

Article:

Land use change net removals associated with sugarcane in Brazil

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Supplementary Material S1

Distribution of excluded and evaluated CARs

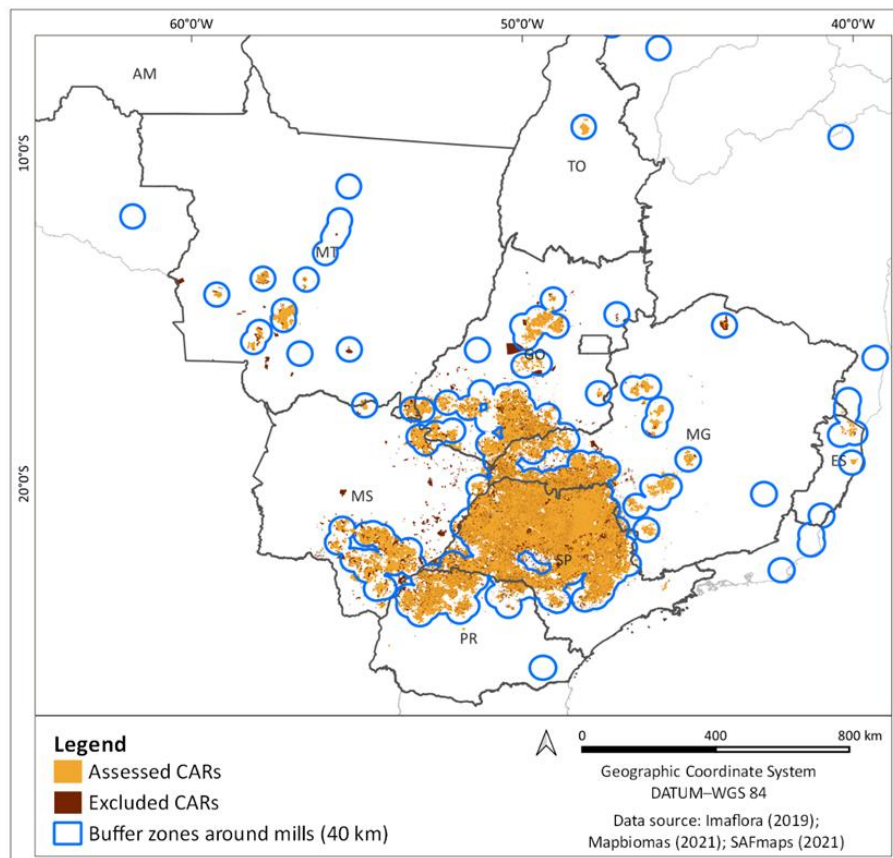


Figure S1. Distribution of evaluated CARs and excluded CARs in the rural properties database verification stage. It was excluded CARs with a mapped sugarcane area of less than 2 hectares; CARs whose area mapped with sugarcane was formed by small scattered pixels, which did not represent a sugarcane plot profile, or which, based on a visual assessment, were identified as mistakenly mapped as sugarcane by automatic land use classification; and CARs located in municipalities that have no sugarcane production, according to the official source for national agricultural production (IBGE, 2022). These criteria led to the exclusion of some large CAR areas for example in GO and MS states, which present very low sugarcane cultivation areas. The excluded areas represent approximately 0.5% of the sugarcane area mapped by MapBiomas within the CARs in the considered states. The data that support the findings of this study are available from the corresponding author on request.

