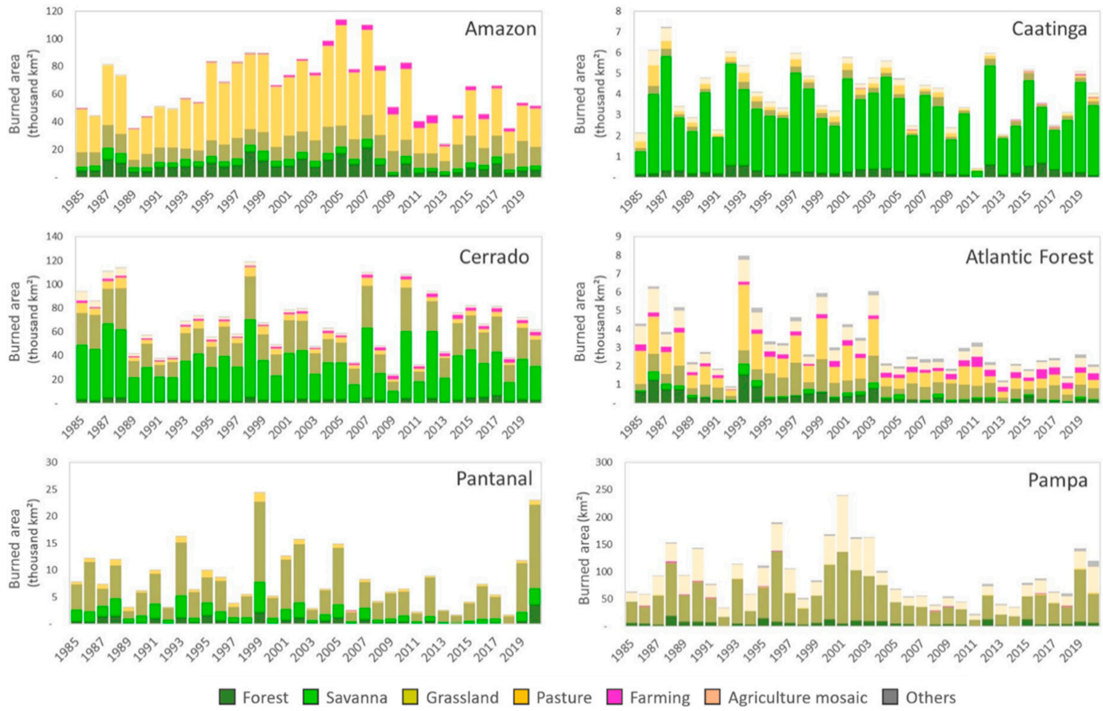

Figure S14. Annual distribution of burned area by land use and land cover by biome from 1985 to 2020.

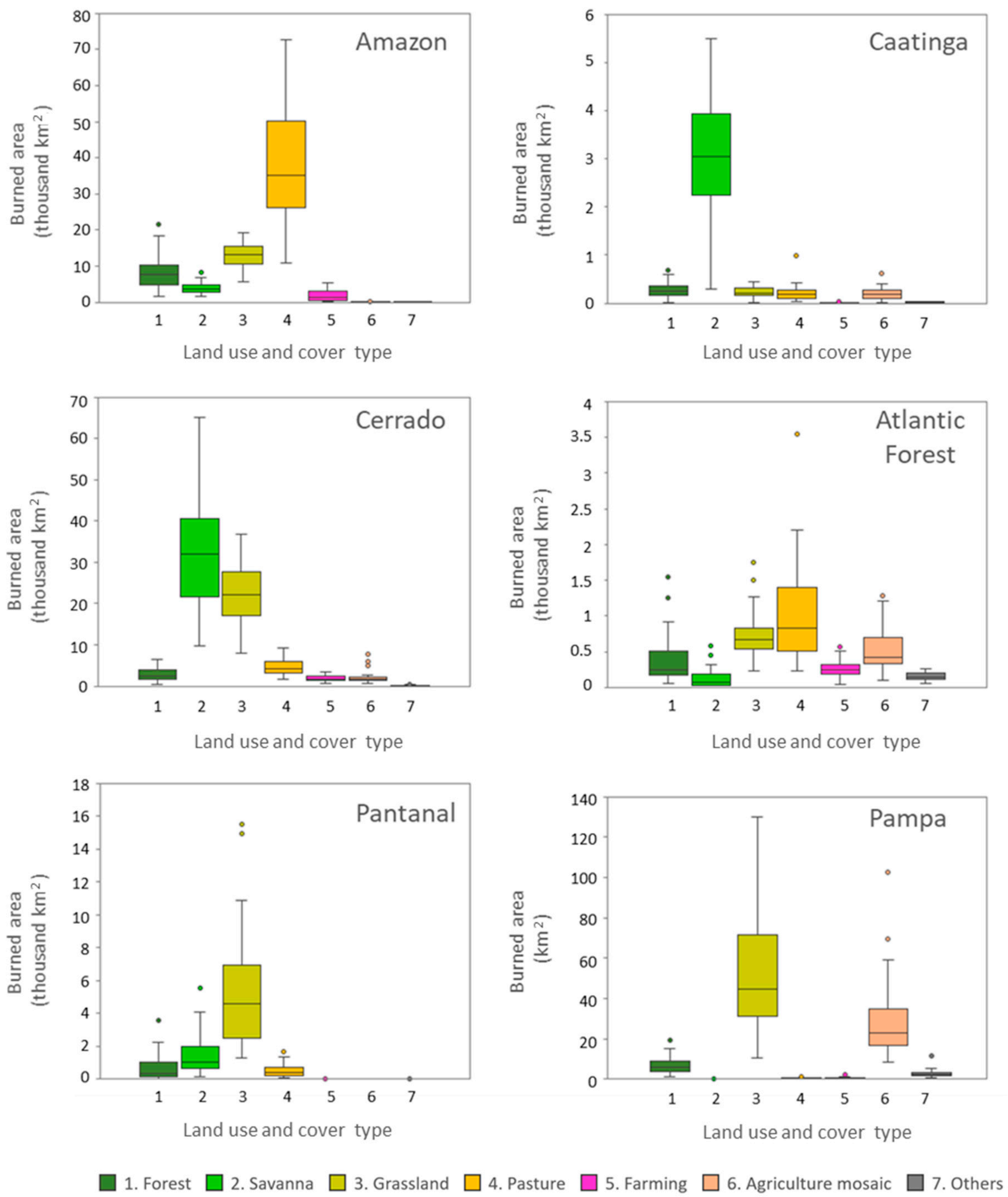

Figure S15. Variance of annual burned area by land use and cover classes from 1985 to 2020 for the Brazilian biomes.

11. References

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