Supporting Information

Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon

Thales A. P. West[1,2,3*], Jan Börner[3,4], Erin O. Sills[5], Andreas Kontoleon[2,6]

[1] *Scion—New Zealand Forest Research Institute, Rotorua, New Zealand*
[2] *Centre for Environment, Energy and Natural Resource Governance (C-EENRG), University of Cambridge, Cambridge, UK*
[3] *Center for Development Research (ZEF), University of Bonn, Bonn, Germany*
[4] *Institute for Food and Resource Economics (ILR), University of Bonn, Bonn, Germany*
[5] *Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, USA*
[6] *Department of Land Economy, University of Cambridge, Cambridge, UK*

*To whom correspondence should be addressed. Email: thales.west@scionresearch.com

Projects excluded from sample

***Ecomapuá project* (VCS-ID 1094).** We did not evaluate this project due to the lack of pre-project information for the construction of a synthetic control. Ecomapuá was certified in 2013 but allegedly started in 2002, years before the REDD+ negotiations gained momentum at the international level[1]. The project reported higher per-hectare stocks of forest carbon than other projects and adopted an unrealistic zero stock in the post-deforestation land-use class (Table S1), which combined maximize carbon offsets.

***Cikel project* (VCS-ID 832) & *Envira project* (VCS-ID 1382).** We did not evaluate these projects because they make fundamentally different assumptions. Their baselines are defined by the amount of forest that can be legally cleared inside the project boundaries in accordance with the Brazilian Forest Code, and they seek to avoid that planned, legal deforestation.

***Fortaleza Ituxi* project (VCS-ID 1654).** We did not evaluate this project because it was not certified by the time we initiated our analysis.

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[1] Pedroni L, Dutschke M, Streck C, Porrúa ME (2009) Creating incentives for avoiding further deforestation: the nested approach. Clim Policy 9(2):207–220.

Deforestation in the projects implemented in protected areas

Both Suruí and Rio Preto-Jacundá projects experienced substantial levels of forest loss due to fires. Graça et al. (2012) estimate that 4187 ha of forest from the Suruí territory was affected by fires during 2010–2011, equivalent to 1.7% of the indigenous land, whereas a report by IMAZON (Araújo et al., 2017) identified the Rio Preto-Jacundá reserve among the top 10 and 20 most deforested protected area in the Brazilian Amazon during 2012–2015 in proportional and absolute terms, respectively.

<u>References</u>

Araújo et al. (2017) Unidades de conservação mais desmatadas da Amazônia Legal 2012–2015. (Belém, Brazil).

Graça PML de A, Vitel CSMN, Fearnside PM (2012) Forest fire scars detection using change-vector analysis in the Sete de Setembro indigenous land - Rondônia. Rev Ambiência 8:511–521.

Selection of deforestation data

Deforestation data for the Brazilian Amazon are available from a number of well-known publicly available datasets. Some examples are PRODES, TerraClass, and MapBiomas. PRODES data result from the official deforestation monitoring program from Brazil's National Institute for Space Research (INPE). Unfortunately, PRODES data, initially available from 2000, underwent a new georectification process in the late 2000s due to incompatibility issues among images from different satellites. The revised version of the data, available in the form of a shapefile, now starts in 2007. We were unable to use the current PRODES data because they would significantly constrain the pretreatment period available for the construction of the synthetic controls.

In contrast, the MapBiomas data are annually available for 1985–2018, but due to a large number of mapped land-use classes (i.e., 6 main classes and 27 subclasses), MapBiomas accuracy is lower than TerraClass. In turn, TerraClass data (also produced by INPE) are not annually available, and therefore could not be used for an annual analysis such as ours. However, as illustrated in Abadie et al. (2003; 2011), covariate data do not need to be available on an annual basis for the construction of synthetic controls. In this study, we attempted to benefit from the higher mapping accuracy from the TerraClass data for the construction of our buffer covariates, while we relied on the MapBiomas data for the annual deforestation estimates.

References

Abadie A, Diamond A, Hainmueller J (2011) Synth: An R package for synthetic control methods in comparative case studies. J Stat Softw 42(13):1–17.

Abadie A, Gardeazabal J (2003) The economic costs of conflict: A case study of the Basque country. Am Econ Rev 93(1):113–132

Deforestation-data processing

Annual deforestation information for the 2001–2017 period was obtained from the Amazon biome land-use/cover (LUC) maps of *MapBiomas*[2] (v.3.1). Maps were resampled at the 250-meter resolution, following Brazil's official deforestation-mapping system (PRODES), and reclassified based on the following land-cover classes: forest, non-forest, and water. We applied a series of spatiotemporal filters to (i) replace each cloud pixel with the pixel's LUC class in the next observable year or mask them from the analysis when the pixel's LUC class was unobserved throughout the study period, (ii) mask pixels that transitioned from forest to water (and vice-versa), (iii) mask forest pixels that transitioned to another class in one year, but transitioned back in the next, and (iv) non-forest pixels that transitioned to forest (because our study is focused on the avoided deforestation of mature forests).
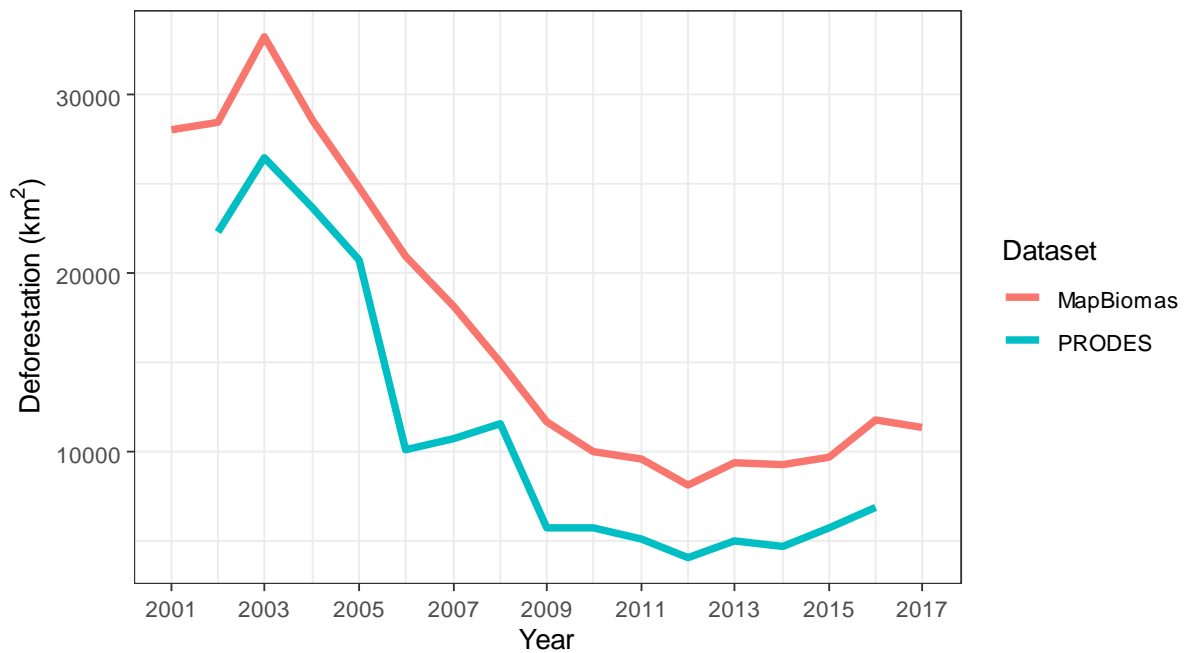

Figure S1. Deforestation in the Amazon biome: *MapBiomas* land-use/-cover dataset (v.3.1) versus PRODES municipality-level dataset (summing across all municipalities at least 50% inside the Amazon forest biome).