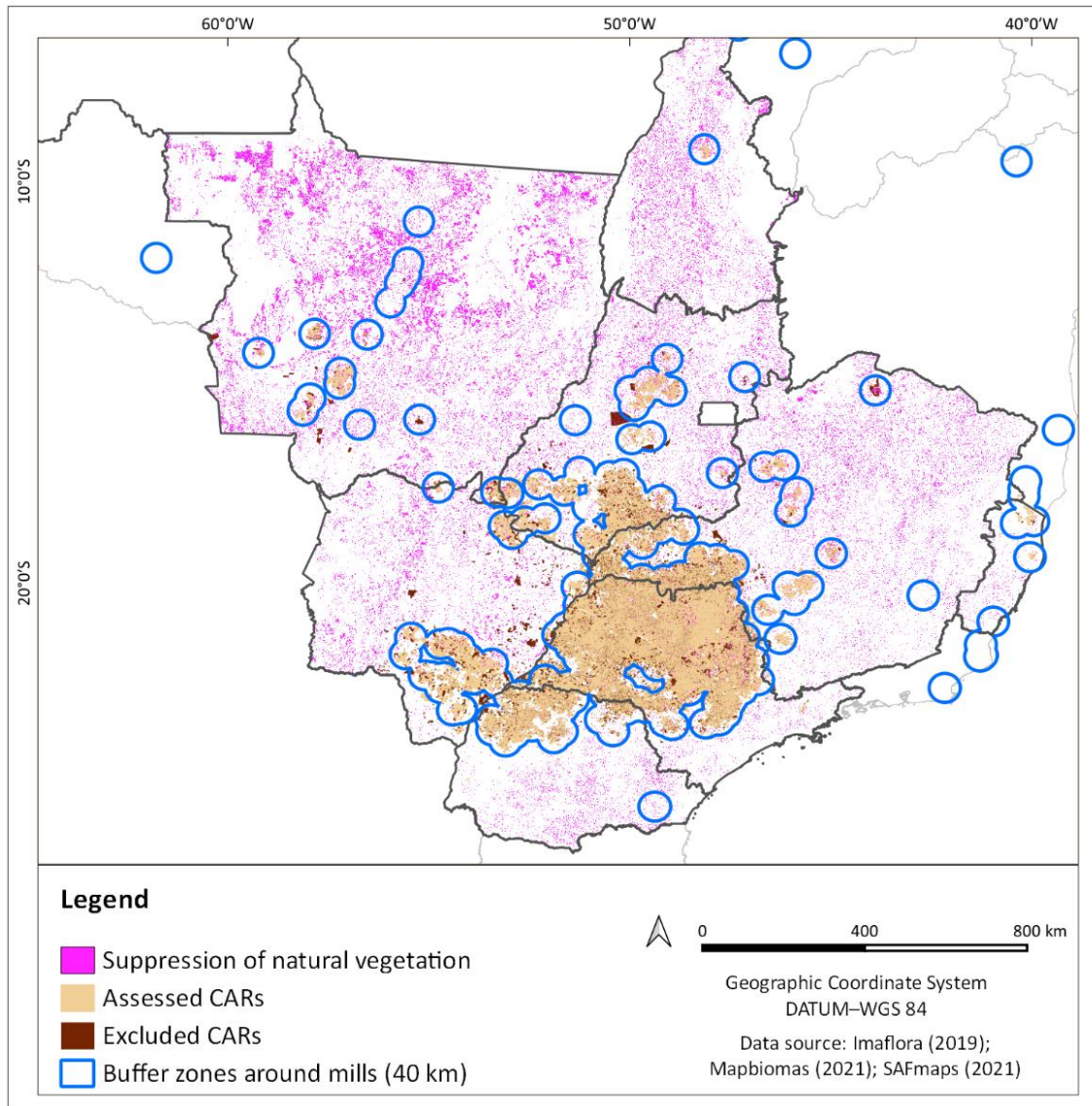


Figure S2. Location of evaluated CARs and excluded CARs in the database verification stage of rural properties, combined with the occurrence of suppression of natural vegetation that occurred between 2000 and 2020, in the evaluated states with the highest concentration of CARs. It was excluded CARs with a mapped sugarcane area of less than 2 hectares; CARs whose area mapped with sugarcane was formed by small scattered pixels, which did not represent a sugarcane plot profile, or which, based on a visual assessment, were identified as mistakenly mapped as sugarcane by automatic land use classification; and CARs located in municipalities that have no sugarcane production, according to the official source for national agricultural production (IBGE, 2022). These criteria led to the exclusion of some large CAR areas for example in GO and MS states, which present very low sugarcane cultivation areas. The excluded areas represent approximately 0.5% of the sugarcane area mapped by MapBiomas within the CARs in the considered states.

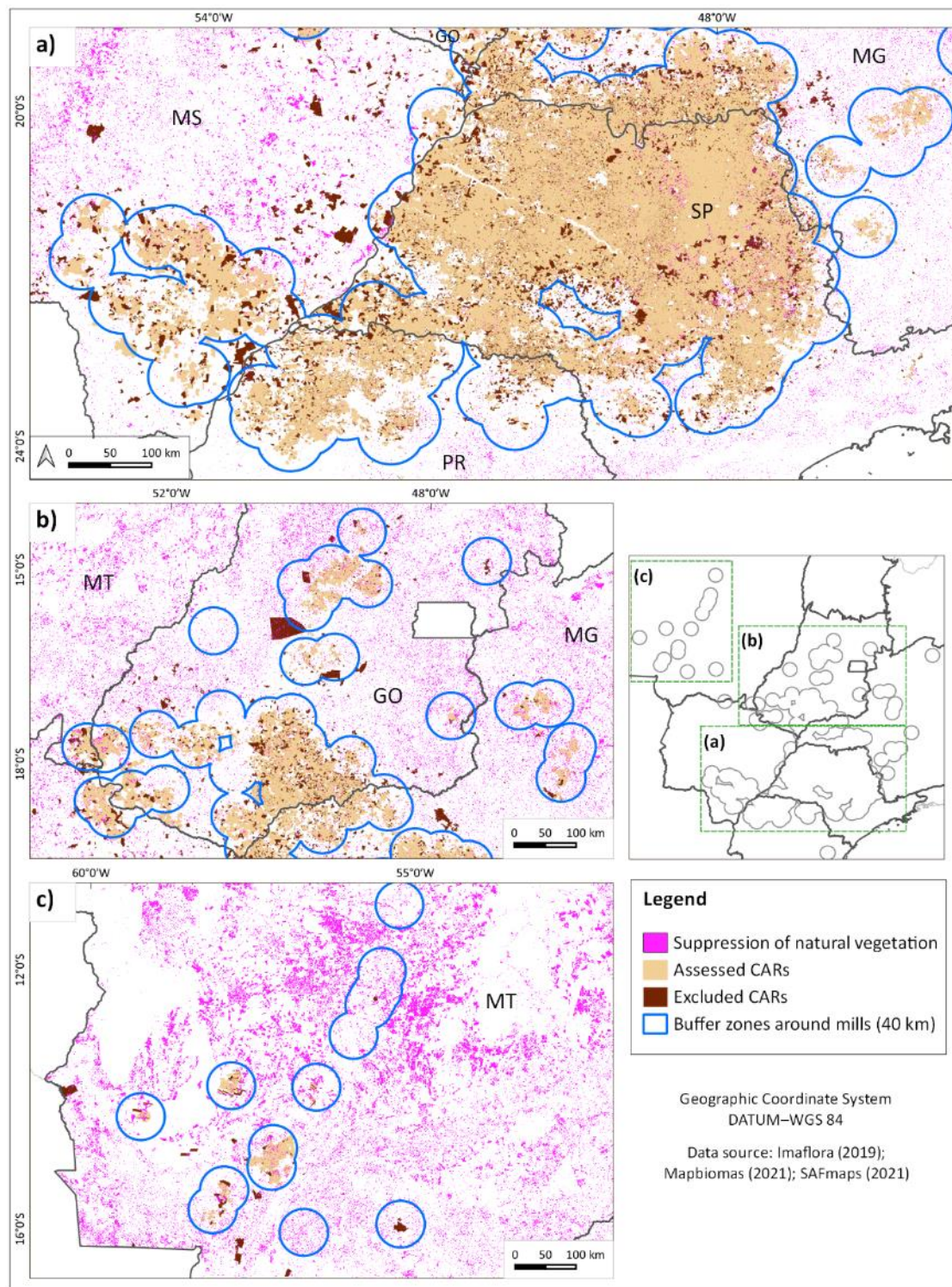


Figure S3. Details of the main regions where CARs were excluded in the database verification stage of rural properties. It was excluded CARs with a mapped sugarcane area of less than 2 hectares; CARs whose area mapped with sugarcane was formed by small scattered pixels, which did not represent a sugarcane plot profile, or which, based on a visual assessment, were identified as mistakenly mapped as sugarcane by automatic land use classification; and CARs located in municipalities that have no sugarcane production, according to the official source for national agricultural production (IBGE, 2022).

Comparison of MapBiomias mapping with industry data

A correspondence of 84.7% was observed between the areas mapped as "sugarcane" according to MapBiomias, in 2020, and the spatialized sugarcane data provided by the industry (Raizen, 2021), in accordance with the global accuracy of the MapBiomias mapping; the other sugarcane areas provided by the industry were predominantly classified as Mosaic by MapBiomias (Figure S4).