Standard methods for the construction of deforestation baseline for voluntary REDD+ projects

Standard deforestation baselines tend to assume the continuation of historical deforestation trends. The period for calculating historical deforestation rates is specified in the VCS-approved methodology adopted by the project proponents (all projects must follow an appropriate VCS-approved methodology). The general VCS rule, from the *VCS Agriculture, Forestry and Other Land Use (AFOLU) Requirements* (v.3.6), is:

> *Methodologies shall set out criteria and procedures to identify where deforestation would likely occur using spatial analysis and projections […] Such analysis shall be based on historical factors over at least the previous 10 years that explain past patterns and can be used to make future projections of deforestation.*

All projects evaluated in our study adopted either VCS's methodology VM0007 or VM0015 (Table S1). Both methodologies are rather similar when it comes to unplanned deforestation baseline development. In general, historical deforestation rates, from a *reference region* that usually encompasses the project area, are extrapolated into the future based on a linear (or non-linear) time trend. In some cases, where there is no clear trend present in the data (or for conservative purposes), the historical average is used (e.g., see the *Florestal Santa Maria* Project in Figure S5). It is also common for project proponents to employ existing land-use/cover change models available in the literature to forecast deforestation. Many of these models, e.g., *Dynamica EGO* (Soares-Filho et al., 2002) and *TerrSet/IDRISI* (West et al., 2020), employ Markov-chain, land-use transition matrices, which imply in an exponential-decay trend of annual deforestation rates (which can be somewhat observed in some of the projects from Figure S5).

The Suruí Project's baseline is an exception to the rule described above. In that case, baseline deforestation rates were informed by a community-specific, system dynamics model, the *SIMSURUI*, developed by Vitel et al. (2013) based on a participatory model development approach:

> *The SIMSURUI model includes components that are specific to the Suruí socio-ecological system, including interactions among demography, economy and landscape. Land use reflects the strategic development of productive activities by different Suruí agent groups. Vegetation dynamics are inferred from these interactions. The systems model was coupled with a cellular automata model to spatially allocate the modeled deforestation rate.*

References

Soares-Filho BS et al. (2002). DINAMICA—a stochastic cellular automata model designed to simulate the landscape dynamics in an Amazonian colonization frontier. Ecol Modell 154, 217–235

Vitel CSMN, et al. (2013) Land-use change modeling in a Brazilian indigenous reserve: Construction of a reference scenario for the Suruí REDD Project. Hum Ecol 41(6):807–826

West TAP et al. (2020) Comparison of spatial modelling frameworks for the identification of future afforestation in New Zealand. Landsc Urban Plan 198, 103780

Criteria for construction and selection of synthetic controls

The construction of synthetic controls (SCs) is sensitive to the heterogeneity of donors. The following criteria were adopted to ensure impartial construction of the SCs:

1. *Donor location*. Donor pools preferably include only parcels in the same state as the REDD+ projects. Pools are expanded to parcels within the Amazon biome if the SC constructed from same-state donors failed to pass quality assessment due to unbalanced covariates.

2. *Quality assessment*. SCs are assessed based on two criteria: (1) pre-treatment cumulative and annual deforestation rates, expected to be within ±10% the average pre-treatment rates observed in the REDD+ project area, and (2) SC area, expected to be within ±25% the REDD+ project area.

3. *Size restrictions*. If the SC area criterion is not met, donor pools are restricted to donors with areas within ±25% the REDD+ project area. If the area criterion remains unmet, the latter interval is expanded to ±50% and the optimal SC with the lowest possible Mean Squared Prediction Error (MSPE) drawing on an Amazon-wide donor pool is selected independent of the quality assessment.

Table S1. Voluntary REDD+ projects.

ID [1]	Project	State [2]	Carbon-accounting (baseline) methodology	Start year	Year of certification (i.e., *validation*)	Average annual baseline deforestation until 2017 (ha year^{-1})	Cumulative baseline deforestation until 2017 (ha)	Forest carbon stock (CO_2 ha^{-1})	Average post-deforestation carbon stock (CO_2 ha^{-1})	Ex-ante net avoided carbon emissions until 2017 [3] (Mg CO_2)	Tradable carbon offsets issued by 2017 [1,4] (Mg CO_2)	Tradable carbon offsets issued as of September 2019 [1,4] (Mg CO_2)	Certified carbon offsets not yet issued for trading as of September 2019 [1] (Mg CO_2)
981	*ADPML Portel-Para*	PA	VM0015	2009	2013	537.2	4835	519.9	51.6	2,147,616	82,000	167,000	310,611
1686	*Agrocortex*	AC, AM	VM0015	2014	2018	949.1	3796	619.5	46.9	1,162,030	0	6550	68,973
875	*Florestal Santa Maria*	MT	VM0007	2009	2012	2038.9	18,350	563.3	77.1	8,555,310	2,564,096	2,564,096	8593
1115	*Jari/Amapá*	AP	VM0015	2011	2013	654.7	4583	566.0	61.2	781,688	275,772	536,560	0
1329	*Maísa*	PA	VM0015	2012	2015	282.8	1697	453.1	61.2	464,012	50,489	52,108	0
1571	*Manoa*	RO	VM0015	2013	2017	424.8	2124	513.0	64.6	677,295	0	482,344	0
963	*Purus*	AC	VM0007	2011	2013	582.9	4080	512.9	46.9	667,064	707,358	979,876	N/A
1503	*Rio Preto-Jacundá*	RO	VM0015	2012	2016	1222	6111	476.8	61.2	1,999,626	654,406	1,063,434	148,092
977	*RMDLT Portel-Para*	PA	VM0015	2008	2013	1237.3	12,373	519.9	51.6	5,512,539	607,622	1,711,334	1,562,406
1112	*Russas*	AC	VM0007	2011	2014	608.9	3653	411.0	35.2	723,893	76,252	84,894	217,733
1118	*Suruí*	RO, MT	VM0015	2009	2012	237.5	2137	633.9	47.0	1,139,504	251,529	251,529	0
1113	*Valparaiso*	AC	VM0007	2011	2014	798.1	4788	440.1	35.2	1,023,826	97,528	114,192	373,168
Total										24,854,403	5,367,052	8,013,917	2,689,576

[1] Obtained from the *Verified Carbon Standard* (VCS)'s project database.

[2] Acre (AC), Amapá (AP), Amazonas (AM), Mato Grosso (MT), Pará (PA), and Rondônia (RO).

[3] Ex-ante avoided net carbon emissions are calculated as the difference between baseline deforestation emissions minus ex-ante (planned) emissions from the REDD+ project. In some cases, there is also a small percentage deduction for assumed leakage emissions.

[4] Tradable offsets can differ from the ex-ante estimates for several reasons: (1) they depend on whether and when verification has occurred to certify net carbon emissions; (2) they are based on ex-post avoided net carbon emissions measurements; and (3) they are discounted by an "insurance" percentage allocated to the VCS's cross-project *pooled buffer account*.

Table S2. Reported versus calculated project area, and deforestation from start date to 2017.

ID [1]	Project	Project area [2] (ha)	Polygon area [3,4] (ha)	Forest cover in the polygon at start date [5] (ha)	Start date	Cumulative deforestation in the polygon from start date to 2017 (ha)	Percent of forest cover in the polygon lost since start date (%)	Maximum deforestation possible outside project boundaries [6] (ha)
981	*ADPML Portel-Para*	135,106	149,147	148,521	2009	600	0.4	13,415
1686	*Agrocortex*	186,219	186,369	186,350	2014	63	<0.0	131
875	*Florestal Santa Maria*	70,000	71,662	71,490	2009	213	0.3	1490
1115	*Jari/Amapá*	65,980	77,857	76,557	2011	3581	4.7	10,577
1329	*Maísa*	28,752	30,976	29,495	2012	131	0.4	743
1571	*Manoa*	72,843	72,899	71,797	2013	13	<0.0	0
963	*Purus*	34,702	35,195	34,931	2011	500	1.4	229
1503	*Rio Preto-Jacundá*	94,289	99,336	99,038	2012	3125	3.2	4749
977	*RMDLT Portel-Para*	177,900	194,550	193,985	2008	694	0.4	16,085
1112	*Russas*	41,976	42,519	42,243	2011	356	0.8	267
1118	*Suruí*	247,796	247,796	244,525	2009	5568	2.3	–
1113	*Valparaiso*	28,096	28,988	28,669	2011	575	2.0	573

[1] Obtained from the *Verified Carbon Standard* (VCS)'s project database.

[2] Reported in the official project description documents.

[3] In the case of the Suruí project, the entire polygon (i.e., indigenous land) serves as the project's buffer zone for leakage assessment. This implies that all deforestation inside the indigenous land is linked to the project.

[4] Obtained from official project KML files (often the same as the polygon from the CAR database).

[5] Processed from the *MapBiomas* dataset (Fig. S1).