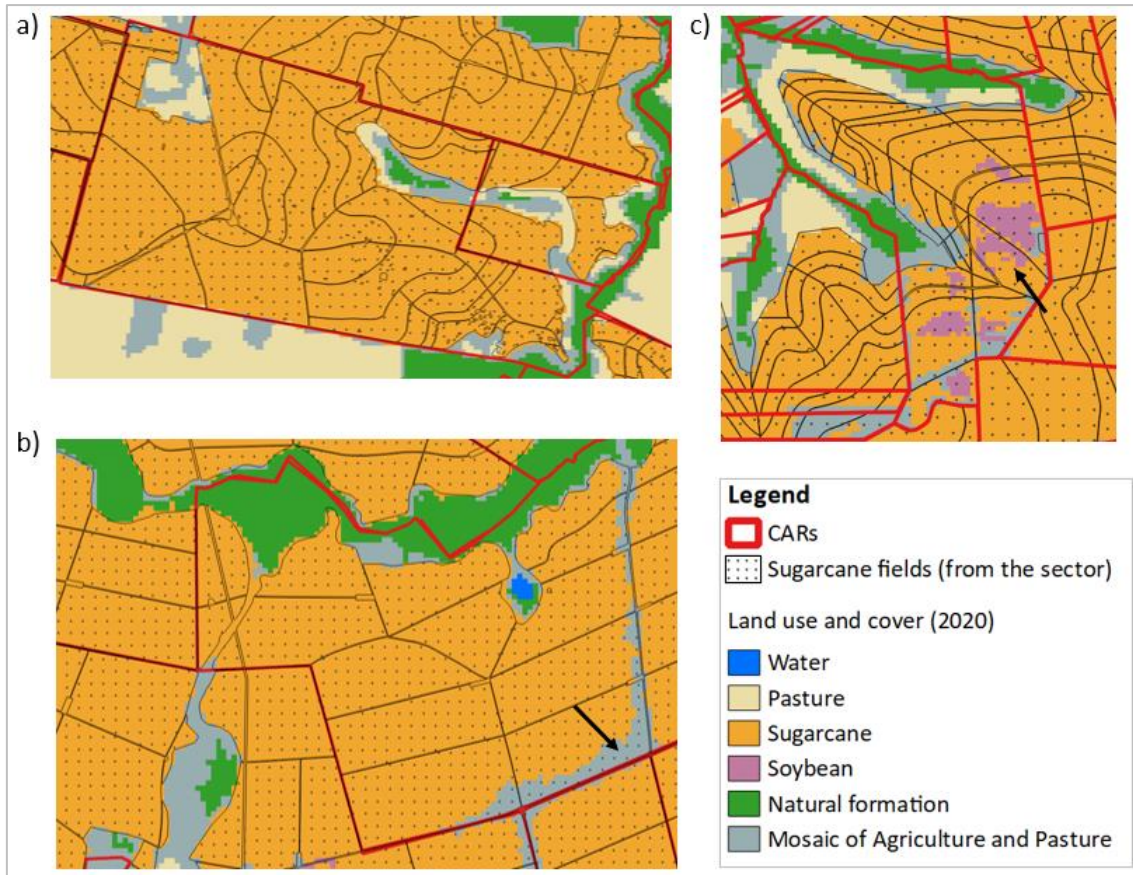


Figure S4. Comparisons between MapBiomias land use and land cover mapping (based on Landsat satellite images) and the location of sugarcane fields provided by the industry. Emphasis on cases in which the sugarcane mapped by MapBiomias presents accuracy with the plots throughout the CAR (a), or in which areas of sugarcane plots were mapped as a mosaic of agriculture or pasture (b), or soy (c) according to MapBiomias.

Land use and land cover data

Table S1. Areas of land uses and land covers in all CARs of the analyzed region, in 2000, by state. Areas are in hectares x 1000.

Class\State	SP	GO	MT	MS	MG	PR	TO	ES	AM	TOTAL
Sugarcane	2206.79	3.64	18.13	0.71	70.27	90.57	1.10	0.00	-	2391.21
Mosaic of Agriculture and Pasture	1959.29	275.92	5.50	170.58	333.88	172.03	5.52	2.93	-	2925.64
Forest Formation	675.70	175.05	79.34	147.83	135.90	93.08	4.52	1.22	53.05	1365.69
Pasture	3657.45	938.03	186.32	943.34	1055.81	491.75	2.87	23.47	3.78	7302.83
Soybean	100.08	198.98	49.13	76.71	35.10	21.66	9.23	-	-	490.89
Wetland	149.59	58.25	18.26	68.20	41.58	3.20	0.15	0.19	0.02	339.43
Savanna Formation	90.27	148.83	56.00	60.11	127.70	-	25.54	-	0.04	508.50
Other Temporary Crops	303.33	350.29	33.62	78.58	190.29	173.34	2.53	-	0.00	1131.99
Forest Plantation	14.60	0.60	0.04	0.01	5.55	0.90	-	0.25	-	21.95
Grassland	12.50	11.76	24.15	7.44	34.39	-	1.76	-	1.12	93.12
Citrus	31.87	-	-	-	-	-	-	-	-	31.87
River, Lake and Ocean	21.81	5.80	1.18	3.09	3.62	0.96	0.02	0.14	0.01	36.63
Urban Area	6.39	0.22	0.10	0.09	0.38	0.50	0.12	0.01	-	7.81
Other Perennial Crops	0.46	-	-	-	-	-	-	-	-	0.46
Other non Vegetated Areas	4.22	8.15	0.35	0.43	0.75	0.18	1.08	0.01	-	15.18
Coffee	7.14	0.49	-	-	3.36	3.61	-	0.01	-	14.60
Other land uses ¹	0.15	-	-	-	-	-	-	0.06	-	0.21
Total	9,242	2,176	472	1,557	2,039	1,052	54	28	58	16,678

¹ Mining, Rocky Outcrop, Aquaculture, Wooded Restinga and Other non Forest Formations.

Table S2. Areas of land uses and land covers in all CARs of the analyzed region, in 2008, by state. Areas are in hectares x 1000.

Class\State	SP	GO	MT	MS	MG	PR	TO	ES	AM	TOTAL
Sugarcane	4008.63	163.87	56.15	94.20	359.03	352.16	0.10	0.04	4.39	5,039
Mosaic of Agriculture and Pasture	2126.98	307.08	6.11	249.40	404.66	239.10	0.97	4.10	-	3,338
Forest Formation	714.71	175.10	80.33	145.36	137.65	101.73	4.75	1.36	52.65	1,414
Pasture	1897.16	705.60	126.45	720.84	699.43	236.58	2.60	22.04	0.84	4,412
Soybean	52.32	331.23	41.69	168.20	66.14	36.75	18.18	-	-	715
Wetland	147.95	57.39	14.67	67.90	39.97	3.21	0.15	0.32	0.00	332
Savanna Formation	83.49	136.01	54.91	53.57	116.78	-	20.49	-	0.00	465
Other Temporary Crops	118.51	275.06	69.91	46.05	167.67	78.65	6.21	-	0.03	762
Forest Plantation	15.76	0.74	0.07	0.18	1.99	0.44	0.00	0.18	-	19
Grassland	11.34	12.35	19.97	8.03	36.13	-	0.60	0.00	0.11	89
Citrus	22.61	-	-	-	-	-	-	-	-	23
River, Lake and Ocean	20.24	6.78	1.23	2.56	4.08	0.85	0.02	0.15	0.01	36
Urban Area	9.31	0.75	0.13	0.35	0.83	0.74	0.12	0.01	-	12
Other Perennial Crops	0.57	-	-	-	0.18	-	-	-	-	1
Other non Vegetated Areas	4.76	3.80	0.49	0.47	1.06	0.26	0.24	0.01	-	11
Coffee	7.06	0.26	-	-	3.18	1.32	-	0.04	-	12
Other land uses ¹	0.24	-	-	-	-	-	-	0.05	-	0
Total	9,242	2,176	472	1,557	2,039	1,052	54	28	58	16,678

¹ Mining, Rocky Outcrop, Aquaculture, Wooded Restinga and Other non Forest Formations.

Table S3. Areas of land uses and land covers in all CARs of the analyzed region, in 2020, by state. Areas are in hectares x 1000.

Class\State	SP	GO	MT	MS	MG	PR	TO	ES	AM	TOTAL
Sugarcane	5546.36	808.80	116.78	602.93	819.81	542.45	10.08	0.69	4.27	8,452.19
Mosaic of Agriculture and Pasture	1673.07	404.50	17.79	243.75	437.93	227.47	7.34	3.84	-	3,015.68
Forest Formation	755.90	179.62	86.97	150.21	146.33	110.87	5.77	1.43	52.83	1,489.93
Pasture	715.02	347.74	112.64	224.40	312.76	96.79	4.67	21.41	0.76	1,836.19
Soybean	127.43	193.24	35.78	187.96	88.96	55.29	4.71	-	-	693.36
Wetland	152.81	54.88	12.29	70.16	38.19	3.98	0.15	0.25	0.00	332.70
Savanna Formation	58.38	112.41	48.37	44.68	104.75	-	19.14	-	0.00	387.74
Other Temporary Crops	45.50	46.37	15.27	17.81	38.37	9.07	1.54	-	0.01	173.94
Forest Plantation	37.05	3.14	0.26	2.17	5.16	2.05	-	0.34	-	50.18
Grassland	9.34	12.47	23.74	8.53	34.93	0.00	0.54	0.00	0.14	89.68
Citrus	55.61	-	-	-	-	-	-	-	-	55.61
River, Lake and Ocean	16.91	6.25	1.05	2.46	3.46	0.74	0.02	0.11	0.00	31.00
Urban Area	13.67	1.36	0.30	0.63	1.38	1.00	0.12	0.01	-	18.46
Other Perennial Crops	10.47	-	-	-	0.89	-	-	-	-	11.37
Other non Vegetated Areas	6.86	5.10	0.87	1.43	1.51	0.88	0.37	0.00	-	17.02
Coffee	16.95	0.11	-	-	4.16	1.19	-	0.09	-	22.51
Other land uses ¹	0.23	-	-	-	0.00	-	-	0.11	-	0.34
Total	9,242	2,176	472	1,557	2,039	1,052	54	28	58	16,678

¹ Mining, Rocky Outcrop, Aquaculture, Wooded Restinga and Other non Forest Formations.