[6] Computed as *forest cover in the polygon at start date* (ha) minus *project area* (ha). Note that if there was more forest cover outside the Project Area than the area recorded as deforested, then it is theoretically possible that all of that deforestation occurred outside the official project boundaries.
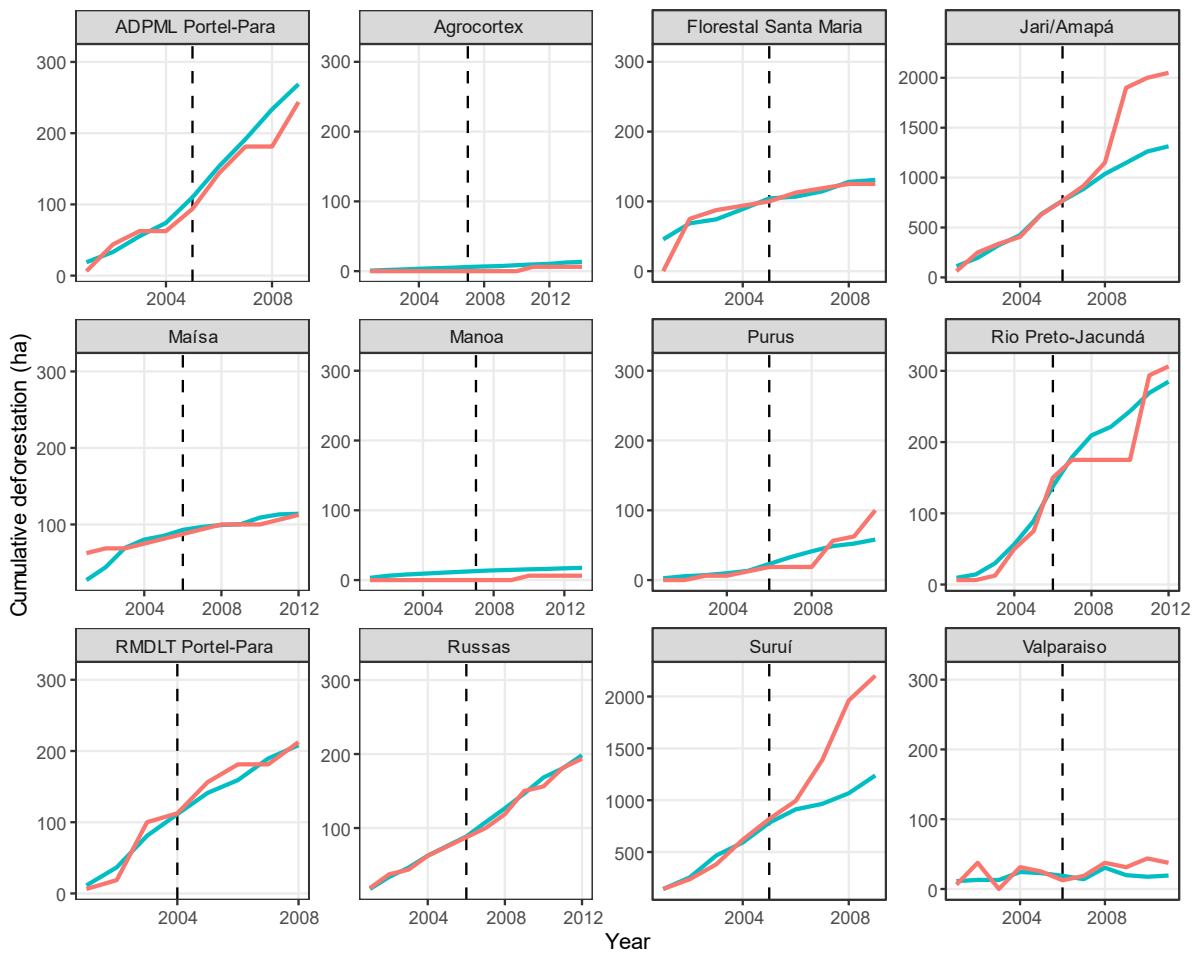
Figure S2. "Proof-of-concept" results from the synthetic control method. Pretreatment deforestation in areas with REDD+ projects (red) versus synthetic controls (blue). Dashed black lines separate "training" and "testing" periods.

Table S3. "Proof-of-concept" results from the synthetic control method. Pretreatment mean squared prediction errors (MSPEs) from the "training" and "testing" periods.