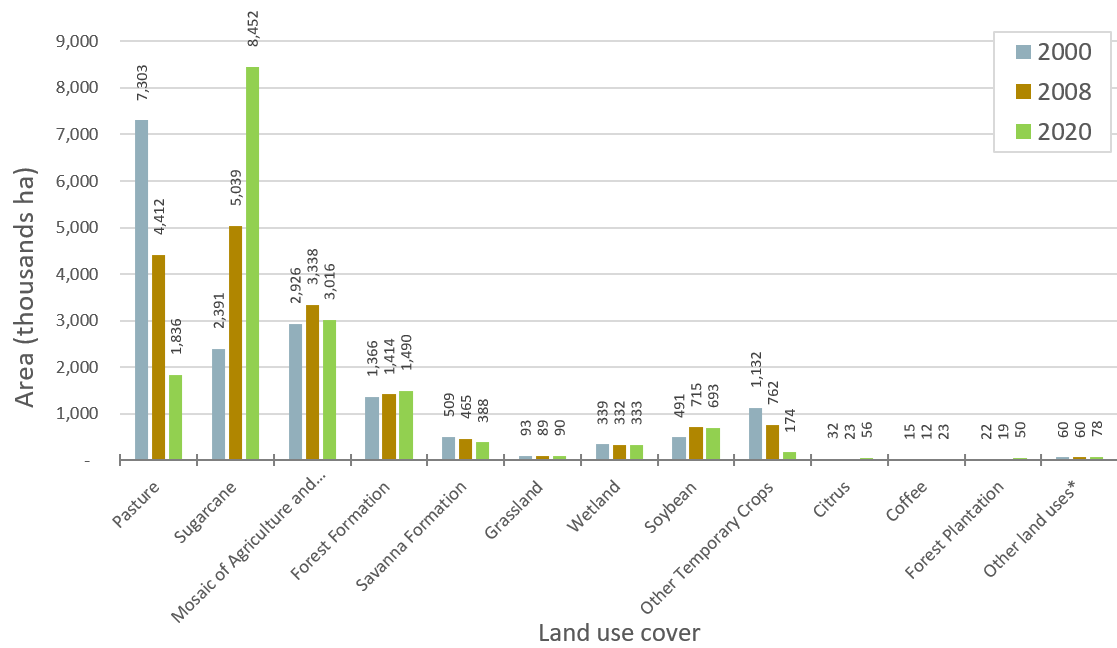


Figure S5. Area of land use and land cover in all CARs of the analyzed region, in the years 2000, 2008 and 2000. *Other land uses: include Aquaculture; Mining; Other non Forest Formations; Other non Vegetated Areas; Other Perennial Crops; River, Lake and Ocean; Rocky Outcrop; Urban Area; Wooded Restinga

Table S4. Dynamics of native vegetation cover in all CARs

Natural Vegetation	Area (ha)			Variation (2000 – 2020)		Variation (2008 – 2020)	
	2000	2008	2020	ha	%	ha	%
Forest Formation	1,365,686	1,413,621	1,489,925	124,239	9.1	76,304	5.4
Savanna Formation	508,500	465,248	387,745	-120,755	-23.7	-77,503	-16.7
Grassland	93,118	88,518	89,681	-3,437	-3.7	1,163	1.3
Total	1,967,304	1,967,387	1,967,351	47	0.0	- 36	0.0
Wetland	339,432	331,559	332,703	-6,729	-2.0	1,144	0.3
Total	2,306,736	2,298,947	2,300,054	-6,682	-0.3	1,107	0.0

Table S5. Dynamics of changes between natural vegetation and sugarcane classes.

Sugarcane’s advance over natural vegetation areas						Recovery of sugarcane areas into natural vegetation		
	Area (ha)		% of total sugarcane area ¹		% of sugarcane expanded area ²		Area (ha)	
	2000 – 20	2008 – 20	2000 – 20	2008 – 20	2000 – 20	2008 – 20	2000-20	2008-20
Forest Formation	52,835	35,170	0.63%	0.42%	0.84%	0.88%	8,297	8,482
Grassland	14,330	6,535	0.17%	0.08%	0.23%	0.16%	1,123	2,326
Savanna Formation	61,060	32,163	0.72%	0.38%	0.97%	0.80%	697	1,094
Wetland	5,650	2,540	0.07%	0.03%	0.09%	0.06%	992	1,948
Total	133,874	76,408	1.58%	0.90%	2.12%	1.91%	11,109	13,851

¹Relative percentage considering the total sugarcane area in 2020

²Relative percentage considering the total sugarcane area in 2020, excluding the areas that already had sugarcane at the beginning of the period

Table S6. Sugarcane expansion (2020) over land uses as of 2000. Areas are in hectares x 1000

From	Total	SP	MG	PR	MT	MS	GO	TO	ES	AM
Sugarcane	2,139.77	2,000.41	57.04	67.66	10.84	0.58	2.85	0.40	-	-
Pasture	3,759.71	2,156.30	463.45	271.65	60.43	456.24	347.56	0.90	0.63	2.54
Mosaic	1,371.79	989.26	132.42	77.37	1.08	58.49	111.34	1.78	0.05	-
Natural Vegetation	133.87	61.11	21.33	1.73	13.39	13.59	19.17	1.82	0.00	1.73
Temporary Crops	1,010.82	311.07	144.25	121.97	31.06	73.96	323.69	4.83	-	0.00
Perennial Crop	23.83	19.28	0.44	1.77	-	-	0.01	-	0.00	-
Forest Plantation	6.57	5.46	0.72	0.28	-	-	0.09	-	0.02	-
Other	5.71	1.01	0.15	0.02	0.01	0.07	4.10	0.35	-	-

Table S7. Sugarcane expansion (2020) over land uses as of 2008. Areas are in hectares x 1000

From	Total	SP	MG	PR	MT	MS	GO	TO	ES	AM
Sugarcane	4,455.03	3642.29	296.93	281.02	35.48	70.93	124.09	0.07	-	4.22
Pasture	1,755.84	848.14	228.39	97.94	27.52	327.19	225.77	0.27	0.62	0.02
Mosaic	1,361.49	894.63	148.51	100.23	0.87	107.99	109.04	0.16	0.06	-
Natural Vegetation	76.41	48.52	7.24	0.66	8.08	3.83	7.79	0.24	0.00	0.04
Temporary Crops	787.33	98.94	138.09	62.21	44.83	92.97	341.05	9.24	-	0.00
Perennial Crop	10.29	9.75	0.17	0.36	-	-	0.01	-	-	-
Forest Plantation	3.21	2.94	0.20	0.00	0.00	-	0.05	-	0.01	-
Other	2.40	0.98	0.27	0.02	0.01	0.02	1.00	0.10	-	0.00

Although sugarcane expansion in the state of Amazonas occurred predominantly over pastures and natural vegetation, the reduction of vegetation in the CARs due to sugarcane reduced significantly after 2008 (1.730 ha between 2000 – 20, and 39 ha between 2008 – 20) (Figure 5). The sugarcane production in this state is destined for the production of sugar and occupies only 4,275 ha (2020).