Project	Start year	Training period	Training MSPE	Testing period	Testing MSPE	Training/testing MSPE
ADPML Portel-Para	2009	2001–2005	143.8	2006–2009	887.1	6.2
Agrocortex	2014	2001–2007	14.1	2008–2014	41.1	2.9
Jari/Amapá	2011	2001–2006	686.0	2007–2011	407,000	593.3
Maísa	2012	2001–2006	318.9	2007–2012	23.3	0.1
Manoa	2013	2001–2007	86.6	2008–2013	137.2	1.6
Purus	2011	2001–2006	11.6	2007–2011	524.1	45.2
Rio Preto-Jacundá	2012	2001–2006	127.4	2007–2012	1513.7	11.9
RMDLT Portel-Para	2008	2001–2004	177.2	2005–2008	201.1	1.1
Russas	2012	2001–2006	3.8	2007–2012	50.3	13.2
Florestal Santa Maria	2009	2001–2005	466.4	2006–2009	23.4	0.1
Suruí	2009	2001–2005	2035.8	2006–2009	463,179	227.5
Valparaiso	2012	2001–2006	147.1	2007–2012	244.6	1.7
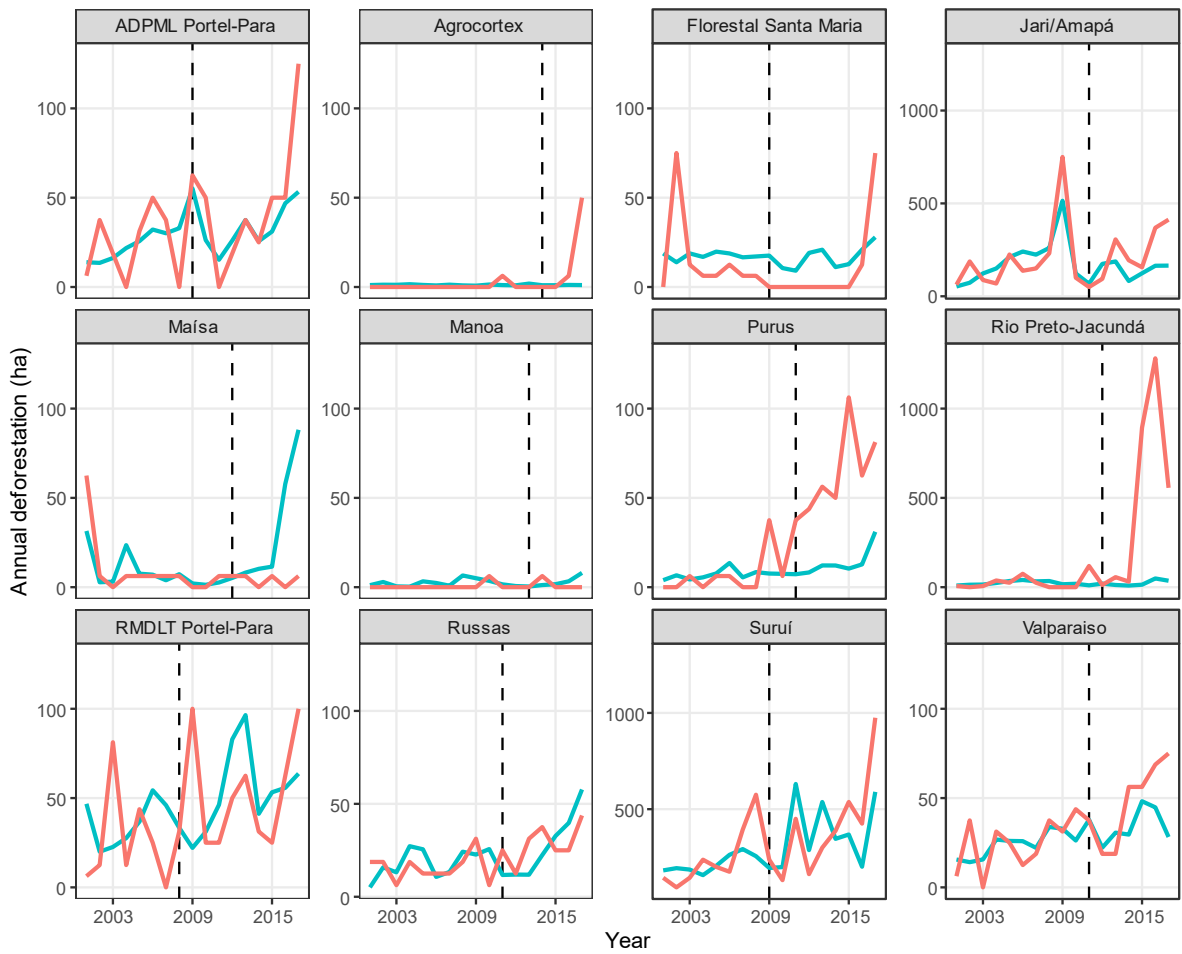
Figure S3. Annual post-2000 deforestation in Amazonian areas with REDD+ projects (red) versus synthetic controls (blue). Dashed black lines are the project start dates.
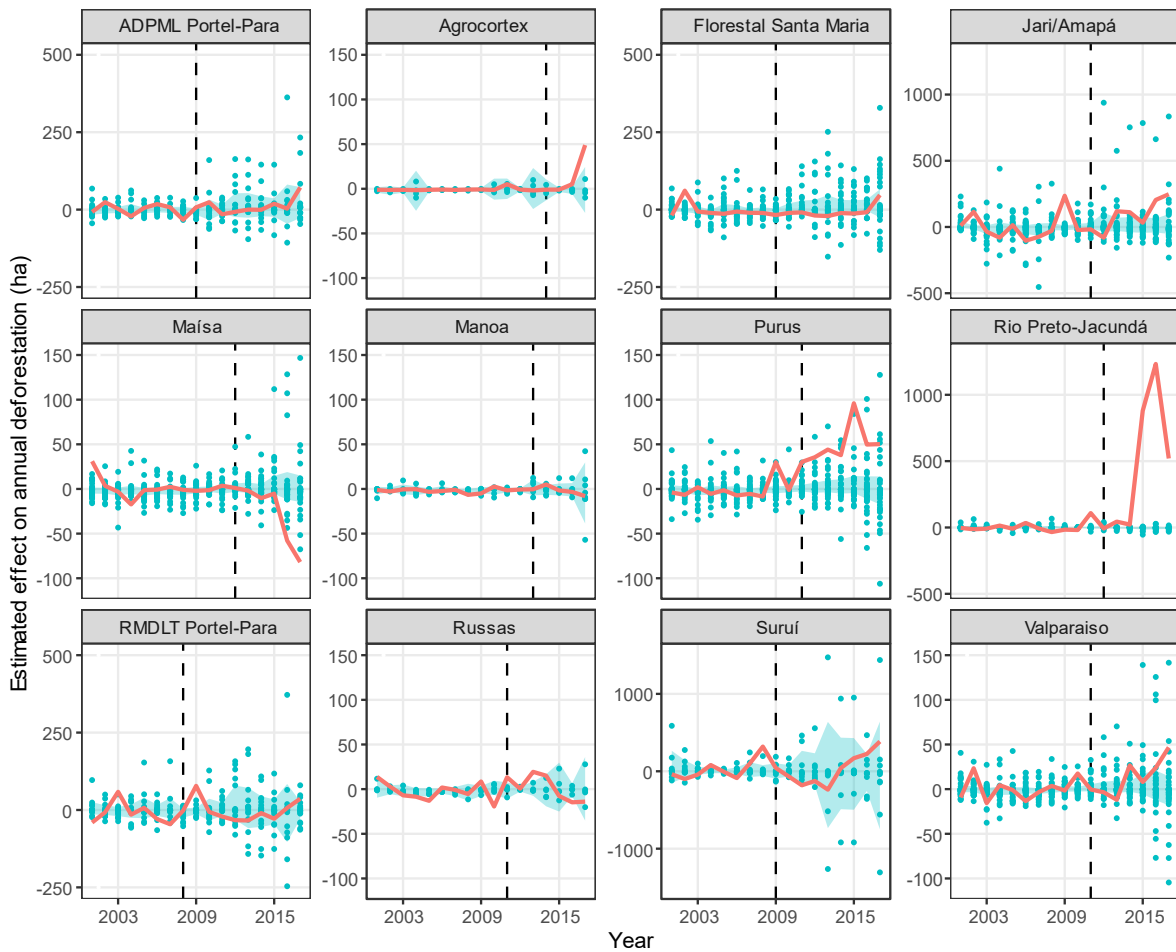
Figure S4. Placebo tests: annual deforestation in REDD+ project areas minus deforestation in their respective synthetic controls (red), and placebos minus their respective synthetic controls (blue dots). Dashed black lines are the project start dates (assumed the same for placebos). Shaded blue areas represent 99% confidence intervals around the mean of the placebos. The number of placebos varies by project based on whether synthetic controls with low mean squared prediction error could be constructed for the placebo tests.
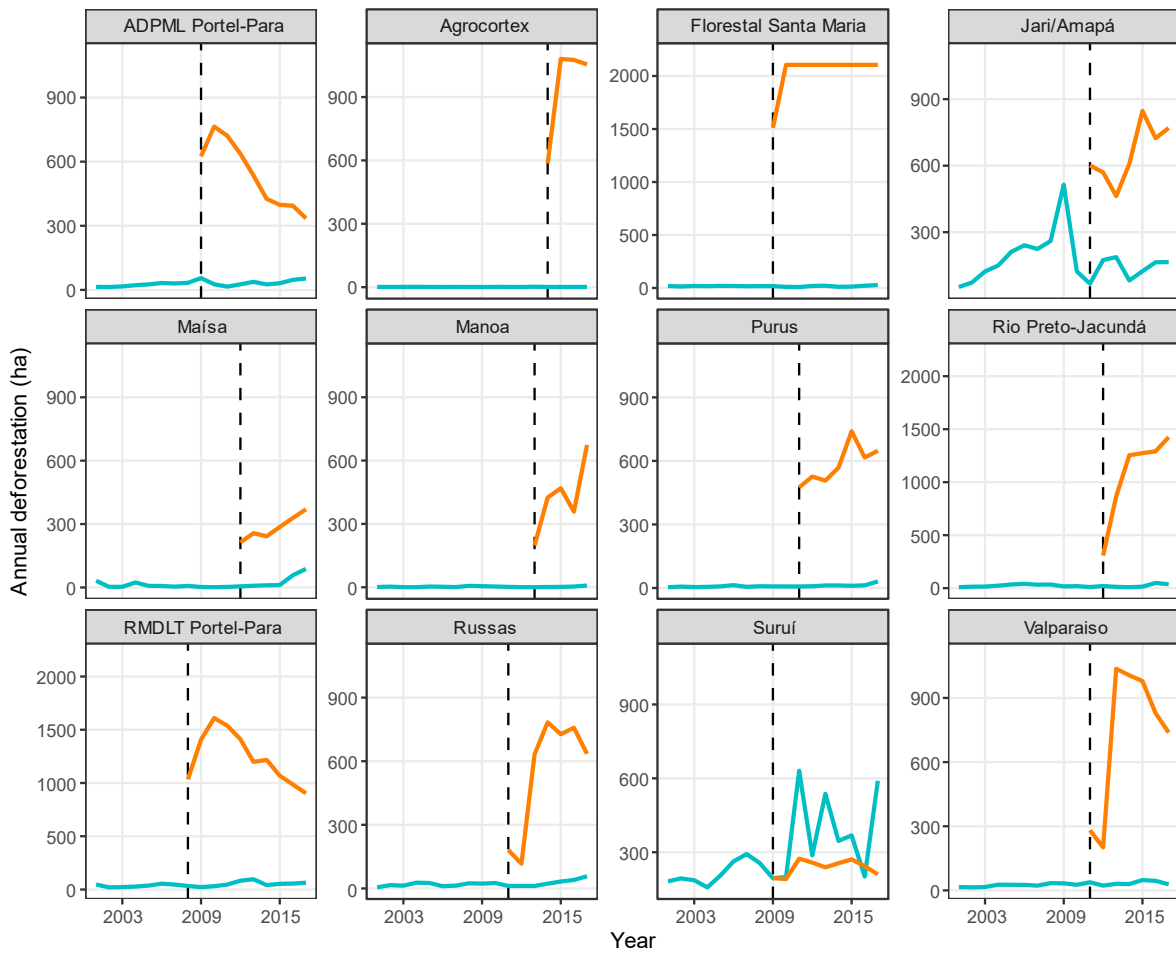
Figure S5. Annual deforestation from the baseline scenarios adopted by the REDD+ projects (orange) versus observed annual deforestation in the synthetic controls (blue). Dashed black lines are the project start dates.
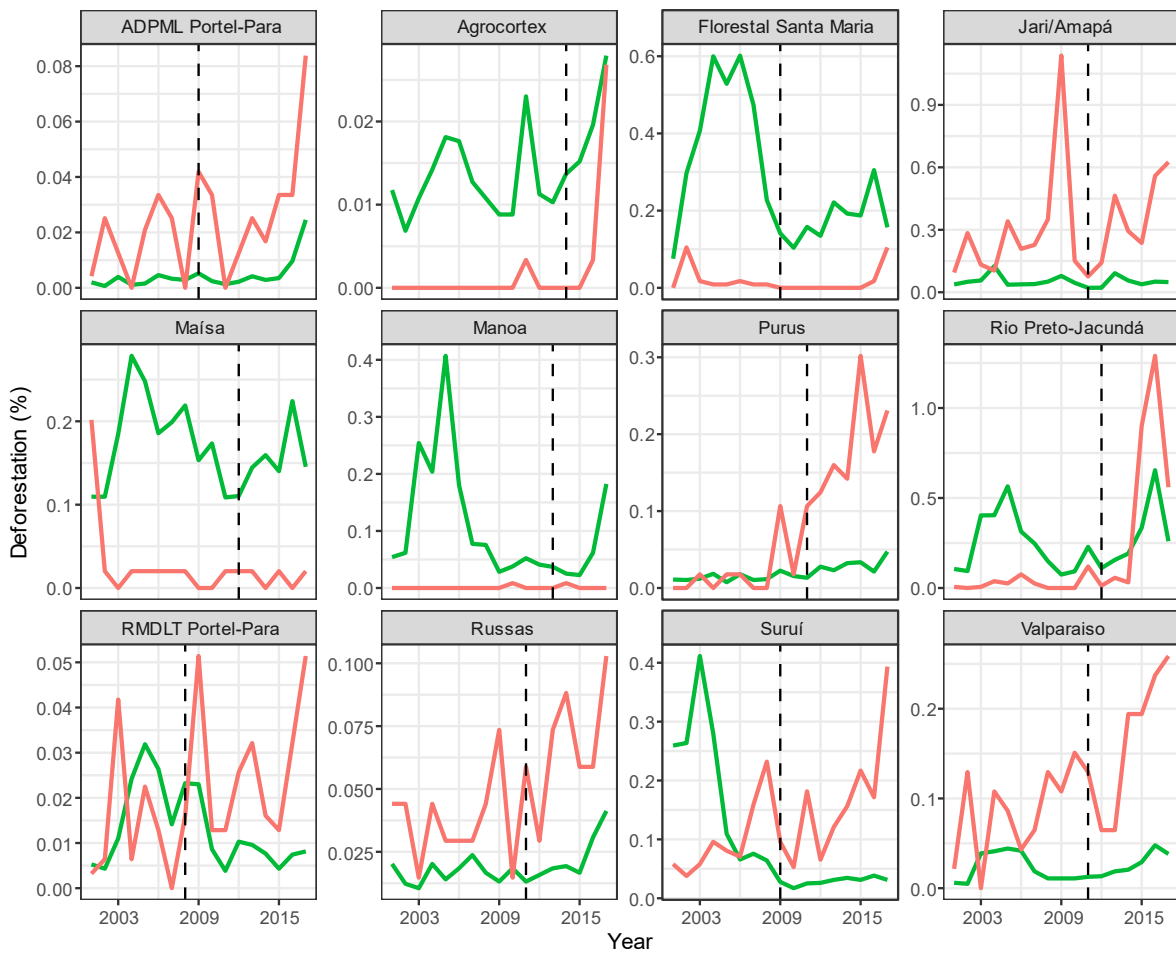
Figure S6. Annual deforestation (proportional to area) in REDD+ project areas (red) and 10-km buffer zones around the projects (green). Dashed black lines are the project start dates.