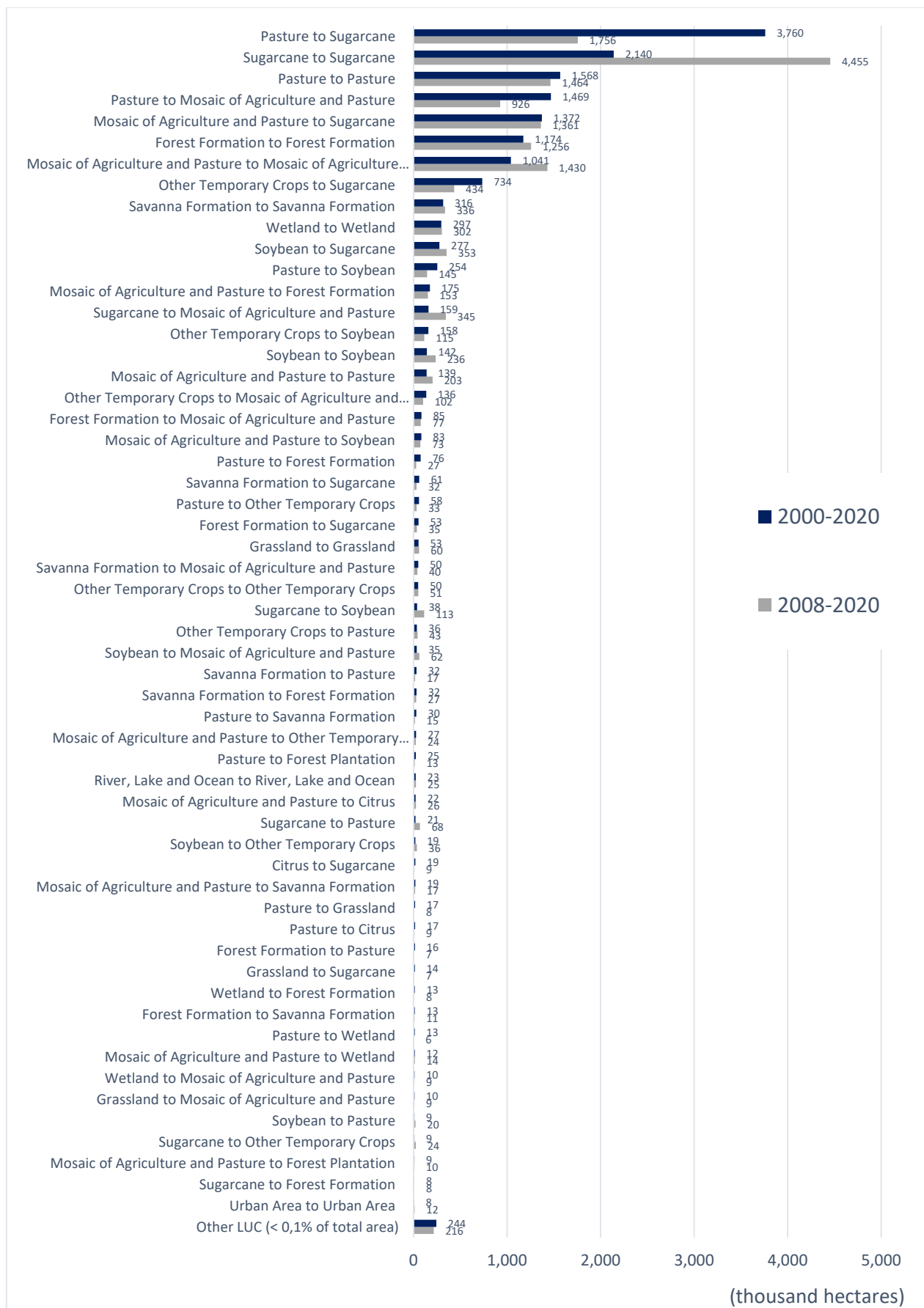


Figure S6. LUC between 2000 – 2020 and 2008 – 2020 in the CARs.