Table S4. Maps used for the creation of spatial covariates.

Map	Description	Source
Distance from state capitals	Euclidean-distance map from state capitals in Brazil	Brazilian Institute of Geography and Statistics (IBGE; available for download here)
Distance from urban centers	Euclidean-distance map from townhalls with government agency offices.	Brazilian Institute of Geography and Statistics (IBGE; available for download here)
Distance from highways	Euclidean-distance map from federal and state highways.	Ministry of Infrastructure (available for download here)
Distance from roads	Euclidean-distance map from regional roads.	Brazilian Institute of Geography and Statistics (IBGE; available for download here)
Slope	Continuous slope map (degrees) on a mosaic of the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global, Digital Elevation Maps (meters)	United States Geological Survey (USGS; available for download here)
Soil quality	Ordinal map that indicates soil agricultural potential, from poor quality (i.e., 0) to excellent quality (i.e., 4).	Brazilian Institute of Geography and Statistics (IBGE; available for download here)

Figure S7. Maps used for the creation of spatial covariates.

Annex 1. Cumulative deforestation analyses: covariate balance between the REDD+ polygons and synthetic controls for the period from 2001 to project start year

Table A1-1. REDD+ project: *ADPML Portel-Para REDD Project*

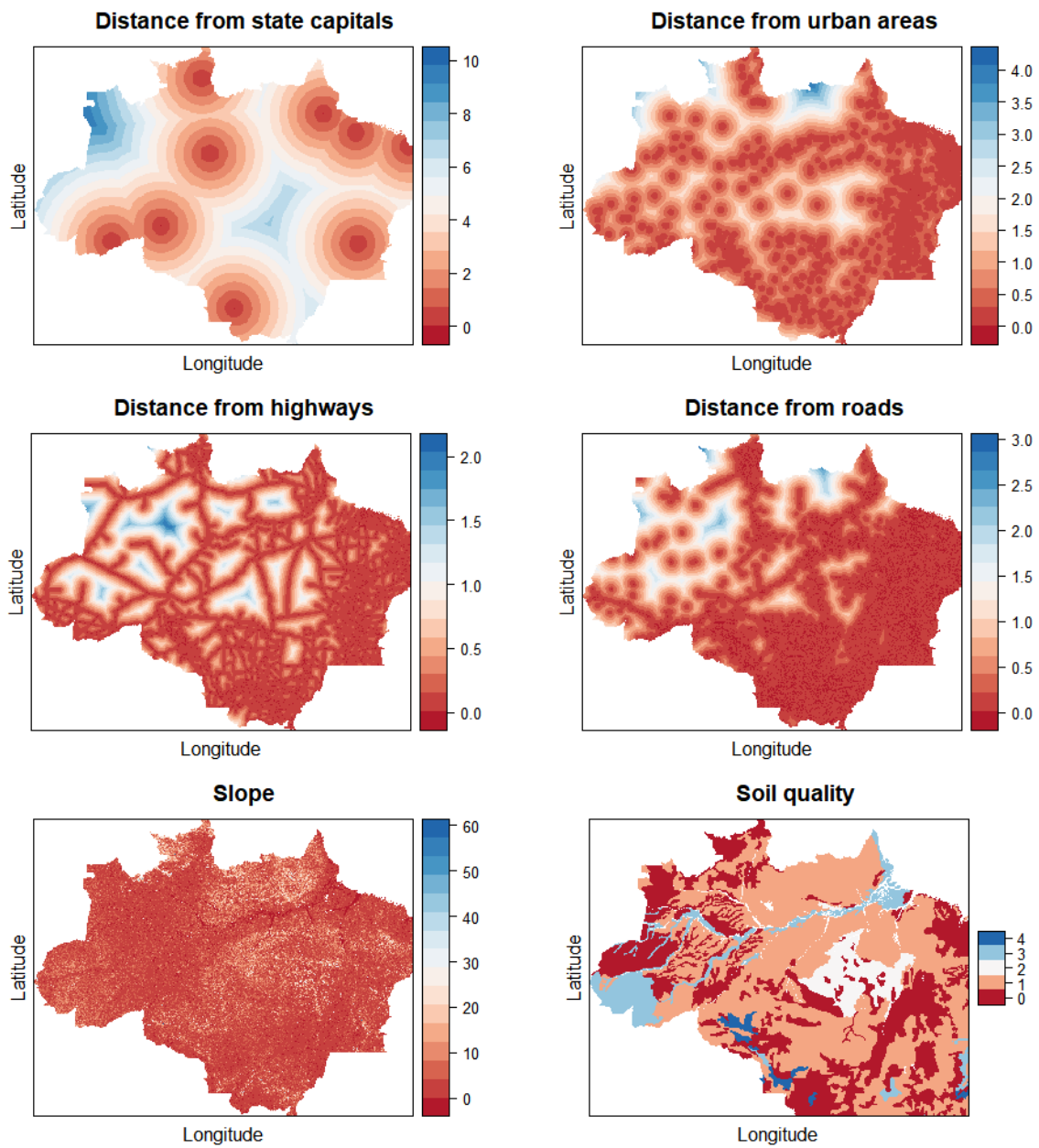| Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	149,147	116,186	116,644
Initial forest cover (%)	99.58	99.72	97.99
Euclidean distance to state capital	2.222	2.047	3.207
Euclidean distance to highways	0.504	0.273	0.242
Average slope	4.036	5.432	5.032
Average soil quality	2.000	2.221	2.474
Euclidean distance to urban areas	0.496	0.507	0.605
Euclidean distance to roads	0.277	0.307	0.276
Average cumulative deforestation (ha)	113.194	115.058	1244.349
Average annual deforestation (ha)	27.083	26.154	266.715
Proportion of primary forests in the buffer zone (%)	83.8	93.7	86.2
Proportion of secondary forests in the buffer zone (%)	1.8	1.4	2.8
Proportion of pastures in the buffer zone (%)	0.8	1.2	4.6
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	153.452	–

*Based on eight synthetic-control donors, five from Pará state, two from Amazonas state, and one from Mato Grosso state.

Table A1-2. REDD+ project: *Agrocortex REDD Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	186,369	114,338	135,140
Initial forest cover (%)	99.99	99.98	98.63
Euclidean distance to state capital	1.975	4.224	3.357
Euclidean distance to highways	0.437	0.387	0.23
Average slope	4.800	4.521	4.693
Average soil quality	3.898	3.611	2.795
Euclidean distance to urban areas	0.450	0.42	0.638
Euclidean distance to roads	0.373	0.444	0.303
Average cumulative deforestation (ha)	1.786	5.49	1461.748
Average annual deforestation (ha)	0.446	0.769	177.397
Proportion of primary forests in the buffer zone (%)	98.2	97.6	89
Proportion of secondary forests in the buffer zone (%)	0.4	0.4	2.6
Proportion of pastures in the buffer zone (%)	0.9	0.2	3.4
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	16.768	–

*Based on six synthetic-control donors, two from Acre state and three from Amazonas state, and one from Pará state.

Table A1-3. REDD+ project: *Florestal Santa Maria Project* (FSM)

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	71,662	64,901	55,940
Initial forest cover (%)	99.76	99.57	97.81
Euclidean distance to state capital	4.663	3.083	3.223
Euclidean distance to highways	0.155	0.131	0.245
Average slope	5.115	4.405	5.557
Average soil quality	2.000	2.001	2.440
Euclidean distance to urban areas	0.346	0.650	0.614
Euclidean distance to roads	0.040	0.240	0.202
Average cumulative deforestation (ha)	93.056	93.345	1952.358
Average annual deforestation (ha)	13.889	15.613	425.723
Proportion of primary forests in the buffer zone (%)	82.6	83.0	82.1
Proportion of secondary forests in the buffer zone (%)	1.4	4.6	3.0
Proportion of pastures in the buffer zone (%)	10.1	10.0	6.7
Proportion of agriculture in the buffer zone (%)	0.0	0.4	0.7
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	322.745	–

*Based on four synthetic-control donors, one from Amazonas state, one from Mato Grosso state, and two from Pará state.

Table A1-4. REDD+ project: *Jari/Amapá REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	77,857	73,950	75,533
Initial forest cover (%)	98.33	99.11	97.21
Euclidean distance to state capital	1.544	2.397	2.787
Euclidean distance to highways	0.059	0.227	0.255
Average slope	8.422	8.401	5.970
Average soil quality	2.000	2.007	2.291
Euclidean distance to urban areas	0.231	0.446	0.562
Euclidean distance to roads	0.055	0.32	0.274
Average cumulative deforestation (ha)	952.273	954.89	1458.452
Average annual deforestation (ha)	186.364	184.881	251.243
Proportion of primary forests in the buffer zone (%)	75.5	81.8	84.4
Proportion of secondary forests in the buffer zone (%)	4.0	5.5	3.1
Proportion of pastures in the buffer zone (%)	2.1	2.5	4.8
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.3
Proportion of urban areas in the buffer zone (%)	0.2	0.0	0.0
Mean squared prediction error (Loss V)	–	6505.548	–

*Based on nine synthetic-control donors, two from Pará state, two from Mato Grosso state, three from Acre state, and two from Amazonas state.

Table A1-5. REDD+ project: *Maísa REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	30,976	28,992	31,502
Initial forest cover (%)	95.22	98.03	98.64
Euclidean distance to state capital	1.993	2.110	3.083
Euclidean distance to highways	0.188	0.168	0.259
Average slope	3.704	3.914	5.262
Average soil quality	2.000	1.962	2.473
Euclidean distance to urban areas	0.486	0.718	0.634
Euclidean distance to roads	0.021	0.046	0.218
Average cumulative deforestation (ha)	88.021	87.159	1046.79
Average annual deforestation (ha)	9.375	9.614	145.417
Proportion of primary forests in the buffer zone (%)	75.2	79.0	85.6
Proportion of secondary forests in the buffer zone (%)	8.1	5.9	2.4
Proportion of pastures in the buffer zone (%)	11.8	11.9	7.0
Proportion of agriculture in the buffer zone (%)	0.0	0.5	1.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	171.922	–

*Based on five synthetic-control donors, one from Amazonas state, two from Acre state, two one from Pará state.

Table A1-6. REDD+ project: *Manoa REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	72,899	73,271	70,370
Initial forest cover (%)	99.86	99.72	97.67
Euclidean distance to state capital	1.213	2.590	2.815
Euclidean distance to highways	0.238	0.260	0.276
Average slope	4.096	5.748	5.679
Average soil quality	2.000	2.355	2.450
Euclidean distance to urban areas	0.501	0.656	0.622
Euclidean distance to roads	0.146	0.575	0.296
Average cumulative deforestation (ha)	1.923	7.791	1326.224
Average annual deforestation (ha)	0.481	0.970	185.468
Proportion of primary forests in the buffer zone (%)	93.4	97.3	85.6
Proportion of secondary forests in the buffer zone (%)	1.0	0.3	2.6
Proportion of pastures in the buffer zone (%)	4.7	0.1	4.5
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.4
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	40.597	–

*Based on nine synthetic-control donors, one from Mato Grosso state, one from Acre state, four from Amazonas state, and three from Pará state.

Table A1-7. REDD+ project: *The Purus Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	35,194	28,331	30,639
Initial forest cover (%)	99.25	99.63	99.21
Euclidean distance to state capital	1.956	2.849	2.576
Euclidean distance to highways	0.190	0.129	0.137
Average slope	5.202	5.323	5.611
Average soil quality	4.000	3.887	3.667
Euclidean distance to urban areas	0.303	0.328	0.525
Euclidean distance to roads	0.176	0.245	0.273
Average cumulative deforestation (ha)	27.273	33.753	101.705
Average annual deforestation (ha)	9.091	6.419	19.271
Proportion of primary forests in the buffer zone (%)	98.2	93.9	95.1
Proportion of secondary forests in the buffer zone (%)	0.3	2.8	1.9
Proportion of pastures in the buffer zone (%)	0.7	2.5	2.4
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	215.954	–

*Based on four synthetic-control donors from Acre state.