Table S8. History of mechanized harvesting of sugarcane in 2000s harvest seasons (%)

	2000/01	01/02	02/03	03/04	04/05	05/06	06/07	07/08	08/09	09/10	10/11	11/12	12/13	13/14	14/15	15/16	16/17	17/18	18/19	19/20	20/21	21/22	22/23 ⁽¹⁾
AM	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80.0	61.5	63.7	63.0	85.4	95.5	95.1	98.4	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
TO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.0	36.0	50.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
MT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	33.3	46.3	57.3	64.3	75.1	77.9	80.0	87.3	97.7	92.5	91.7	92.7	93.6	93.6	100.0	100.0
MS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.0	34.3	63.3	80.6	89.9	87.2	99.9	90.8	95.8	99.8	99.1	99.9	100.0	100.0	100.0	100.0
GO	0.0	0.0	0.0	0.0	0.0	0.0	0.0	31.5	48.8	64.7	75.8	79.6	83.5	88.0	84.4	91.8	95.9	95.8	96.0	96.3	98.5	97.8	97.8
MG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.4	37.5	47.5	61.5	73.2	80.3	80.0	84.8	98.0	97.0	99.5	99.8	95.2	93.3	97.9	97.5
ES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.7	11.7	22.3	19.3	39.6	50.6	63.5	65.0	70.3	60.8	73.8	75.1	82.2	86.0	80.9	80.0
SP	30.5	29.0	28.0	26.0	28.0	28.0	34.5	33.0	47.6	58.6	62.7	72.2	77.7	81.3	85.1	94.5	94.5	95.9	93.3	97.2	98.3	96.9	99.3
PR	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.4	18.4	26.9	42.0	48.3	59.1	65.3	72.8	74.7	86.6	86.1	79.4	97.3	94.2	95.6	98.4
Brazil	15.8	15.0	14.6	13.6	14.7	15.6	19.7	24.4	37.1	47.6	55.1	63.7	69.2	74.0	76.8	85.1	89.8	90.2	91.6	91.8	89.4	89.4	90.5

Elaborated by authors based on Packer et al. (2015), from 2000 to 2006, and Conab (2022), from 2007 to 2020. ⁽¹⁾ Estimated in April, 2022.

Table S9. Total, net and gross emission/removal due to all LUCs in the CARs (2000–2020), and the percentual of gross removals/emissions due to LUC related to sugarcane cultivation.

Total emission/removal resulting from the conversion of use (tCO ₂ .year ⁻¹) – Period 2000–2020									Net emission/ removal (tCO ₂ .yr ⁻¹)	Total gross emissions (tCO ₂ .yr ⁻¹)	Total gross removals (tCO ₂ .yr ⁻¹)
FROM (2000) TO (2020)	Natural vegetation	Pasture	Sugarcane	Temporary Crop	Perennial Crop	Forest Plantation	Mosaic	Other			
Natural vegetation	-	-1,933,101	-189,606	-221,844	-15,690	-21,607	-3,528,475	-156,619	-6,066,943	0	-6,066,943
Pasture	561,285	-869,947	1,039	-35,210	4,308	3,489	-58,887	-8,868	-402,790	570,121	-972,911
Sugarcane	1,611,133	-6,297,497	-1,887,716	-1,727,429	82,433	22,367	-1,577,482	-52,335	-9,826,525	1,715,934	-11,542,459
Temporary Crop	244,000	57,582	31,083	-	13,580	22,389	31,532	-9,359	390,807	400,166	-9,359
Perennial Crop	136,201	-127,381	-22,217	-17,107	-	-20	-121,061	-179	-151,765	136,201	-287,966
Forest Plantation	48,910	-119,230	-15,126	-9,391	166	-	-37,376	-347	-132,394	49,076	-181,470
Mosaic	1,917,332	-1,785,189	-127,879	-219,149	18,439	11,290	-1,039,951	-84,780	-1,309,885	1,947,061	-3,256,947
Other	115,434	64,426	22,172	28,701	-6,199	560	72,069	-3	297,160	303,363	-6,203
TOTAL	4,634,296	-11,010,336	-2,188,250	-2,201,429	97,037	38,469	-6,259,630	-312,491	-17,202,336	4,769,802	-21,972,137
% of gross removals due to sugarcane cultivation ¹	-	54.6%	16.4%	15.0%	-	-	13.7%	0.5%			
% of gross emissions due to sugarcane cultivation ²	93.9%	-	-	-	4.8%	1.3%	-	-			
% of gross removals due to the respective LUC ³		50.1%	10.0%	10.0%			28.5%	1.4%			
% of gross emissions due to the respective LUC ⁴	97.2%				2.0%	0.8%					

¹ For example, the sugarcane expansion over pastures promoted a removal of -6,297,497 tCO₂.year⁻¹, which corresponds to 54.5% of the total gross removals due to sugarcane cultivation (-11,542,459 tCO₂.year⁻¹).

² For example, the sugarcane expansion over natural vegetation was responsible for the emission of 1,611,133 tCO₂.year⁻¹, which corresponds to 93.9% of the total gross removals due to sugarcane cultivation (1,715,934 tCO₂.year⁻¹).

³ For example, all LUCs over pastures were responsible for the removal of -11,010,336 tCO₂.year⁻¹, which corresponds to 50.1% of the total gross removals due to LUC that provided removals (-21,972,137 tCO₂.year⁻¹, the sum of the negative values in the line "TOTAL").

⁴ For example, all LUCs over natural vegetation were responsible for the emission of 4,634,296 tCO₂.year⁻¹, which corresponds to 97.2% of the total gross emissions due to LUC that provided removals (4,769,802 tCO₂.year⁻¹, the sum of the positive values in the line "TOTAL").