Table A1-8. REDD+ project: *Resex Rio Preto-Jacundá REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	99,336	94,986	115,265
Initial forest cover (%)	99.70	96.493	94.877
Euclidean distance to state capital	1.644	3.188	3.169
Euclidean distance to highways	0.059	0.154	0.164
Average slope	3.657	3.791	3.363
Average soil quality	2.000	1.729	1.884
Euclidean distance to urban areas	0.519	0.818	0.824
Euclidean distance to roads	0.113	0.192	0.279
Average cumulative deforestation (ha)	133.333	138.734	178.542
Average annual deforestation (ha)	25.521	22.809	27.833
Proportion of primary forests in the buffer zone (%)	84.1	65.1	73.1
Proportion of secondary forests in the buffer zone (%)	2.5	1.0	1.8
Proportion of pastures in the buffer zone (%)	9.9	2.2	5.8
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	888.765	–

*Based on two synthetic-control donors from sustainable-use reserves.

Table A1-9. REDD+ project: *RMDLT Portel-Para REDD Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	194,550	183,877	162,053
Initial forest cover (%)	99.71	99.41	98.896
Euclidean distance to state capital	2.553	3.434	3.434
Euclidean distance to highways	0.298	0.272	0.206
Average slope	4.683	6.027	5.065
Average soil quality	2.000	3.990	3.278
Euclidean distance to urban areas	0.636	0.559	0.636
Euclidean distance to roads	0.129	0.430	0.225
Average cumulative deforestation (ha)	121.094	127.782	1399.609
Average annual deforestation (ha)	26.562	30.847	315.938
Proportion of primary forests in the buffer zone (%)	94.3	97.2	92.1
Proportion of secondary forests in the buffer zone (%)	1.4	1.1	2.4
Proportion of pastures in the buffer zone (%)	0.7	0.8	3.0
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	996.405	–

*Based on six synthetic-control donors, one from Pará state, two from Amazonas state, and three from Acre state.

Table A1-10. REDD+ project: *The Russas Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	42,519	38,853	41,637
Initial forest cover (%)	99.35	99.24	99.22
Euclidean distance to state capital	5.128	3.541	2.759
Euclidean distance to highways	0.044	0.135	0.148
Average slope	3.533	5.974	5.934
Average soil quality	2.730	3.955	3.479
Euclidean distance to urban areas	0.174	0.355	0.481
Euclidean distance to roads	0.174	0.244	0.276
Average cumulative deforestation (ha)	102.083	98.993	216.732
Average annual deforestation (ha)	16.146	15.893	35.677
Proportion of primary forests in the buffer zone (%)	94.9	93.4	93.2
Proportion of secondary forests in the buffer zone (%)	2.8	2.3	2.1
Proportion of pastures in the buffer zone (%)	1.9	3.8	4.2
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	72.338	–

*Based on three synthetic-control donors from Acre state.

Table A1-11. REDD+ project: *Suruí Forest Carbon Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	247,796	250,867	218,195
Initial forest cover (%)	98.68	98.58	98.57
Euclidean distance to state capital	3.493	3.875	3.459
Euclidean distance to highways	0.193	0.275	0.319
Average slope	5.809	5.838	4.714
Average soil quality	4.359	1.912	2.106
Euclidean distance to urban areas	0.314	0.636	0.603
Euclidean distance to roads	0.097	0.133	0.193
Average cumulative deforestation (ha)	971.528	1022.954	853.725
Average annual deforestation (ha)	244.444	215.119	171.086
Proportion of primary forests in the buffer zone (%)	44.8	60.7	71.3
Proportion of secondary forests in the buffer zone (%)	7.8	5.3	3.7
Proportion of pastures in the buffer zone (%)	46.4	29.6	19.0
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	29,106.07	–

*Based on 11 synthetic-control donors from indigenous lands.

Table A1-12. REDD+ project: *The Valparaiso Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	28,988	29,906	29,700
Initial forest cover (%)	98.90	99.32	99.11
Euclidean distance to state capital	5.050	2.074	2.69
Euclidean distance to highways	0.124	0.138	0.136
Average slope	3.621	5.140	5.874
Average soil quality	3.243	3.299	3.733
Euclidean distance to urban areas	0.297	0.421	0.581
Euclidean distance to roads	0.181	0.245	0.311
Average cumulative deforestation (ha)	142.188	127.974	108.295
Average annual deforestation (ha)		25.692	20.076
Proportion of primary forests in the buffer zone (%)	97.0	95.5	95.6
Proportion of secondary forests in the buffer zone (%)	1.7	1.9	1.9
Proportion of pastures in the buffer zone (%)	1.0	2.1	2.1
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	56.164	–

*Based on five synthetic-control donors from Acre state.

Annex 2. Annual deforestation analyses: covariate balance between the REDD+ polygons and synthetic controls for the period from 2001 to project start year

Table A2-1. REDD+ project: *ADPML Portel-Para REDD Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	149,147	99,167	116,644
Initial forest cover (%)	99.58	99.72	97.99
Euclidean distance to state capital	2.222	2.705	3.207
Euclidean distance to highways	0.504	0.48	0.242
Average slope	4.036	6.406	5.032
Average soil quality	2.000	2.597	2.474
Euclidean distance to urban areas	0.496	0.542	0.605
Euclidean distance to roads	0.277	0.288	0.276
Average cumulative deforestation (ha)	113.194	105.051	1244.349
Average annual deforestation (ha)	27.083	26.824	266.715
Proportion of primary forests in the buffer zone (%)	83.8	89.9	86.2
Proportion of secondary forests in the buffer zone (%)	1.8	1.8	2.8
Proportion of pastures in the buffer zone (%)	0.1	1.3	4.6
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	295.161	–

*Based on 12 synthetic-control donors, four from Pará state, two from Acre state, and six from Amazonas state.

Table A2-2. REDD+ project: *Agrocortex REDD Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	186,369	115,623	135,140
Initial forest cover (%)	99.99	99.98	98.63
Euclidean distance to state capital	1.975	4.212	3.357
Euclidean distance to highways	0.437	0.41	0.23
Average slope	4.800	4.755	4.693
Average soil quality	3.898	3.848	2.795
Euclidean distance to urban areas	0.450	0.410	0.638
Euclidean distance to roads	0.373	0.359	0.303
Average cumulative deforestation (ha)	1.786	8.758	1461.748
Average annual deforestation (ha)	0.446	1.166	177.397
Proportion of primary forests in the buffer zone (%)	98.2	97.7	89.0
Proportion of secondary forests in the buffer zone (%)	0.4	0.5	2.6
Proportion of pastures in the buffer zone (%)	0.9	0.2	3.4
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	6.832	–

*Based on 13 synthetic-control donors, four from Acre state, two from Mato Grosso state, five from Amazonas state, and two from Pará state.

Table A2-3. REDD+ project: *Florestal Santa Maria Project* (FSM)

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	71,662	72,504	77,054
Initial forest cover (%)	99.76	99.29	97.89
Euclidean distance to state capital	4.663	2.220	2.892
Euclidean distance to highways	0.155	0.315	0.250
Average slope	5.115	5.800	5.267
Average soil quality	2.000	2.071	2.286
Euclidean distance to urban areas	0.346	0.663	0.644
Euclidean distance to roads	0.040	0.290	0.328
Average cumulative deforestation (ha)	93.056	87.595	943.310
Average annual deforestation (ha)	13.889	17.573	207.639
Proportion of primary forests in the buffer zone (%)	86.0	89.9	85.6
Proportion of secondary forests in the buffer zone (%)	1.4	1.9	2.7
Proportion of pastures in the buffer zone (%)	10.1	1.3	4.2
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.2
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	555.622	–

*Based on 18 synthetic-control donors, one from Acre state, seven from Pará state, seven from Amazonas state, and three from Mato Grosso state.

Table A2-4. REDD+ project: *Jari/Amapá REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	77,857	76,081	75,533
Initial forest cover (%)	98.33	98.89	97.21
Euclidean distance to state capital	1.544	2.155	2.787
Euclidean distance to highways	0.059	0.289	0.255
Average slope	8.422	8.369	5.97
Average soil quality	2.000	2.000	2.291
Euclidean distance to urban areas	0.231	0.447	0.562
Euclidean distance to roads	0.055	0.116	0.274
Average cumulative deforestation (ha)	952.273	959.812	1458.452
Average annual deforestation (ha)	186.364	185.472	251.243
Proportion of primary forests in the buffer zone (%)	75.5	77.4	84.4
Proportion of secondary forests in the buffer zone (%)	4.0	4.4	3.1
Proportion of pastures in the buffer zone (%)	2.1	3.3	4.8
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.3
Proportion of urban areas in the buffer zone (%)	0.2	0.0	0.0
Mean squared prediction error (Loss V)	–	8609.226	–

*Based on four synthetic-control donors, two Amazonas state and two from Acre state.

Table A2-5. REDD+ project: *Maísa REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	30,976	28,545	31,502
Initial forest cover (%)	95.22	97.46	98.64
Euclidean distance to state capital	1.993	1.968	3.083
Euclidean distance to highways	0.188	0.158	0.259
Average slope	3.704	3.877	5.262
Average soil quality	2.000	2.038	2.473
Euclidean distance to urban areas	0.486	0.741	0.634
Euclidean distance to roads	0.021	0.026	0.218
Average cumulative deforestation (ha)	88.021	70.223	1046.79
Average annual deforestation (ha)	9.375	8.150	145.417
Proportion of primary forests in the buffer zone (%)	75.2	76.0	85.6
Proportion of secondary forests in the buffer zone (%)	8.1	6.6	2.4
Proportion of pastures in the buffer zone (%)	11.8	13.3	7.0
Proportion of agriculture in the buffer zone (%)	0.0	0.5	1.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	109.321	–

*Based on three synthetic-control donors, one Pará state, one from Acre state, and one from Amazonas state.

Table A2-6. REDD+ project: *Manoa REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	72,899	72,858	70,370
Initial forest cover (%)	99.86	99.64	97.67
Euclidean distance to state capital	1.213	2.550	2.815
Euclidean distance to highways	0.238	0.297	0.276
Average slope	4.096	5.994	5.679
Average soil quality	2.000	2.061	2.450
Euclidean distance to urban areas	0.501	0.607	0.622
Euclidean distance to roads	0.146	0.536	0.296
Average cumulative deforestation (ha)	1.923	15.115	1326.224
Average annual deforestation (ha)	0.481	2.226	185.468
Proportion of primary forests in the buffer zone (%)	93.4	94.0	85.6
Proportion of secondary forests in the buffer zone (%)	1.0	1.1	2.6
Proportion of pastures in the buffer zone (%)	4.7	0.2	4.5
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.4
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	8.120	–

*Based on five synthetic-control donors, one from Amazonas state, one from Mato Grosso state, two from Pará state, and one from Acre state.

Table A2-7. REDD+ project: *The Purus Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	35,195	34,186	33,347
Initial forest cover (%)	99.25	99.08	98.21
Euclidean distance to state capital	1.956	2.335	3.017
Euclidean distance to highways	0.19	0.129	0.276
Average slope	5.202	6.712	5.158
Average soil quality	4.000	3.905	2.371
Euclidean distance to urban areas	0.303	0.349	0.614
Euclidean distance to roads	0.176	0.23	0.19
Average cumulative deforestation (ha)	27.273	39.475	1495.718
Average annual deforestation (ha)	9.091	7.088	240.838
Proportion of primary forests in the buffer zone (%)	98.4	95.8	84.5
Proportion of secondary forests in the buffer zone (%)	0.3	1.7	2.8
Proportion of pastures in the buffer zone (%)	0.7	2.0	7.0
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	187.141	–

*Based on three synthetic-control donors, one from Mato Grosso state and two from Amazonas state.

Table A2-8. REDD+ project: *Resex Rio Preto-Jacundá REDD+ Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	99,337	107,867	115,265
Initial forest cover (%)	99.70	95.77	94.88
Euclidean distance to state capital	1.644	3.139	3.169
Euclidean distance to highways	0.059	0.152	0.164
Average slope	3.657	3.538	3.363
Average soil quality	2.000	1.878	1.884
Euclidean distance to urban areas	0.519	0.962	0.824
Euclidean distance to roads	0.113	0.328	0.279
Average cumulative deforestation (ha)	133.333	143.032	178.542
Average annual deforestation (ha)	25.521	22.478	27.833
Proportion of primary forests in the buffer zone (%)	84.1	79.5	73.1
Proportion of secondary forests in the buffer zone (%)	2.5	1.1	1.8
Proportion of pastures in the buffer zone (%)	9.9	2.0	5.8
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.4
Mean squared prediction error (Loss V)	–	1284.135	–

*Based on three synthetic-control donors from sustainable-use reserves.

Table A2-9. REDD+ project: *RMDLT Portel-Para REDD Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	194,550	180,027	162,053
Initial forest cover (%)	99.71	99.424	98.896
Euclidean distance to state capital	2.553	3.539	3.434
Euclidean distance to highways	0.298	0.295	0.206
Average slope	4.683	6.043	5.065
Average soil quality	2.000	3.992	3.278
Euclidean distance to urban areas	0.636	0.561	0.636
Euclidean distance to roads	0.129	0.435	0.225
Average cumulative deforestation (ha)	121.094	152.906	1399.609
Average annual deforestation (ha)	26.562	35.934	315.938
Proportion of primary forests in the buffer zone (%)	94.3	97.3	92.1
Proportion of secondary forests in the buffer zone (%)	1.4	1.1	2.4
Proportion of pastures in the buffer zone (%)	0.7	0.8	3.0
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.8
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	1049.508	–

*Based on eight synthetic-control donors, three from Pará state, two from Amazonas state, and three from Acre state.

Table A2-10. REDD+ project: *The Russas Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	42,519	38,875	41,637
Initial forest cover (%)	99.35	99.26	99.22
Euclidean distance to state capital	5.128	3.607	2.759
Euclidean distance to highways	0.044	0.143	0.148
Average slope	3.533	5.836	5.934
Average soil quality	2.730	3.937	3.479
Euclidean distance to urban areas	0.174	0.343	0.481
Euclidean distance to roads	0.174	0.236	0.276
Average cumulative deforestation (ha)	102.083	107.934	216.732
Average annual deforestation (ha)	16.146	17.263	35.677
Proportion of primary forests in the buffer zone (%)	94.9	92.1	93.2
Proportion of secondary forests in the buffer zone (%)	2.8	2.6	2.1
Proportion of pastures in the buffer zone (%)	1.9	4.7	4.2
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	95.576	–

*Based on eight synthetic-control donors from Acre state.

Table A2-11. REDD+ project: *Suruí Forest Carbon Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	247,796	258,174	218,195
Initial forest cover (%)	98.68	98.53	98.57
Euclidean distance to state capital	3.493	3.702	3.459
Euclidean distance to highways	0.193	0.275	0.319
Average slope	5.809	5.882	4.714
Average soil quality	4.359	1.937	2.106
Euclidean distance to urban areas	0.314	0.647	0.603
Euclidean distance to roads	0.097	0.127	0.193
Average cumulative deforestation (ha)	971.528	1010.878	853.725
Average annual deforestation (ha)	244.444	214.523	171.086
Proportion of primary forests in the buffer zone (%)	44.8	59.6	71.3
Proportion of secondary forests in the buffer zone (%)	7.8	5.5	3.7
Proportion of pastures in the buffer zone (%)	46.4	30.5	19.0
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.1	0.0
Mean squared prediction error (Loss V)	–	15,703.52	–

*Based on eight synthetic-control donors from indigenous lands.

Table A2-12. REDD+ project: *The Valparaiso Project*

Variable	Project	Synthetic control*	Donor-pool mean
Area (ha)	28,988	29,767	29,700
Initial forest cover (%)	98.90	99.12	99.11
Euclidean distance to state capital	5.050	2.731	2.69
Euclidean distance to highways	0.124	0.148	0.136
Average slope	3.621	5.221	5.874
Average soil quality	3.243	3.49	3.733
Euclidean distance to urban areas	0.297	0.417	0.581
Euclidean distance to roads	0.181	0.242	0.311
Average cumulative deforestation (ha)	127.841	130.909	108.295
Average annual deforestation (ha)	25.000	25.178	20.076
Proportion of primary forests in the buffer zone (%)	96.8	92.3	95.6
Proportion of secondary forests in the buffer zone (%)	1.7	2.7	1.9
Proportion of pastures in the buffer zone (%)	1.3	4.3	2.1
Proportion of agriculture in the buffer zone (%)	0.0	0.0	0.0
Proportion of urban areas in the buffer zone (%)	0.0	0.0	0.0
Mean squared prediction error (Loss V)	–	128.364	–

*Based on six synthetic-control donors from Acre state.